DYNAMIC RESPONSES OF A SPAR PLATFORM DUE TO WAVES AND CURRENT

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

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Approved by,

(AP Dr. Kurian V John)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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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.

MELVIN LAU IK YEONG

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ABSTRACT

The SPAR is a floating offshore structure which is gaining consideration as the solution to deepwater drilling and production due to its hydrodynamic stability. This report describes a theoretical analysis of the dynamic motion responses of a spar due to wave and current, in correlation to model deviations recorded from laboratory testing. Frequency domain analyses are run on a full-scale classic spar with real design environmental parameters, as well as a scaled-down model subject to laboratory conditions. As a parametric study, the effect of current velocity on the hydrodynamic motions is investigated for both spars. As a result, surge motion was observed the most significant, heave responses generally of magnitude about 25% of surge, and very benign pitch responses were obtained. Increase in current velocity principally increases surge motions, have little impact on pitch, and almost negligible impact on heave responses.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

As oil and gas exploration and production venture into deepwater reserves, so does the challenge arise for offshore structures to sustain such operations. The spar, a deepwater drilling and/or production platform design is considered an effective solution in response to such a challenge, for water depths of 1000-3000m.

The floating structure comprises a topside supported by a buoyant cylindrical hull sitting vertically in water, station-kept by a taut catenary mooring system. The spar is favourable because of its hydrodynamic stability, as a result of:

- Deep hull draft, provided by variable ballast in the hard tank as well as fixed ballast in compartments at the keel
- A low centre of gravity which is always below the centre of buoyancy, providing restoring moments against rotational motions
- The taut mooring lines near the CG that provide lateral resistance to motions of the spar
- Helical strakes around the hull designed to resist vortex shedding

In addition, the spar design allows dry tree technology where wellhead equipment is located on the platform instead of on the seabed, allowing cost- and time-effective well intervention.

Another advantage of the spar platform is the shielding of conductors and risers from hydrodynamic loading near the water surface where wave and current action are most pronounced. They are safely located and flexibly connected in the hull centerwell.

1.1.1 Generations of Spar Designs

To date, the spars in operation and under construction in the world have seen three generations of design, in chronological order: the classic (caisson), truss and cell spar.

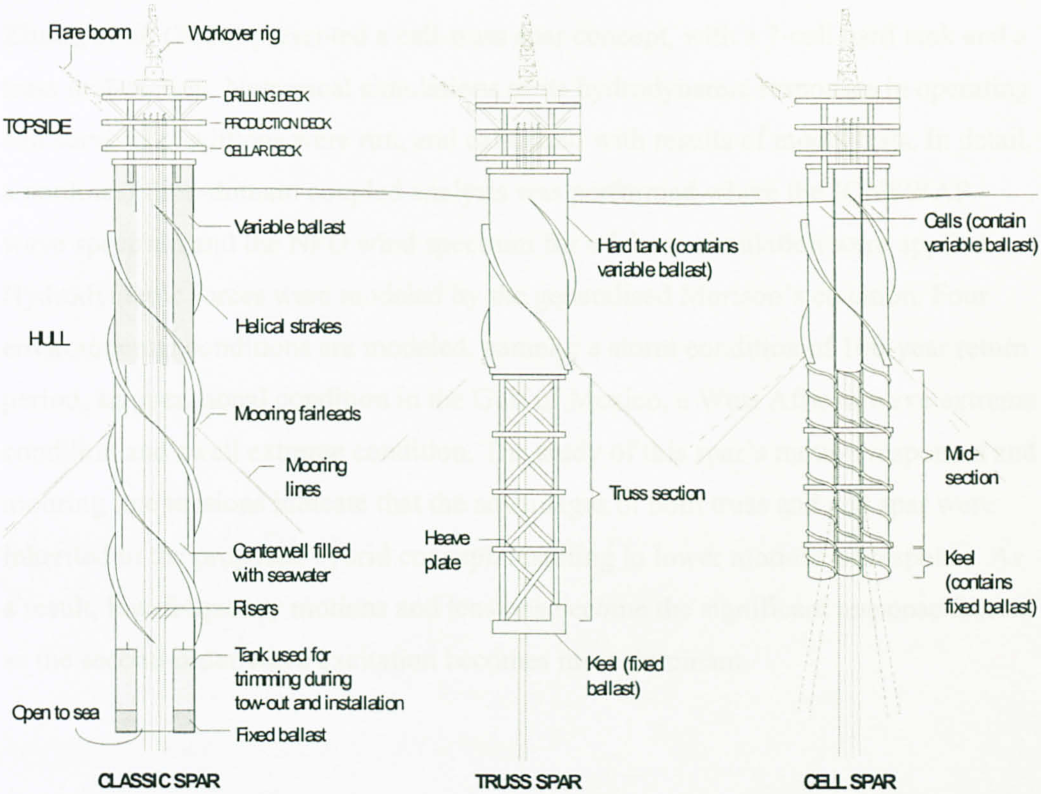

Figure 1 Three generations of the spar design

The classic spar hull is simply a cylindrical caisson, comprising a hard tank near the top in which variable ballasting controls the spar's buoyancy, a hollow mid-section that is typically free-flooded with seawater, and a soft tank at the keel that contains fixed ballast for stability. Above the fixed ballast is a tank specifically used to upend the spar during installation.

The truss spar replaces the classic spar's mid-section with a truss structure. The trusses are further strengthened by heave plates between truss bays. The truss section not only reduces weight and cost but also the area hit by wave and current, hence lowering the hydrodynamic forces and overturning moments experienced. The heave plates impede vertical movement of water mass that contributes to heave motion.

The third-generation spar known as the cell spar comprises multiple cylindrical tanks or 'cells', typically in a hexagonal formation surrounding a central cell. The primary cells extend below the hard tank to form the keel. This assembly is simpler and more economical than constructing a single large caisson, while the multiple cylinders contribute to lower vortex-induced vibration (VIV) effects compared to the classic spar's single cylindrical hull (**Chakrabarti, 2005**).

Zhang et al. (2006) presented a cell-truss spar concept, with a 7-cell hard tank and a truss mid-section. Numerical simulations of its hydrodynamic responses in operating and survival conditions were run, and calibrated with results of model tests. In detail, a nonlinear time-domain coupled analysis was performed where the JONSWAP wave spectrum and the NPD wind spectrum for a 3-hour simulation were applied. Hydrodynamic forces were modeled by the generalised Morison's equation. Four environmental conditions are modeled, namely: a storm condition of 100-year return period, an operational condition in the Gulf of Mexico, a West African wave extreme condition and swell extreme condition. The study of this spar's motion responses and mooring line tensions indicate that the advantages of both truss and cell spar were inherited in the proposed hybrid concept, resulting in lower motions of response. As a result, low-frequency motions and tensions become the significant response factors as the second-order wave excitation becomes more dominant.

1.1.2 Worldwide Spar Survey

Spars were historically employed for gathering of oceanographic data, oil storage and offloading (Shells' Brent Spar in the North Sea, installed in 1975) or as marker buoys (Agip's flare spar off West Africa, installed in 1992).

The world's first production spar, the Neptune platform in the Gulf of Mexico was installed by Kerr-McGee (formerly Oryx) in 1996. As of this report, there are 16 spars operating in the world and one under construction, the basic details tabulated below:

Table 1: Spars In Operation And Under Construction Worldwide

Year	Name	Type	Location	Dia. (m)	Lgh. (m)	W.D. (m)	Constructed by
1996	Neptune	Classic	GOM	22	215	590	JRayMcDermott
1998	Genesis	Classic	GOM	37	215	790	Technip
2000	Diana	Classic	GOM	37	215	1450	Technip
2001	Nansen	Truss	GOM	28	166	1125	Technip
2002	Boomvang	Truss	GOM	28	166	1055	Technip
2003	Horn Mountain	Truss	GOM	32	169	1650	Technip
2003	Gunnison	Truss	GOM	30	168	950	Technip
2003	Holstein	Truss	GOM	46	228	1325	Technip
2003	Front Runner	Truss	GOM	29	179	1006	JRayMcDermott
2003	Medusa	Truss	GOM	29	179	680	JRayMcDermott
2003	Devil's Tower	Truss	GOM	29	179	1710	JRayMcDermott
2005	Mad Dog	Truss	GOM	39	169	1375	Technip
2004	Red Hawk	Cell	GOM	20	171	1620	Technip
2006	Constitution	Truss	GOM	30	168	1525	Technip
2007	Kikeh	Truss	Malaysia	32	142	1330	Technip
2008	Tahiti	Truss	GOM	39	170	1280	Technip
U/C*	Perdido	Truss	GOM	36	269	2440	Technip

*U/C – Under Construction

GOM – Gulf of Mexico, USA

The first Malaysian spar, which also happens to be the first outside the Mexican Gulf was engineered, constructed and installed by Technip in the Kikeh Development Field off Sabah in 2006, at a water depth of 1330m. The Kikeh Dry Tree Unit holds the world record for first spar topside (single integrated deck) installed by catamaran floatover, a technique devised by Technip.

The latest spar in construction is Shell's Perdido spar, awarded to Technip for EPC (Engineering, Procurement and Commissioning) and to begin production at the end of 2009. It is set to be the deepest spar production facility in the world, to be moored in about 2440m depth (ultra-deepwater) in the Gulf of Mexico.

1.2 PROBLEM STATEMENT

1.2.1 The Research Problem

Malaysia is the pioneer in deepwater drilling and production in Asia, marked by the employment of the region's first spar in the recently discovered Kikeh field. The spar is recognized as an economical yet effective floating platform for the deepwater environment, yet only few corporations in the world have the expertise in designing such a structure to meet its heightened environmental challenges. PETRONAS stands a challenging opportunity in establishing and developing a regional knowledge base in spar platform analyses. This dissertation addresses this interest by examining the general behaviour and magnitudes of a spar's hydrodynamic responses in the frequency domain.

1.2.2 The Industry Problem

Extreme spar responses introduce risks such as tabulated below:

Table 2: Risks and their contributing factors

Risk	Contributing factors
Deck accelerations	Pitch response
Riser stresses and fatigue at keel	Pitch response
Riser stresses and fatigue at mudline	Surge, sway responses
Mooring line tensions	Currents, wind and wave loading
Riser stroke	Surge, sway responses Heave (important but not dominant)

The cyclic motions/responses of a spar due to wave and current are to be studied to determine if the displacements are within tolerable limits. Ultimately, the understanding of these motions will facilitate future innovative designs.

1.3 OBJECTIVES OF STUDY

1. To prepare a detailed literature survey report about the spar platform existing and under design or construction stage.
2. To analyse the motions of the platform subjected to random waves and current.
3. To determine the effect of various current speeds on the responses.
4. To test a model in the wave tank and/or flume and determine the responses for comparison with analytical results.

1.4 SCOPE OF OBJECTIVES

1. The literature survey is conducted with sources from the UTP Information Resource Centre and journals available from online resources.
2. The analyses are confined to frequency-domain dynamic analyses.
3. The Pierson-Moskowitz wave spectrum is used in the analyses.
4. A model is conceived whereby its dimensions are fixed with a specific ratio to an actual structure.

CHAPTER 2

LITERATURE REVIEW

2.1 THEORY

2.1.1 Methods of Analyses

Hydrodynamic forces and responses of a spar platform due to wave and current can be approximated by two methods: frequency domain or time domain analysis. Frequency domain analysis uses spectral formulations to estimate the structure's responses to due to a random, irregular wave. Its limitation is that nonlinearities in the equations of motion are replaced by linear approximations. Time domain analyses on the other hand involves numerical integration of the equations of motion, incorporating nonlinearities due to drag-related forces as a result of the interaction between wave motion and structural members, e.g. mooring line forces and viscous damping.

The frequency domain approach was selected considering its relative simplicity for modeling and interpretation, compared to the more complex time domain analyses which also consume longer processing time.

2.1.2 Environmental Simulation

A design wave environment is simulated by adopting a suitable wave spectrum model, which is ideally formulated based on wave statistics recorded at a site of interest. However, because local statistically-generated wave spectra are not available, a theoretical spectrum model is adopted: the Pierson-Moskowitz (P-M) spectrum, a simple yet common model applicable to most waters in the world. The P-M model assumes fully-developed wind waves in an open sea, where the duration and fetch are long enough for equilibrium to be attained between waves and wind.

The spectral energy density, S(*f*) as a function of cyclic frequency, *f* is given by:

$$S(f) = \frac{0.0081g^2}{(2\pi)^4} f^{-5} \exp\left[1.25\left(\frac{f}{\frac{1}{2\pi}\sqrt{\frac{0.161g}{H_s}}}\right)^{-4}\right] \quad (2.1)$$

Where H_s – significant wave height at the geographical site of interest

g – gravitational acceleration

The irregular wave can be visualized as a combination of many component waves, each with its own energy and frequency. The energy spectrum describes the distribution of these component waves by frequency. The wave height, $H(f)$ at a particular frequency f can be obtained from the spectrum by the following equation:

$$H(f) = 2\sqrt{2 \cdot S(f) \cdot \Delta f} \quad (2.2)$$

With known H values for each frequency within the range of the spectrum, the combined force due to all wave components can be computed.

2.1.3 Motion Response Approximation

A Response-Amplitude Operator (RAO) is a normalized response function constructed for a range of wave spectrum frequencies, transferring exciting waves into structural responses. RAO is defined as response amplitude per wave amplitude.

Considering an uncoupled SDOF and linearly damped system, the equation of motion in an arbitrary translational x-direction is

$$m\ddot{x} + C\dot{x} + K_x x = F\cos(2\pi f t) \quad (2.3)$$

And the equation of a rotational motion of angular distance x is

$$I\ddot{x} + C\dot{x} + K_x x = M\cos(2\pi f t) \quad (2.4)$$

In the above equations, m = total mass of the system, I = mass moment of inertia about the axis of rotation, C = damping coefficient, K_x = stiffness of the system in the direction of motion, F = force amplitude, M = moment amplitude; $\ddot{x}$, $\dot{x}$, and x

respectively acceleration, velocity and displacement in the direction of motion (S.I. units are metres for translational motion and radians for rotational motion.)

The motion spectrum is obtained in terms of the wave spectrum and RAO:

$$S_x(f) = RAO_x(f)^2 \cdot S(f) \tag{2.5}$$

where for translational motion,

$$RAO_x(f) = \frac{F_x/(\frac{H}{2})}{\sqrt{(K_x - m\cdot(2\pi f)^2)^2 + (C\cdot 2\pi f)^2}} \tag{2.6}$$

and for rotational motion,

$$RAO_x(f) = \frac{M/(\frac{H}{2})}{\sqrt{(K_x - I\cdot(2\pi f)^2)^2 + (C\cdot 2\pi f)^2}} \tag{2.7}$$

Equation 2.6 is a modified RAO formula where the inertial force term, F_I in the conventional formula has been replaced with the total force term, F_x. This is significant for surge motion as the effect of current in the drag force component is of interest in this study.

The total mass term in the equations above is the sum of structural mass and added mass. The added mass (dependent on type of motion) and viscous damping terms in this analysis are assumed as linear constants.

2.2 LITERATURE REVIEW

K. Sadeghi et al. (2003) performed a frequency-domain response analysis on a truss spar, where the wave excitation forces acting on the truss portion are derived by an unconventional, simplified method – by force decomposition of the Morison equation – where viscous effects were added to the linear equations of motion, and where the nonlinear equations of heave motion were solved without iteration in the frequency domain. This approach is verified with the conventional numerical analysis and experimental data.

The results of heave motion was found to agree closely with experimental data and was significantly higher than their conventional numerical results. Pitch motion was found to be underpredicted, and as pitch is inversely proportional to surge, it can be inferred that the latter was overpredicted.

The article concludes that this new approach is effectively accurate with respect to experimental results and more efficient computationally than conventional numerical analysis.

Tao et al. (2004) studied the heave response of a classic spar with constant cross-sectional area, and 4 similar spars with alternative hull shapes. Linear and nonlinear wave loads were evaluated by the potential theory, incorporating viscous damping.

The heave natural periods of the spars with alternative hull shapes were found to be higher than the classic spar, because of their larger mass and increase in the added mass. The higher the heave added mass coefficient, the larger the natural period, the further the peak heave RAOs fall outside of the wave frequency range plotted by the JONSWAP spectrum and thus the more efficient the spar hull design. However, this method of stabilising a spar is not economical as it increases material consumption.

From another perspective, the heave exciting forces can be reduced by increasing the draft or enhancing the counteractive force mechanism of the alternative hull shapes, the latter being more practical in this study. The alternatively-shaped spars were found to experience higher heave excitation forces than the classic spar at low wave periods but lower forces at higher wave periods.

Applying linear viscous damping for the classic spar and 4 alternative hull shapes without helical strakes and excluding the mooring lines, the heave RAOs for all these spars were found to be greatly reduced. In reality, damping forces from the mooring system contribute to further heave reduction, thus realistic heave responses would be lower than those obtained in this study. It was concluded that a beneficial shape would be a cylindrical spar hull with a thin disk attached to the keel.

I. Anam and **J. M. Roesset** (2002) compared three types of methods to approximate nonlinear wave kinematics and forces acting on a spar up to the instantaneous free water surface. The methods are Extrapolation and Stretching, both modifications of the Linear Wave Theory, and the Hybrid Wave Model. The second order difference frequency forces from the Morison equation are hence used in the analysis.

Three types of Extrapolation schemes – hyperbolic, linear and uniform extrapolation – returned identical results (in terms of forces due to free surface fluctuation) up to the second order. Their differences in the third order indicates reasonable consistency between hyperbolic and linear extrapolation but not uniform extrapolation.

Two types of Stretching methods, proposed by Wheeler 1969 and Chakrabarti 1971 were employed and found to produce similar offsets and first-order responses, also comparing well with the Extrapolation methods. The second-order responses at the difference frequency were agreeable between the Stretching methods, but are smaller than Extrapolation results by 40-48% for surge and 18-29% for pitch values. Nonetheless, the second-order forces integrated up to the free water surface predicted by the Stretching methods are identical to that predicted by the Linear Wave Theory integrated up to the mean water level.

For the Hybrid Wave Model, the decomposition of wave data are only valid up to the second order. It was found that in the time domain, decomposition results in a lower response in terms of surge. However, in the frequency domain, wave decomposition produces a higher response. Transient effects are suppressed in the frequency domain, and these differences demonstrate that the time domain takes into account the higher-order effects – which may be caused by drag and nonlinear geometry.

A.K. Agarwal and **A.K. Jain** (2003) conducted a dynamic wave response analysis on an integrated spar-and-mooring-line model in the time domain. The iterative incremental Newmark's Beta approach was used. Wind and current effects are not included in this study. Two cases of initial horizontal force, namely 2500 kN and 2000 kN respectively are presented. The stiffness matrix coupling, structural damping, inertia coefficient C_m, and drag coefficient C_d were also manipulated to study their influence on the steady state time histories of response.

The numerical results indicate that the force-excursion relationship of the mooring lines can be reasonably approximated by a nonlinear model with different stiffnesses, compared to that of a mooring line with multilinear segments. The effect of each manipulated parameter is also discussed:

- The lower the initial horizontal force, the lower the horizontal response.
- The influence of structural damping is minimal when considering higher structural damping ratios, considering horizontal mooring line displacement. Structural damping effects are influential for lower structural damping ratios concerning horizontal mooring line displacement, or when both horizontal and vertical mooring line excursion are considered.
- The coupling of the stiffness matrix, as well as accurate application of C_m and C_d were found to significant affect the dynamic response.

CHAPTER 3

METHODOLOGY

In a nutshell, numerical analyses for a full-scale spar and a scaled-down model, as well as laboratory model testing were carried out; the theoretical and experimental results for the model respectively correlated to achieve agreement in terms of **dynamic** time histories of responses and their respective amplitude **range**. The general flow of work is as follows.

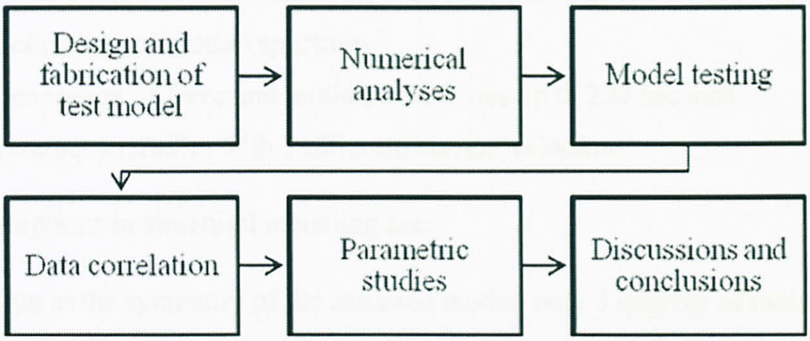

Figure 2 Research Methodology

3.1 NUMERICAL ANALYSES

The theoretical calculations were jointly conducted with Microsoft Office 2007 and Wolfram Mathematica 6.0. Macro-enabled spreadsheets were developed separately for surge, heave and pitch response of a spar (frequency domain, SDOF). Numerical analyses are run on a full-scale Neptune spar as well as a scaled-down test model.

The general flow of analysis for each motion is as follows:

1. Generation of wave energy spectrum and wave elevation time series.
2. Computation of forces and Response Amplitude Operators (RAO)
3. Generation of motion spectrum
4. Generation of force and motion time series up to 200 seconds
5. Parametric studies with 3 different current velocities

The assumptions in structural modeling are:

- Due to the symmetry of the assumed model, only 3 degrees of motion – surge, heave and pitch – are significant. Each of these 3 motions is studied considering an uncoupled Single Degree-of-Freedom (SDOF) system.

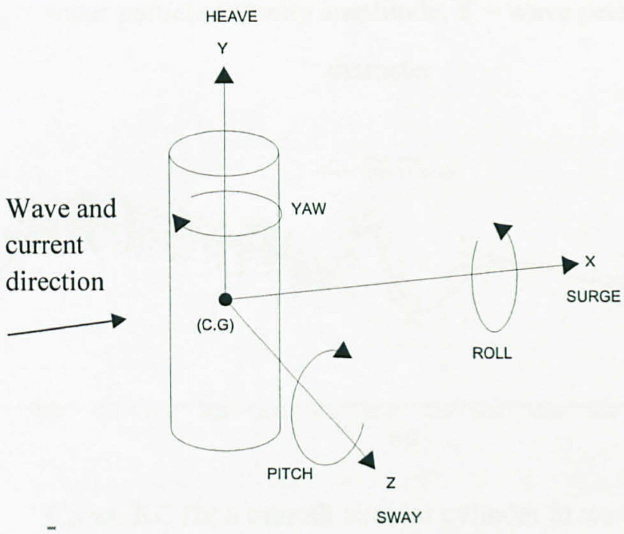

Figure 3 Six degrees of motion of a floating cylinder

- The spar is modelled as a rigid cylinder, without internal stiffness (flexural and axial). Its static resistance is contributed by hydrostatic stiffness. The spar's mooring stiffness is neglected in the computations.
- A unidirectional wave (0° incident angle) and a collinear, horizontal current velocity vector are considered. The current velocity is linearised (assumed constant) along the draft, considering that current velocity does not vary much with depth near the water surface.
- As damping is contributed significantly by Morison drag forces, the other sources such as structural, radiation and wave drift damping are negligible. A damping ratio of 0.02 is assumed.
- Wind forces are neglected and the slope of seabed/tank is assumed constant.
- Drag and mass coefficients (C_D and C_M) for the full-scale model are assumed to be 0.65 and 1.6 respectively (with reference to PTS clause 4.5(a), assuming clean members). C_D and C_M in the experiments are obtained from the Keulegan-Carpenter number, given the current velocity and wave period.

$$KC = \frac{u_0 * T}{D} \tag{3.1}$$

Where u_0 = water particle velocity amplitude, T = wave period and D = member diameter

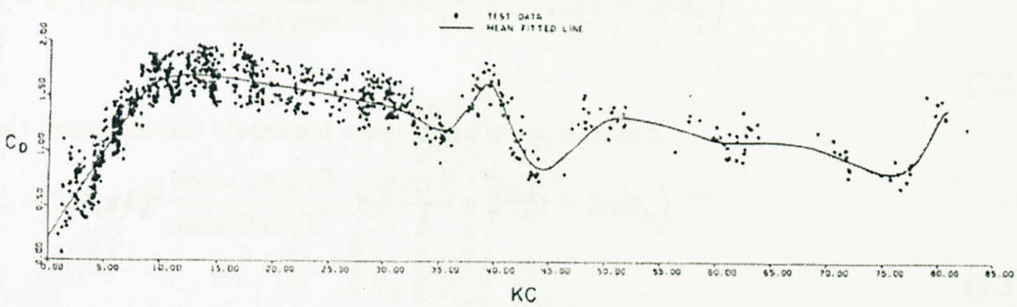

Figure 4 C_D vs. KC for a smooth circular cylinder in waves (Chakrabarti, 2001)

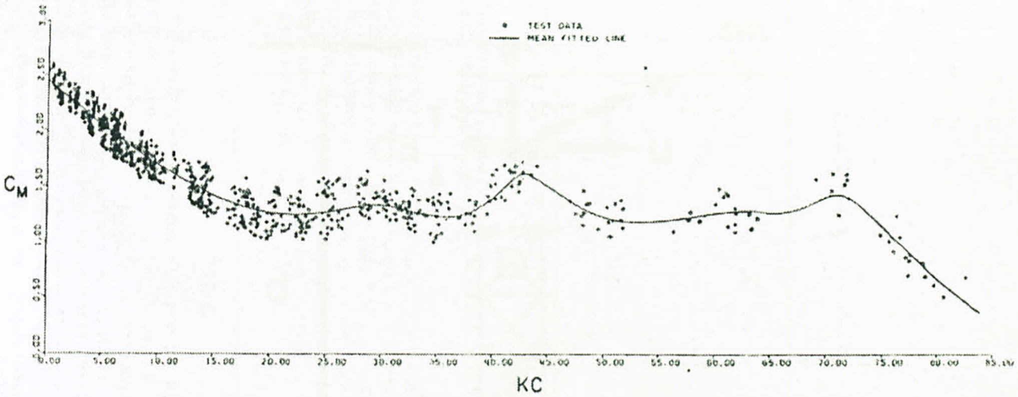

Figure 5 C_M vs KC for a smooth circular cylinder in waves (Chakrabarti, 2001)

3.1.1 Surge Forces

The Morison equation is used to calculate surge forces on the spar due to wave and current. This method is appropriate for computing wave forces on structures that are small relative to wavelength, where diffraction is negligible. This condition is assumed to hold true for the slender-bodied spar. The Morison equation assumes that the wave force comprises a drag and inertia component.

The Linear Wave Theory gives the instantaneous horizontal water particle velocity,

$$u = u_c(s) + \pi H f \frac{\cosh(2\pi s/L)}{\sinh(2\pi d/L)} \cos\left(\frac{2\pi x}{L} - 2\pi f t + 2\pi R_n\right) \quad (3.2)$$

and instantaneous horizontal water particle acceleration,

$$\dot{u} = 2H(\pi f)^2 \frac{\cosh(2\pi s/L)}{\sinh(2\pi d/L)} \sin\left(\frac{2\pi x}{L} - 2\pi f t + 2\pi R_n\right) \quad (3.3)$$

where $u_c(s)$ is the current velocity at elevation s from seabed

d is the water depth at the site of interest

Coordinates s and x are illustrated in **Figure 6**

t is elapsed time and R_n a random number between 0 and 1

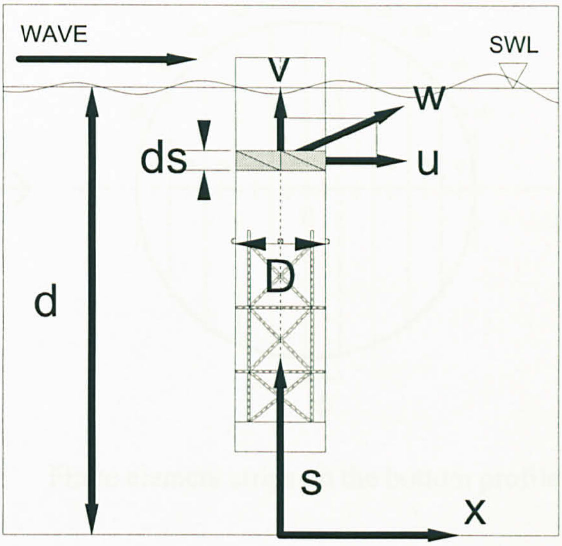

Figure 6 Graphical representation of coordinates and variables

For each segment ds along the draft at time t,

Drag force component, $F_E = 0.5 C_D \rho D |u| u \, ds$ (3.4)

Inertia force component, $F_I = C_M \rho \frac{\pi}{4} D^2 \dot{u} \, ds$ (3.5)

Where ρ is the water density, D the spar diameter and ds a small segment of the cylindrical hull as shown in **Figure 6** above.

Total surge force, $F = F_D + F_I$ (3.6)

3.1.2 Heave Forces

The dynamic pressure at an elevation s from the seabed is given by:

$$p(t) = \rho g \frac{H \cosh(2\pi s/L)}{2 \cosh(2\pi d/L)} \cos(kx - 2\pi f t)$$

(3.7)

The heave force acting on the base sectional area is a product of this dynamic pressure and the area acted upon. However, as the dynamic pressure varies with x-coordinate (in the wave propagation direction) and an actual size spar can have diameters up to 40m, it is necessary to divide the bottom section into finite elements, or strips perpendicular to the wave direction.

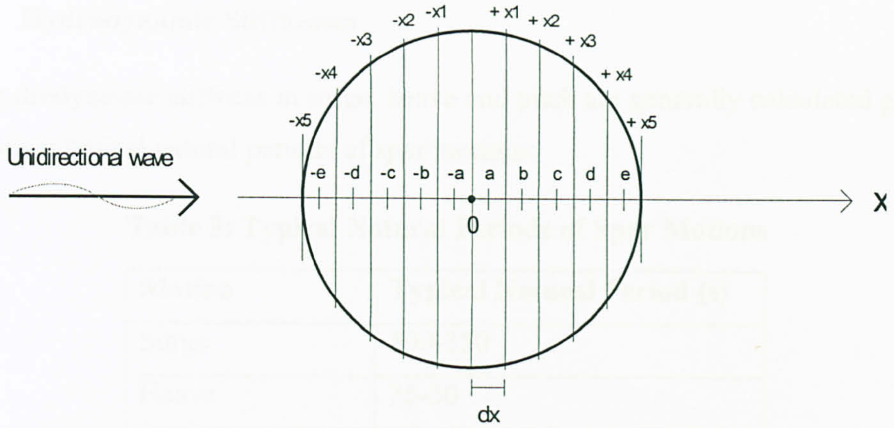

Figure 7 Finite element strips on the bottom profile of the spar

The heave force acting on individual strips are summed to obtain the total heave force acting on the spar. For example, for a section divided into 10 strips, the strip bordered by 0 and $+x1$ has the x-coordinate of a and thus the dynamic heave force acting on it is

$$F_{z,a}(t) = \rho g \frac{H}{2} \frac{\cosh(2\pi s/L)}{\cosh(2\pi d/L)} \cos(ka - 2\pi f t) * 2 * \int_{0}^{x1} \sqrt{r^2 - a^2}\, dx$$

(3.8)

In actual fact, the elevation s changes with dynamic heave motions, and if accuracy was of severe concern the old s value should be superseded in computations for the next time step. However, for simplicity s is assumed constant, taken as the elevation of the spar base when it is in equilibrium with still water.

3.1.3 Pitch Moments

The overall pitch moment experienced by the spar are calculated from the surge forces along the hull (and assuming heave forces do not contribute), estimated as

$$M = \sum F_{surge} \cdot \delta \tag{3.9}$$

where δ is the lever arm, i.e. the distance between the surge force and the spar's Centre of Gravity.

3.1.4 Hydrodynamic Stiffnesses

The hydrodynamic stiffness in surge, heave and pitch are generally calculated given the known typical natural periods of spar motions:

Table 3: Typical Natural Periods of Spar Motions

Motion	Typical Natural Period (s)
Surge	300-350
Heave	25-30
Pitch	50-100

The heave hydrodynamic stiffness can also be calculated by

$$K_z = \rho g * A_{water\ plane} \tag{3.10}$$

3.1.5 NEPTUNE Spar Input Parameters

The environmental and structural parameters applied in calculating the Neptune spar responses are as follow:

Seawater density	1025 kg/m^3
Significant wave height, GOM	10 m
P-M spectral frequency range	0.03 – 0.3 Hz
Water depth at location	590 m
Current velocities	0, 0.5 and 1.0 m/s
Drag coefficient, C_D	1.0
Inertia coefficient, C_M	2.0
Spar diameter	22 m
Spar length and draft	215 m and 198 m, respectively
Spar mass on land	77.13 E+06 kg
Radius of gyration (pitch)	67.36 m (assumed)
Distance of CG from base of spar	95 m (assumed, knowing fairleads position)
Damping ratio	0.05 (5%)
Surge natural period, stiffness	325 secs, 5.766E+04 N/m
Heave natural period, stiffness	30 secs, 3.509E+06 N/m
Pitch natural period, stiffness	75 secs, 1.083E+06 Nm/rad

3.2 MODEL SETUP AND TESTING

The test model is a classic spar without helical strakes around the hull. It is modeled after the Neptune spar, on a scale of approximately 1:340 to adopt reasonable proportions. The model setup is illustrated below:

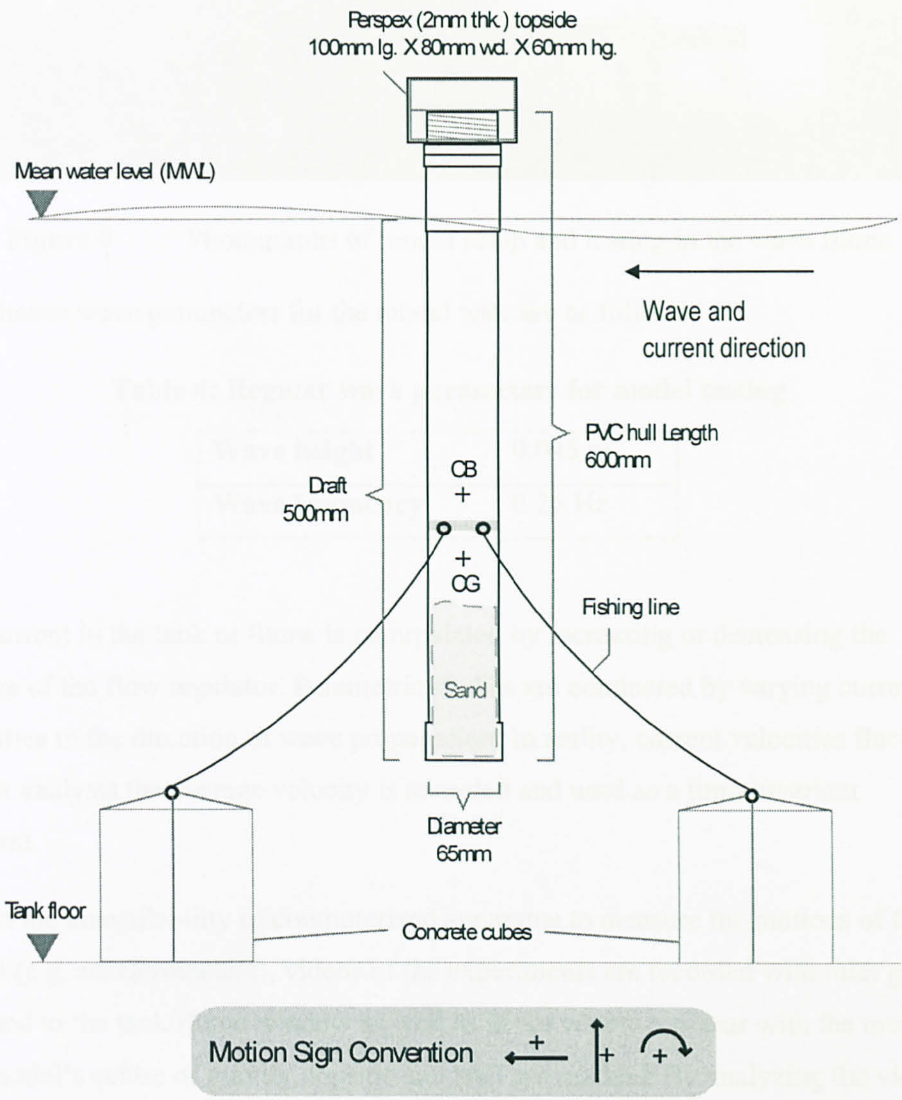

Figure 8 The Model Setup

The hull of the test model is 0.065m in diameter and 0.6m long, constructed of a hollow polyvinyl chloride (PVC) pipe with a water-tight closed fitting at the bottom end. Sand is used to ballast the cylinder to a desired draft of 0.5m. Assembled on the top end is a detachable, custom-fabricated Perspex topside which allows storage for additional ballasting weights. The mooring system is formed by 6 fishing lines spaced equally apart: each approximately 0.6 m long, its top end attached to fairleads located between the CG and CB of the spar, and the other end tied to a concrete cube on the tank floor.

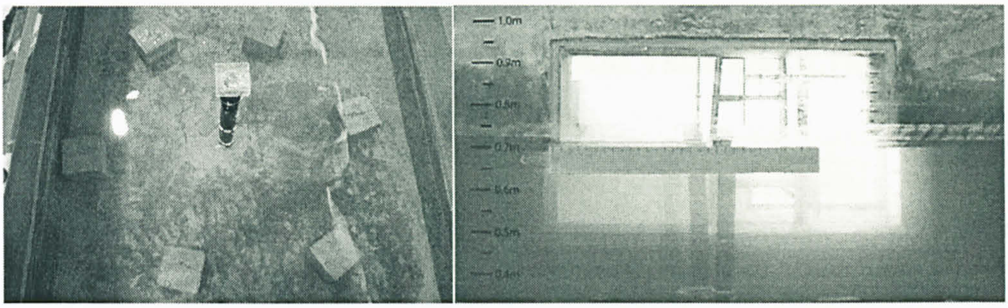

Figure 9 Photographs of model setup and testing in the wave flume

The chosen wave parameters for the model tests are as follows:

Table 4: Regular wave parameters for model testing

Wave height	0.045 m
Wave frequency	0.25 Hz

The current in the tank or flume is manipulated by increasing or decreasing the voltage of the flow regulator. Parametric studies are conducted by varying current velocities in the direction of wave propagation. In reality, current velocities fluctuate but for analysis the average velocity is recorded and used as a time-invariant constant.

Due to the unavailability of computerized apparatus to measure the motions of the model (e.g. accelerometers), videos of the experiments are recorded with ruler guides attached to the tank/flume window as well as in the water, coplanar with the model. The model's centre of gravity, topside and keel are marked. By analyzing the video stills on 1-second intervals, the markers are used to roughly produce time histories of surge, heave and pitch. Adobe Photoshop is employed for this purpose.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 FULL-SCALE SPAR (NEPTUNE) ANALYSES RESULTS

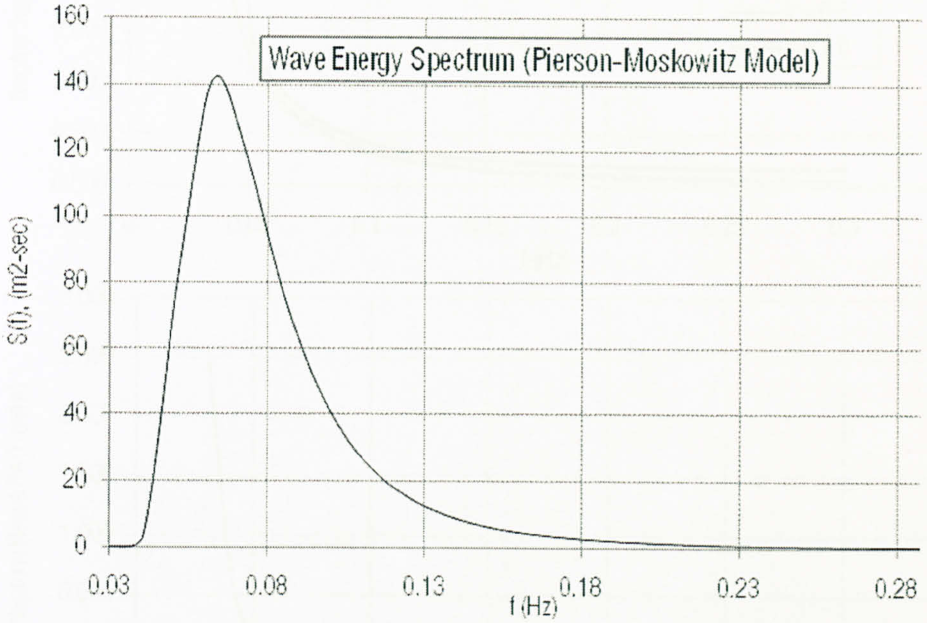

Figure 10 The P-M Wave Energy Density Spectrum

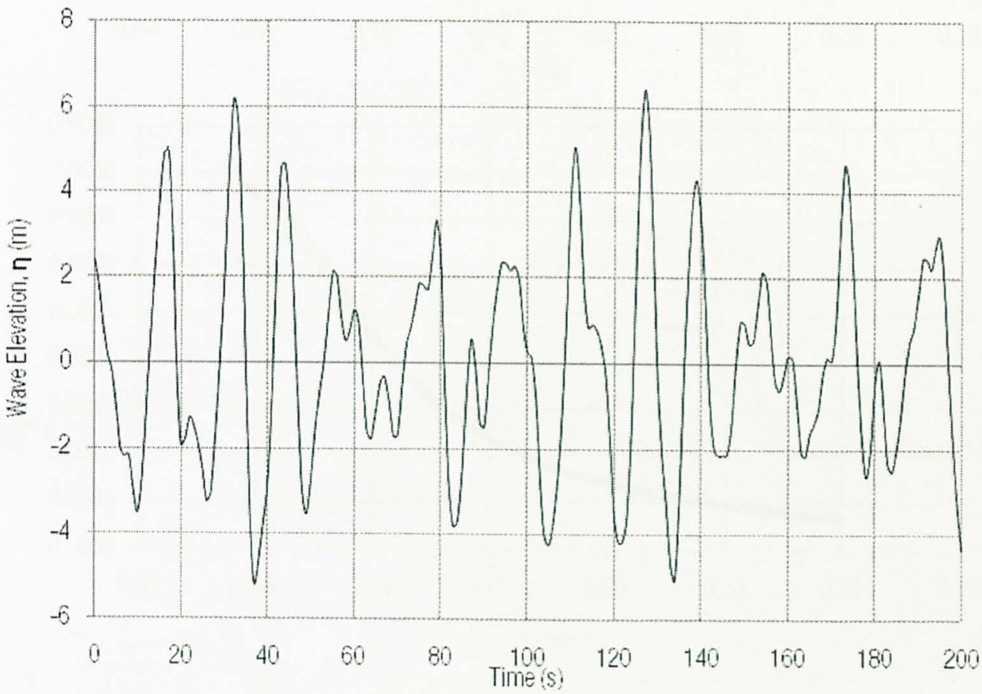

Figure 11 The Time Series of Wave Elevation

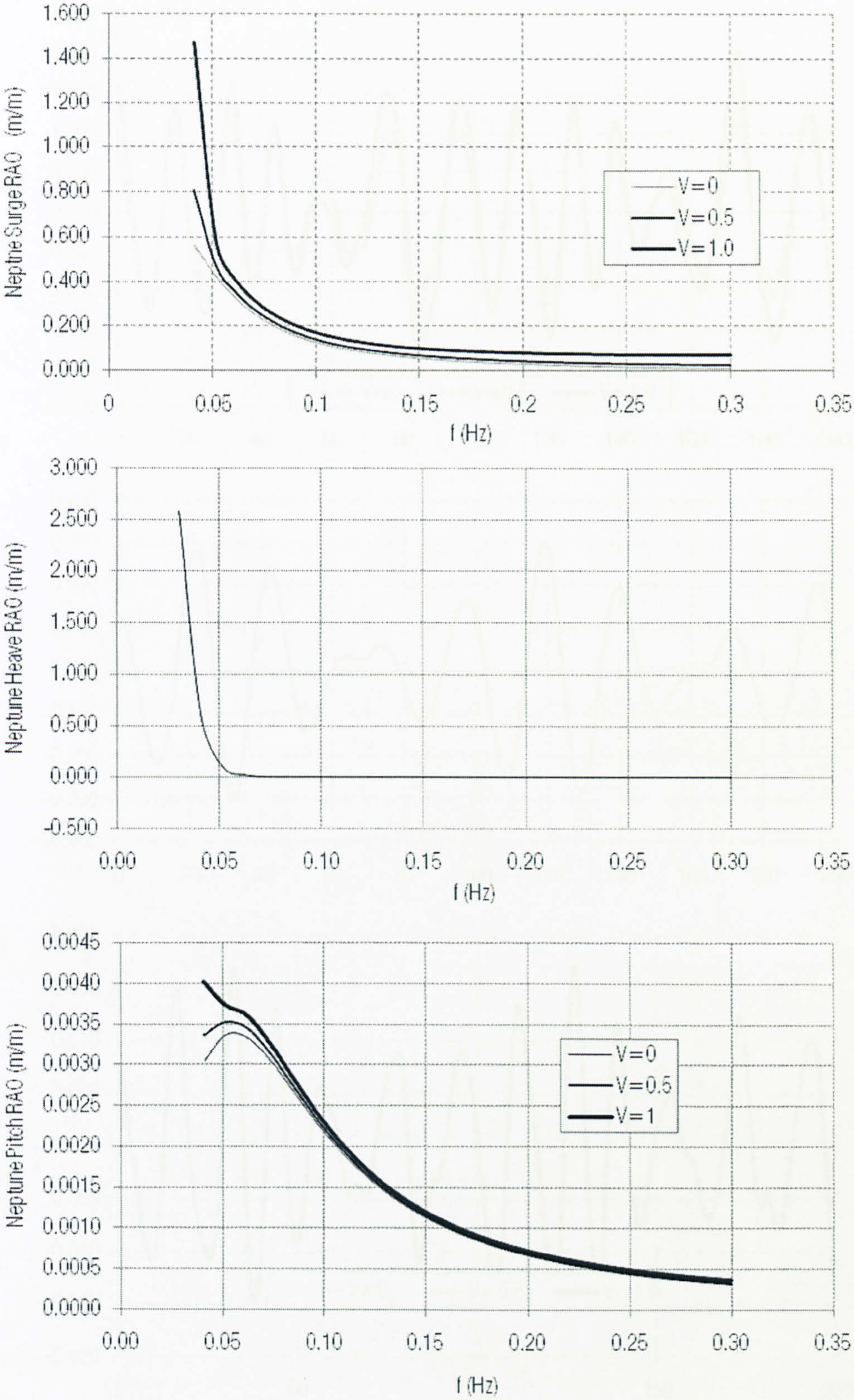

Figure 12 Response Amplitude Operators

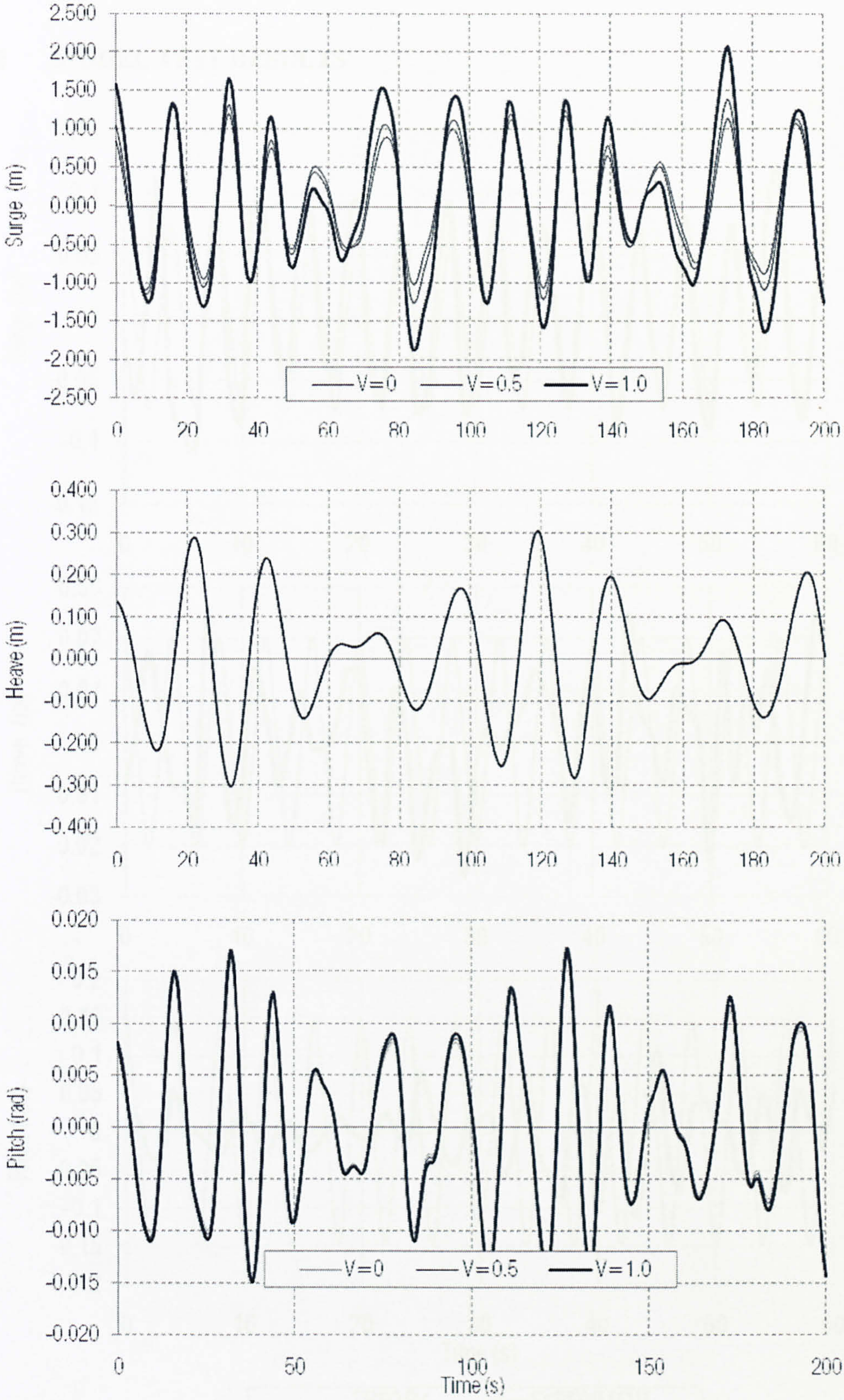

Figure 13 Time Series of Responses

4.2 MODEL TEST RESULTS

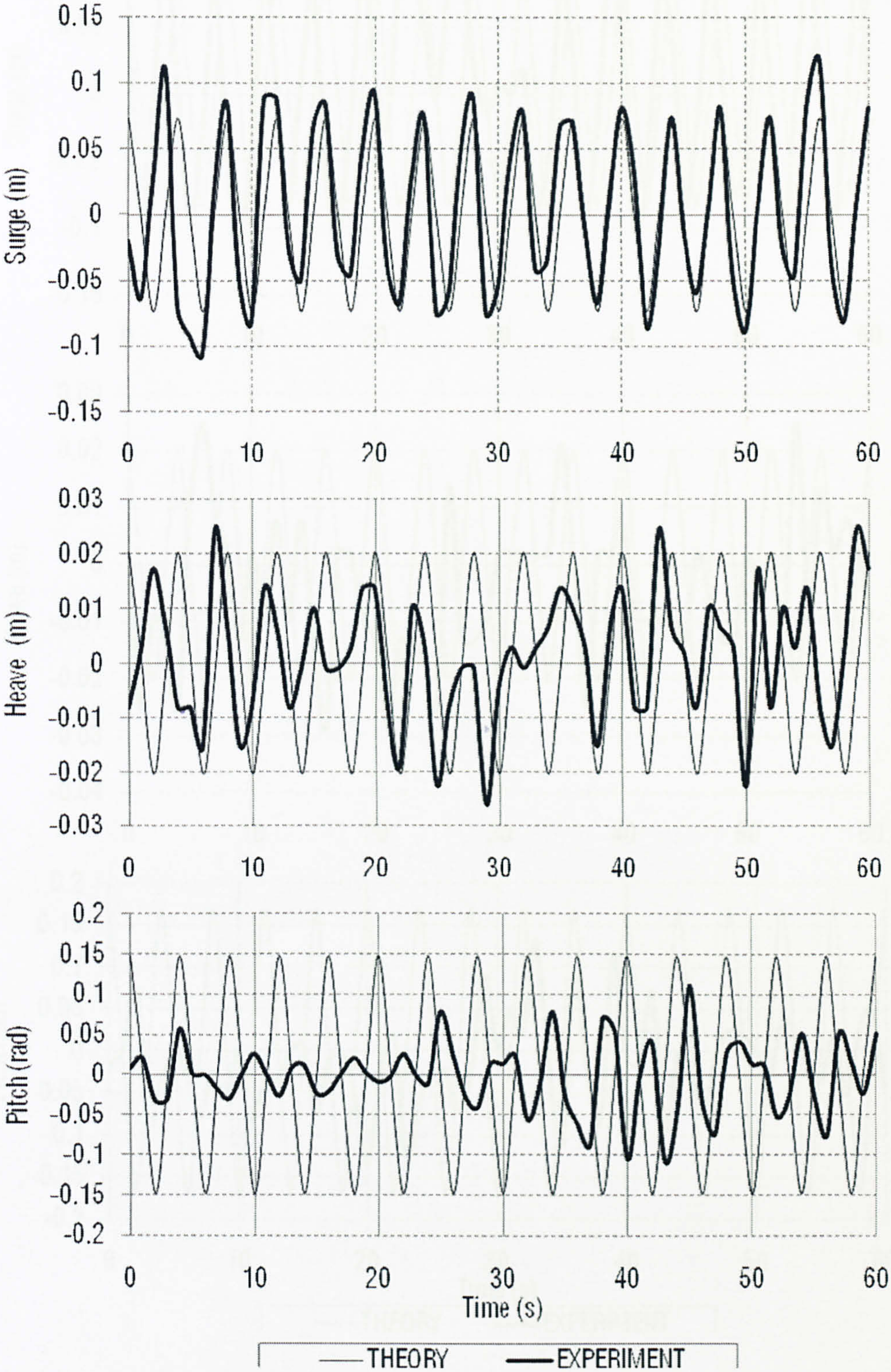

Figure 14 Time Series of Test Model Responses for V = 0.5 cm/s

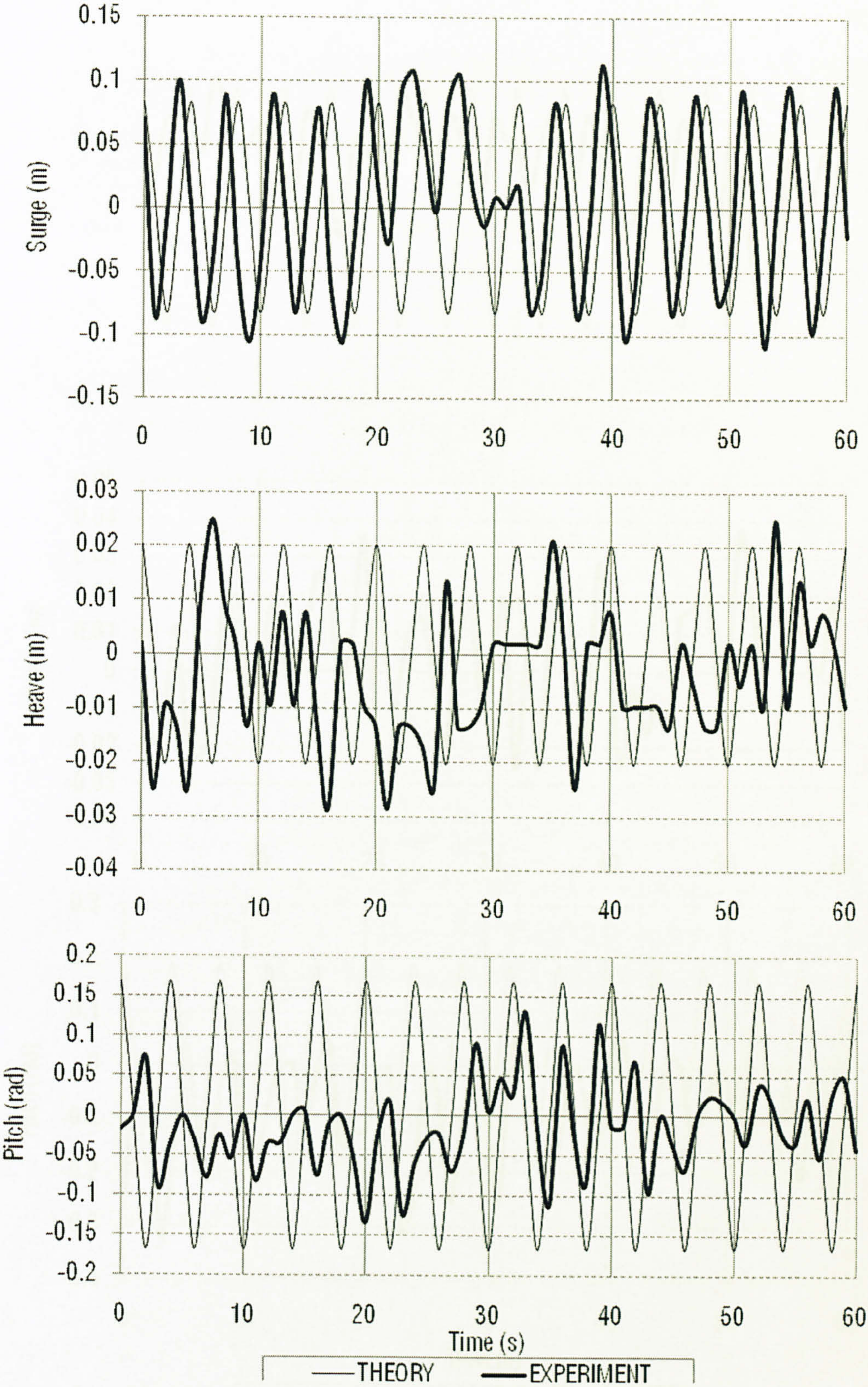

Figure 15 Time Series of Test Model Responses for V = 7 cm/s

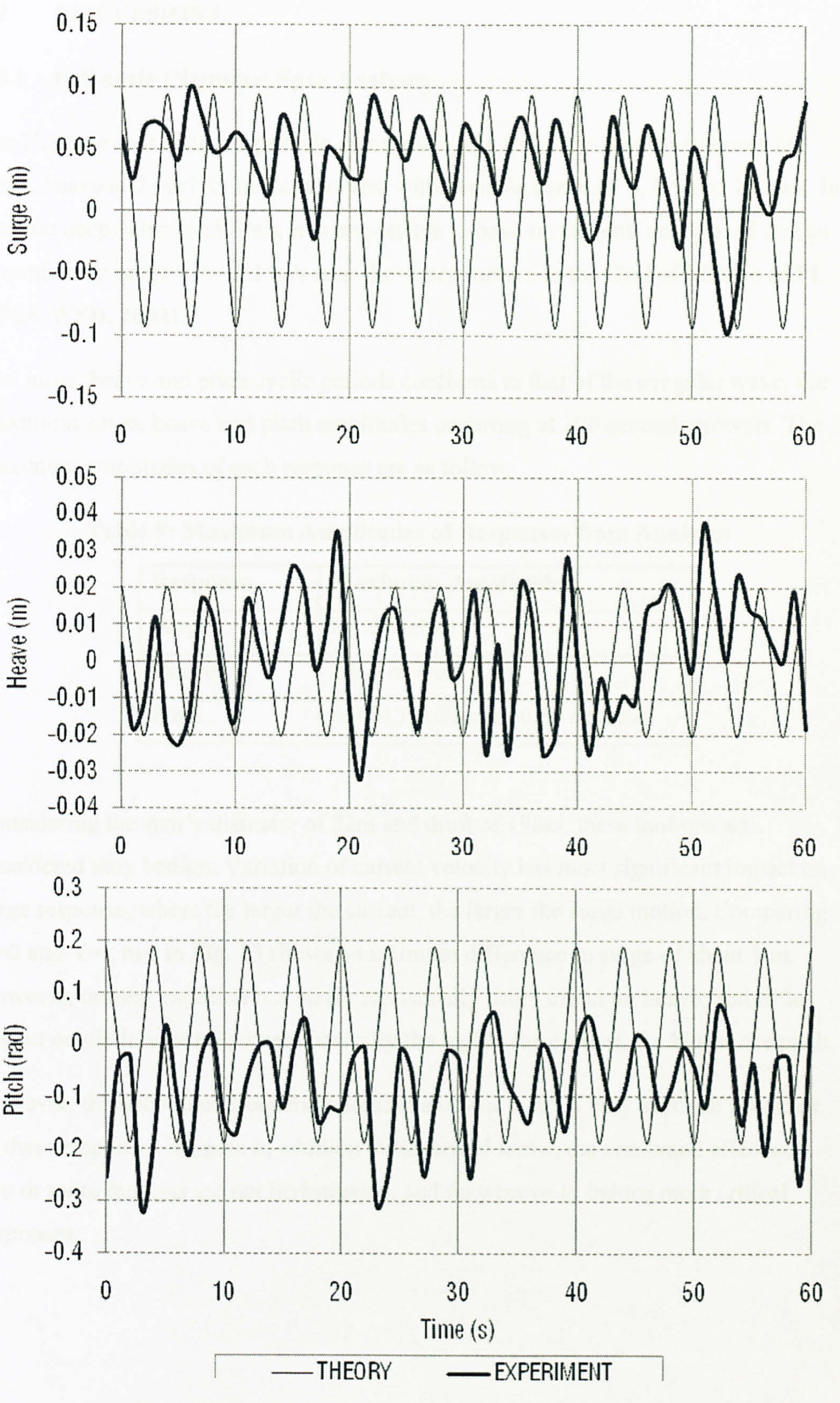

Figure 16 Time Series of Test Model Responses for V = 11 cm/s

4.3 DISCUSSIONS

4.3.1 Full-scale (Neptune) Spar Analyses

The Neptune spar analyses provide an estimate of a full-scale spar's responses in surge, heave and pitch in random waves, with variable currents: 0, 0.5 and 1.0 m/s. In realistic deepwater conditions, it is impossible to have no current; and typical design currents may range 0.7 – 1.1 m/s near the water surface in the Gulf of Mexico **(API RP2A-WSD, 2002)**.

The surge, heave and pitch cyclic periods conforms to that of the irregular wave; the maximum surge, heave and pitch amplitudes occurring at 100-second intervals. The maximum amplitudes of each response are as follow:

Table 5: Maximum Amplitudes of Responses from Analyses

Response	Maximum Amplitude
Surge	± 1.5 metres
Heave	± 0.3 metres
Pitch	± 0.015 radians or 0.86 degrees

Considering the spar's diameter of 22m and draft of 198m, these motions are considered very benign. Variation of current velocity has most significant impact on surge response, where the larger the current, the larger the surge motion. Comparing V=0 and V=1 m/s in **Fig. 13** shows a maximum difference in surge of about 1 m. However, current variation has no (or realistically little) effect on heave; and little impact on pitch response, where basically the higher the current, the higher the pitch.

However, the uncoupled frequency-domain analysis is not a very accurate predictor of these responses because in addition to linearised terms, the combined effects of two or more motions are not investigated, and may prove to induce more critical responses.

4.3.2 Model Tests

The model tests were run by generating a regular wave, although in reality not perfectly so, which accounts for the random variations in the amplitudes of motions studied. The variations in experimental heave are explainable by the fact that the analysis was conducted assuming a purely horizontal current velocity vector but in actual fact, the currents in the flume are random, varying in magnitude and direction with time.

Surge and heave seem to be predicted well for the first two currents, 0.5 cm/s and 7 cm/s **(Figs. 14 and 15)** in terms of the amplitude of displacements and frequency of oscillation. Generally, heave response amplitudes are approximately 25% that of surge. In these 2 tests, pitch appears to be slightly over-predicted, but the calculated pitch amplitude is comparable with the maximum rotation measured in the tests.

For a large current (relative to the model spar's size and weight), 11 cm/s **(Fig. 16)**, the experiment time series show surge and pitch are eccentric in the direction of current. Constantly applied current-drag on the spar prevents it from surge oscillation about its equilibrium **(Fig. 16, Surge)**, but the spar tends to drift away with the current. Higher current velocities near the water surface also cause negative moments (refer to sign convention on **Fig. 8**) to predominate **(Fig. 16, Pitch)**. Generally, heave is observed to be little or not affected by this increase in current velocity.

An important observation is that at large currents (11cm/s) the maximum surge and pitch are limited by mooring line stiffness, where the tendency of the spar to drift away or rotate further is resisted by tension in the mooring lines.

The theoretical frequency-domain calculations could not account for this eccentricity or offset of motions induced by high current, nevertheless the oscillatory range of surge and pitch are agreeable.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In light of the findings, several conclusions have been made:

- Model testing not only offers confirmation in terms of the frequency and amplitudes of the predicted motions, but also provides a picture of actual responses which cannot be obtained from theoretical calculations in the uncoupled SDOF, frequency domain alone.
- The computations on the full-scale Neptune spar are important to provide an idea of actual magnitudes of the responses.
- Generally, the responses are in phase (or with little lag) with the wave cycles, and are benign – thus justifying the spar's effectiveness as a deepwater offshore platform.
- An increase in ocean current causes a significant yet non-extreme increase in surge response, but is not likely to affect heave motions. An increase in current velocity also generally contributes to larger pitch, but at an insignificant scale.
- High ocean currents do not necessarily result in a large oscillatory range of surge and pitch, but if current is acting constantly, it will cause the surge and pitch oscillations to offset, or be eccentric in the direction of the current.
- Therefore, mooring lines are crucial in station-keeping at conditions of large current, such as a 100-year storm or hurricane condition.

Recommended further developments on this project are possibly:

- Coupled time domain analyses – to incorporate nonlinearities and combined effects of all degrees of motion, preferably with coupling between spar and mooring lines as well.
- Analyses on variable spar geometry – to investigate and innovate spar designs which will reduce the effect of wave and current on the responses.

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APPENDICES

APPENDIX A

TEST MODEL STRUCTURAL CALCULATIONS

A.1 CENTRE OF GRAVITY

The hull is divided into 5 distinct components, and the centre of gravity (CG) of the entire model is found by taking moments of component weights against the base of the spar and then dividing by total weight of the model.

	CS Area (m2)	Height (m)	Density (kg/m3)	Mass (kg)	Lever arm frm base (m)	M (N.m)
Hull-Sect-1	0.000584336	0.03	1390	0.0243668	0.585	0.13979477
Hull-Sect-2	0.00111448	0.08	1390	0.1239302	0.53	0.64415311
Hull-Sect-3	0.000584336	0.455	1390	0.3695635	0.2625	0.95138105
Keel	0.00111448	0.035	1390	0.0542195	0.0175	0.00930528
Sand	0.002733971	0.13699188	1602	0.6	0.0715	0.4207203
Sum		**0.6**		**1.17208**		2.16535451

C.O. Gravity	Theoretical CG (from base)	0.1883804
C.O. Buoyancy	Draft (m)	0.5
	CB (from base)= draft/2	0.25
Metcentric Hgt	Area mom of I at WPA (m4)	3.023E-07
	Vol of fluid displaced (m3)	0.0016592
	CG - CB	-0.06162
	Metacentric hgt (m)	0.0618019 positive, hence stable

A.2 MASS MOMENT OF INERTIA (PITCH)

The mass moment of inertia about the pitch rotation axis is calculated for each component. The mass moment of inertia of the entire model is found by using the parallel axis theorem: $I_{global} = \sum (I_{component} + \text{Component Mass} * d^2)$

	Height (m)	R,outer (m)	R,inner (m)	Mass (kg)	Dist of cg to CGM	Icg	I-CG model (kg.m2)
Hull-Sect-1	0.030	0.0325	0.0295	0.024	0.397	0.0000	0.0038
Hull-Sect-2	0.080	0.035	0.0295	0.124	0.342	0.0001	0.0146
Hull-Sect-3	0.455	0.0325	0.0295	0.370	0.074	0.0066	0.0086
Keel	0.035	0.035	0.0295	0.054	0.171	0.0000	0.0016
Sand	0.137	0.0295	SOLID	0.600	0.117	0.0011	0.0093
						TOTAL	**0.0379**

d - parallel distance between component CG and model CG

M - mass

CG - cg of component

CGM - cg of entire model

APPENDIX B

TEST MODEL ANALYSIS PROGRAM (MATHEMATICA)

B.1 SURGE CALCULATIONS FOR TEST MODEL

```
(* SURGE / TESTMODEL / REGULARWAVE, Rev. 02 Apr '09 20h30;

---------------   EDITABLE PARAMETERS (SURGE Only)   -------------*)

H (* Waveheight, m *) = 0.04;
f (* Frequency, Hz *)= 0.25;
Tnat (* Natural Surge Period, s *)=35;
Dens (* Seawater Density^ *) = 1000;
d (* Water Depth, m *) = 0.71;
Vc (* Current Velocity, m/s *) = 0.005;
Dia (* Spar Diameter, m *) =0.065;
h (* Spar Draft, m *) = 0.5;
Cd (* Drag Coefficient *) = 0.3;
Cm (* Inertia Coefficient *) = 2.5;
m0 (* Structural Mass, kg *) = 1.17208;
x (* Horizontal Coordinate *)=0;
ds (* Incremental segment height, m *) = 0.005;
dt (* Time Increment, s *) = 1;
Tlimit (* Timelimit, s *) = 60;
DampRatio (* Damping Ratio *) =0.05;

(*----------   END OF EDITABLE PARAMETERS (SURGE Only)   ----------*)

pi=N[Pi,10];g = 9.807;
s0 =d-h+(ds/2);s1 = d-(ds/2);
SurgeAddedMass =Dens*pi/4*Dia^2*h;
M = m0 + SurgeAddedMass;
K0 = 4*pi^2*M/(Tnat^2);
C0 = DampRatio*2*(K0*M)^0.5;

Print["f= ",f  ];
Print["M= ",M  ];
Print["K0= ",K0  ];
Print["C0= ",C0  ];

omega=2*pi*f;
ksolver=FindRoot[omega^2==g*b*Tanh[b*d],{b,.5}];k=ksolver[[1,2]];

s=s0; Fmax=0;
While[s≤s1,
 umax=Vc+pi*H*f*Cosh[k*s]/Sinh[k*d];
 amax=2*H*(pi*f)^2*Cosh[k*s]/Sinh[k*d];

Fmax=Fmax+(0.5*Cd*Dens*Dia*Abs[umax]*umax*ds)+(Cm*Dens*pi/4*Dia^2*am
ax*ds);
 s=s+ds]

RAOnom = Abs[Fmax]/(H/2); RAOdenom = ((K0-
M*omega^2)^2+(C0*omega)^2)^0.5;
RAO=RAOnom/RAOdenom; Print["RAO = ",RAO];
```

```
Print["------------------- Time Series ---------------------"];

Array[n,Tlimit];Array[Fsurge,Tlimit];Array[Xsurge,Tlimit];
t=0;
While[t≤Tlimit,
 n[t]=0;Xt=0;Ft=0;
 s=s0;
 While[s≤s1,
  (* Velocity, independent *)
u=Vc+(pi*H*f*Cosh[k*s]/Sinh[k*d]*Cos[k*x-omega*t]);
  (* Acceleration, independent *)
a=2*H*(pi*f)^2*Cosh[k*s]/Sinh[k*d]*Sin[k*x-omega*t];
  Ft+=(0.5*Cd*Dens*Dia*Abs[u]*u*ds)+(Cm*Dens*pi/4*Dia^2*a*ds);
  s+=ds];

 n[t]=(H/2)*Cos[k*x-omega*t];
 Xt=RAO*(H/2)*Cos[k*x-omega*t];

 Fsurge[t]=Ft;
 Xsurge[t]=Xt;

 t+=dt]

ListPlot[Table[n[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Wave Elevation (m)"}]
ListPlot[Table[Fsurge[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Surge Force (N)"}]
ListPlot[Table[Xsurge[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Surge Response (m)"}]
```

B.2 HEAVE CALCULATIONS FOR TEST MODEL

```
(* HEAVE/TESTMODEL/REGULARWAVE, Rev. 02 Apr '09 23h00;

----------------   EDITABLE PARAMETERS (HEAVE Only)   ------------*)

H (* Wave Height *)=0.04;
f (* Wave Frequency *)=0.25;
Dens (* Seawater Density^ *) = 1000;
d (* Water Depth, m *) =0.71;
Vc (* Current Velocity, m/s *) = 0.005;
Dia (* Spar Diameter, m *) = 0.065;
h (* Spar Draft, m *) = 0.5;
Cd (* Drag Coefficient *) = 0.3; Cm (* Inertia Coefficient *) = 2.5;
m0 (* Structural Mass, kg *) = 1.17208;
dx (* Incremental x-coord, m *) = 0.0065; (* For ease dx = Dia/10
hence 10 finite strips *)
dt (* Time Increment, s *) = 1; Tlimit (* Timelimit, s *) = 60;
DampRatio (* Damping Ratio *)=0.05;

(*---------   END OF EDITABLE PARAMETERS (HEAVE Only)   ----------*)

pi=N[Pi,10]; g = 9.807;
s =d-h;
r=Dia/2;
HeaveAddedMass=Dens*pi/12* Dia^3;

M = m0 + HeaveAddedMass;
K0 = Dens*9.807*(pi/4* Dia^2);
C0 = DampRatio*2*(K0*M)^.5;

Print["M= ",M ];
Print["K0 = ",K0 ];
Print["C0 = ",C0 ];

omega=2*pi*f;
ksolver=FindRoot[omega^2==g*b*Tanh[b*d],{b,.5}];
k=ksolver[[1,2]];

Fmax=Dens*g*H/2*Cosh[k*s]/Cosh[k*d]*pi/4*Dia^2;
RAOnom=Abs[Fmax]/(H/2);
RAOdenom=((K0-M*omega^2)^2+(C0*omega)^2)^0.5;
RAO=RAOnom/RAOdenom;
Print["RAO =",RAO];

Print["--------------------   Time Series   ----------------------"];

Array[n,Tlimit];Array[Fheave,Tlimit];Array[Zheave,Tlimit];

t=0;
While[t≤Tlimit,
 Ft=0;Zt=0;x=0;
 Ft=Dens*g*H/2*Cosh[k*s]/Cosh[k*d]*Cos[k*x-omega*t]*pi/4*Dia^2;
 n[t]=H/2*Cos[k*x-omega*t];
 Zt=RAO*n[t];

 Fheave[t]=Ft;
 Zheave[t]=Zt;
```

```
 t+=dt]

ListPlot[Table[n[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Wave Elevation (m)"}]
ListPlot[Table[Fheave[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Heave Force (N)"}]
ListPlot[Table[Zheave[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Heave Response (m)"}]
```

B.3 PITCH CALCULATIONS FOR TEST MODEL

```
(* PITCH/TESTMODEL/REGULARWAVE, Rev 04 Apr '09 00h30;

--------------   EDITABLE PARAMETERS (PITCH Only)  ---------------*)
H (* Waveheight, m *) = 0.04;
f (* Frequency, Hz *)= 0.25;
Tnat (* Pitch Natural Period, s *)=18;

Dens (* Seawater Density^ *) = 1000;
d (* Water Depth, m *) = 0.71;
Vc (* Current Velocity, m/s *) = 0.005;

Dia (* Spar Diameter, m *) =0.065;
h (* Spar Draft, m *) = 0.5;

Cd (* Drag Coefficient *) = 0.3; Cm (* Inertia Coefficient *) = 2.5;

m0 (* Structural Mass, kg *)=1.17208;
CG (* Distance of Centre of Gravity from base *)=0.188380357;
Iy0(* Mass Moment of Inertia, kg-m^2 *) = 0.0379;

x (* Horizontal Coordinate *)=0;
ds (* Incremental segment height, m *) = 0.005;
dt (* Time Increment, s *) = 1; Tlimit (* Timelimit, s *) = 60;
DampRatio (* Damping Ratio *) =0.05;

(*---------   END OF EDITABLE PARAMETERS (PITCH Only)   ----------*)

pi=N[Pi,10];g = 9.807;
s0 =d-h+(ds/2);s1 = d-(ds/2);
sCG=CG+s0;
SurgeAddedMass =Dens*pi/4*Dia^2*h;

Iy=Iy0+Iy0*(SurgeAddedMass/m0);
K0 = 4*pi^2*Iy/(Tnat^2);
C0 = DampRatio*2*(K0*Iy)^0.5;

Print["f= ",f  ];
Print["K0= ",K0  ];
Print["C0= ",C0  ];

omega=2*pi*f;
ksolver=FindRoot[omega^2==g*b*Tanh[b*d],{b,.5}];
k=ksolver[[1,2]];

s=s0;Mmax=0;
While[s≤s1,
 umax=Vc+pi*H*f*Cosh[k*s]/Sinh[k*d];
 amax=2*H*(pi*f)^2*Cosh[k*s]/Sinh[k*d];

Fmax=(0.5*Cd*Dens*Dia*Abs[umax]*umax*ds)+(Cm*Dens*pi/4*Dia^2*amax*ds
);
 Mmax+=Fmax*(sCG-s);
 s+=ds]

RAOnom = Abs[Mmax]/(H/2);
RAOdenom = ((K0-Iy*omega^2)^2+(C0*omega)^2)^0.5;
```

```
RAO=RAOnom/RAOdenom;
Print["RAO = ",RAO];

Array[n,Tlimit];Array[Moment,Tlimit];Array[Pitch,Tlimit];
Print["------------------ Time Series -------------------------"];
t=0;
While[t≤Tlimit,

 n[t]=0;Moment[n]=0;Pitch[n]=0;
 s=s0;
 While[s≤s1,
  u=Vc+(pi*H*f*Cosh[k*s]/Sinh[k*d]*Cos[k*x-omega*t]);
  a=2*H*(pi*f)^2*Cosh[k*s]/Sinh[k*d]*Sin[k*x-omega*t];

Moment[t]=(0.5*Cd*Dens*Dia*Abs[u]*u*ds+Cm*Dens*pi/4*Dia^2*a*ds)*(sCG
-s);
  s+=ds];

 n[t]=(H/2)*Cos[k*x-omega*t];
 Pitch[t]=RAO*(H/2)*Cos[k*x-omega*t];

 t+=dt]

ListPlot[Table[n[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Wave Elevation (m)"}]
ListPlot[Table[Moment[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Pitch Moment (N-m)"}]
ListPlot[Table[Pitch[t],{t,0,Tlimit}],Joined→True,AxesLabel→{"Time
(t)","Pitch Response (rad)"}]
```

APPENDIX C

NEPTUNE SPAR ANALYSIS PROGRAM (MS. EXCEL)

C.1 SURGE CALCULATIONS FOR NEPTUNE

ENVIRONMENTAL PARAMS		STRUCTURAL PARAMETERS				PIERSON-MOSKOWITZ SPECTRUM		TIMESERIES PARAM	
ρ, water (kg/m3)	1025	Drag coeff., Cd	1	Mass (kg)	7.71E+07	Upper freq boundary (Hz)	0.3	x (m)	0
Hs (m)	10	Inertia coeff., Cm	2	Added M	7.715E+07	Lower freq boundary (Hz)	0.03	ds (m)	1
Water depth, d (m)	590	Spar diameter (m)	22	Total Mass	1.543E+08	No. of components	25		
Current V (m/s)	0	Draft (m)	198	K (N/m)	5.766E+04	Δf (Hz)	0.0108	dt (s)	1
				DampRatio	0.05	Peak ang.freq, ω0 (rad/s)	0.40	Endtime (s)	200
				C	2.983E+05	Peak cyclic freq, f0 (Hz)	0.06		

FREQUENCY DOMAIN

No.	f (Hz)	S(f)	H(f) (m)	ε=2πRn	L (m)	L solver	k (/m)	Fmax (N)	RAOx (m/m)	Sx(f)
1	0.03	0.0000	0.0002	0.8159	1691.49	0.0000	0.0037	2.2329E+06	4476.33	7.85
2	0.0408	3.2496	0.5299	6.1598	936.95	0.0000	0.0067	3.8938E+06	1.46	6.91
3	0.0516	81.4124	2.6522	5.4409	586.21	0.0000	0.0107	1.2045E+07	0.56	25.72
4	0.0624	141.3093	3.4942	5.5488	400.85	0.0000	0.0157	1.6094E+07	0.39	21.43
5	0.0732	118.5310	3.2002	1.5037	291.30	0.0000	0.0216	1.5190E+07	0.29	10.06
6	0.084	79.9884	2.6289	3.8001	221.21	0.0000	0.0284	1.2885E+07	0.23	4.17
7	0.0948	50.9662	2.0984	1.1806	173.68	0.0000	0.0362	1.0694E+07	0.19	1.77
8	0.1056	32.4107	1.6734	3.1777	139.97	0.0000	0.0449	8.9429E+06	0.16	0.80
9	0.1164	20.9783	1.3463	5.9116	115.20	0.0000	0.0545	7.6047E+06	0.14	0.39
10	0.1272	13.9070	1.0962	0.2832	96.47	0.0000	0.0651	6.5885E+06	0.12	0.21
11	0.138	9.4515	0.9037	0.8759	81.96	0.0000	0.0767	5.8111E+06	0.11	0.12
12	0.1488	6.5783	0.7539	5.2470	70.49	0.0000	0.0891	5.2092E+06	0.10	0.07
13	0.1596	4.6805	0.6359	4.7587	61.28	0.0000	0.1025	4.7370E+06	0.10	0.04
14	0.1704	3.3977	0.5418	3.7121	53.75	0.0000	0.1169	4.3616E+06	0.09	0.03
15	0.1812	2.5118	0.4659	0.1548	47.54	0.0000	0.1322	4.0595E+06	0.09	0.02
16	0.192	1.8877	0.4039	3.0863	42.34	0.0000	0.1484	3.8135E+06	0.08	0.01
17	0.2028	1.4400	0.3527	3.4644	37.95	0.0000	0.1656	3.6110E+06	0.08	0.01
18	0.2136	1.1134	0.3102	5.5748	34.21	0.0000	0.1837	3.4428E+06	0.08	0.01
19	0.2244	0.8716	0.2744	4.4220	31.00	0.0000	0.2027	3.3018E+06	0.08	0.01
20	0.2352	0.6899	0.2442	5.8582	28.22	0.0000	0.2227	3.1825E+06	0.08	0.00
21	0.246	0.5518	0.2183	2.8672	25.79	0.0000	0.2436	3.0810E+06	0.08	0.00
22	0.2568	0.4455	0.1962	1.9508	23.67	0.0000	0.2655	2.9939E+06	0.08	0.00
23	0.2676	0.3628	0.1771	1.9762	21.80	0.0000	0.2883	2.9187E+06	0.08	0.00
24	0.2784	0.2979	0.1604	0.0705	20.14	0.0000	0.3120	2.8534E+06	0.08	0.00
25	0.2892	0.2464	0.1459	1.3114	18.66	0.0000	0.3367	2.7965E+06	0.08	0.00
26	0.3	0.2052	0.1331	3.0186	17.34	0.0000	0.3623	2.7465E+06	0.08	0.00

Run Wave Elevation & Surge Forces | Run Surge Response

FD | TS | Chart1 | Chart2 | Chart3 | Chart4 | Chart5 | SURGE | Manual | Manualcurrent

```
Function cosh(m)
    cosh = (Exp(m) + Exp(-m)) / 2
End Function
Function sinh(m)
    sinh = (Exp(m) - Exp(-m)) / 2
End Function

Sub WaveElev_Fx()
'Plots Time Series of (i)Wave Elevation and (ii)Surge Forces calculated by
Morison Equation

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)

    's loop configuration
    Depth = Worksheets("FD").Cells(6, 3)
    Draft = Worksheets("FD").Cells(7, 6)
    ds = Worksheets("FD").Cells(5, 13)
    s0 = Depth - Draft + (ds / 2)
```

```
    s1 = Depth - (ds / 2)

    'Start Looping!
    'for each time step
    For t = 0 To endtime Step dt

        n = 0
        Ftotal = 0

        'for each frequency, where i is the frequency index
        For i = 1 To 26 Step 1

        Fmaxtotal = 0
        'Fmaxtotal is for RAO calc, max surge force at each component
frequency
        'Therefore we reset Fmaxtotal at every new frequency calc set

            'Constants
            d = Worksheets("FD").Cells(6, 3)      'Water depth
            rho = Worksheets("FD").Cells(4, 3)    'Density of Water
            Cd = Worksheets("FD").Cells(4, 6)     'Drag Coefficient
            Cm = Worksheets("FD").Cells(5, 6)     'Mass Coefficient
            dia = Worksheets("FD").Cells(6, 6)    'Spar Diameter
            x = Worksheets("FD").Cells(4, 13)     'Horizontal Coord.
            v = Worksheets("FD").Cells(7, 3)      'Current Velocity

            ds = Worksheets("FD").Cells(5, 13)

            M0 = Worksheets("FD").Cells(6, 8)     'Total Mass
            C0 = Worksheets("FD").Cells(9, 8)     'Damping Constant
            K0 = Worksheets("FD").Cells(7, 8)     'Surge Stiffness

            'Component Wave Parameters (Frequency Dependent)
            Sf = Worksheets("FD").Cells(12 + i, 3)          'Energy Density
            f = Worksheets("FD").Cells(12 + i, 2)
            w = 2 * Pi * f
            Ti = 1 / f                                      'Wave Period
            H = Worksheets("FD").Cells(12 + i, 4)           'Wave Height
            k = Worksheets("FD").Cells(12 + i, 8)           'Wave Number
            eps = Worksheets("FD").Cells(12 + i, 5)         '2*Pi*Rand()



                'for each s coordinate along the draft
                For s = s0 To s1 Step ds

                    'For Time Series:
                    u = v + (Pi * H / Ti) * cosh(k * s) / sinh(k * d) *
Cos(k * x - w * t + eps)
                    udot = 2 * Pi ^ 2 * H / (Ti ^ 2) * cosh(k * s) / sinh(k
* d) * Sin(k * x - w * t + eps)
                    Fd = 0.5 * Cd * rho * dia * Abs(u) * u * ds
                    Fi = Cm * rho * Pi / 4 * dia ^ 2 * udot * ds
                    Ftotal = Ftotal + Fd + Fi

                    'For Frequency Series (RAO and Sxf):
                    umax = v + (Pi * H / Ti) * cosh(k * s) / sinh(k * d)
                    udotmax = 2 * Pi ^ 2 * H / (Ti ^ 2) * cosh(k * s) /
sinh(k * d)
                    FDmax = 0.5 * Cd * rho * dia * Abs(umax) * umax * ds
                    FImax = Cm * rho * Pi / 4 * dia ^ 2 * udotmax * ds
                    Fmaxtotal = Fmaxtotal + FDmax + FImax

                Next s  'FtotalS and FmaxtotalS are the sum of forces for
the entire submerged body at each frequency
```

```
            RAO = (Abs(Fmaxtotal) / (H / 2)) / ((K0 - M0 * w ^ 2) ^ 2 + (C0
* w) ^ 2) ^ 0.5

            'List RAO and Sz(f) in Frequency Series
            If t = 0 Then
                Worksheets("FD").Cells(12 + i, 9).Value = Fmaxtotal
                Worksheets("FD").Cells(12 + i, 10).Value = RAO
                Worksheets("FD").Cells(12 + i, 11).Value = Sf * (RAO ^ 2)
            End If


            'Accumulation of Wave Elevation and Forces
            n = n + (H / 2) * Cos(k * x - w * t + eps)

        Next i 'FtotalSF should be the total for entire submerged body for
all frequencies

        'List these in the Time Series
        Worksheets("TS").Cells(5 + t, 1) = t          'Time(secs)
        Worksheets("TS").Cells(5 + t, 2) = n          'Wave Elevation (metres)
        Worksheets("TS").Cells(5 + t, 3) = Ftotal     'Total Force (newton)

    Next t

End Sub


Sub SurgeResponse()
'Plots Time Series of Surge Response

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)

    'START LOOPING!
    'For each time step
    For t = 0 To endtime Step dt

            Xsurge = 0

            'for each frequency, where i is the frequency index
            For i = 1 To 26 Step 1

                'Component wave parameters
                f = Worksheets("FD").Cells(12 + i, 2)
                w = 2 * Pi * f
                k = Worksheets("FD").Cells(12 + i, 8)
                x = Worksheets("FD").Cells(4, 13)
                eps = Worksheets("FD").Cells(12 + i, 5)
                Sxf = Worksheets("FD").Cells(12 + i, 11)
                df = Worksheets("FD").Cells(7, 11)
                Hx = 2 * (2 * Sxf * df) ^ 0.5

                Xsurge = Xsurge + (Hx / 2) * Cos(k * x - w * t + eps)

            Next i

        Worksheets("TS").Cells(5 + t, 4) = Xsurge

    Next t

End Sub
```

C.2 HEAVE CALCULATIONS FOR NEPTUNE

	A	B	C	D	E	F	G	H	I	J	K	L	M
3	ENVIRONMENTAL PARAMS			STRUCTURAL PARAMETERS					PIERSON-MOSKOWITZ SPECTRUM			TIMESERIES PARAM	
4	p.water (kg/m3)		1025	Drag coeff., Cd		1	Mass (kg)	7.713E+07	Upper freq boundary (Hz)		0.3	s (m)	392
5	Hs (m)		10	Inertia coeff., Cm		2	Added M	2.857E+06	Lower freq boundary (Hz)		0.03	dx (m)	2.2
6	Water depth, d (m)		590	Spar diameter (m)		22	Total M	7.999E+07	No. of components		25		
7				Draft (m)		198	K (N/m)	3.509E+06	Δf (Hz)		0.0108	dt (s)	1
8							DampRatio	0.05	Peak ang.freq, ω0 (rad/s		0.40	Timelimit (s)	200
9				WaterPlane A (m2)		380.1327	C	1.675E+06	Peak cyclic freq, f0 (Hz)		0.06		
10													

FREQUENCY DOMAIN ANALYSIS (row 11)

12	No.	f (Hz)	S(f)	H(f) (m)	ε=2πRn	L (m)	L solver	k (/m)	RAO-heave(m/m)	S-heave	Fheavemax
13	1	0.03	3.915E-07	1.839E-04	3.4324	1691.49	0.0000	0.0037	2.59E+00	2.62E-06	1.754E+02
14	2	0.04	3.250E+00	5.299E-01	5.2923	936.95	0.0000	0.0067	5.65E-01	1.04E+00	2.696E+05
15	3	0.05	8.141E+01	2.652E+00	0.7006	586.21	0.0000	0.0107	9.29E-02	7.02E-01	6.070E+05
16	4	0.06	1.413E+02	3.494E+00	3.2181	400.85	0.0000	0.0157	1.95E-02	5.36E-02	2.997E+05
17	5	0.07	1.185E+02	3.200E+00	4.0960	291.30	0.0000	0.0216	3.97E-03	1.87E-03	8.542E+04
18	6	0.08	7.999E+01	2.629E+00	1.9383	221.21	0.0000	0.0284	7.34E-04	4.31E-05	1.813E+04
19	7	0.09	5.097E+01	2.098E+00	5.4835	173.68	0.0000	0.0362	1.19E-04	7.21E-07	3.106E+03
20	8	0.11	3.241E+01	1.673E+00	2.3036	139.97	0.0000	0.0449	1.66E-05	8.95E-09	4.412E+02
21	9	0.12	2.098E+01	1.346E+00	4.5799	115.20	0.0000	0.0545	1.99E-06	8.27E-11	5.251E+01
22	10	0.13	1.391E+01	1.096E+00	0.8600	96.47	0.0000	0.0651	2.01E-07	5.53E-13	5.251E+00
23	11	0.14	9.451E+00	9.037E-01	1.0829	81.96	0.0000	0.0767	1.73E-08	2.81E-15	4.415E-01
24	12	0.15	6.578E+00	7.539E-01	1.5615	70.49	0.0000	0.0891	1.25E-09	1.02E-17	3.119E-02
25	13	0.16	4.680E+00	6.359E-01	5.6079	61.28	0.0000	0.1025	7.56E-11	2.68E-20	1.850E-03
26	14	0.17	3.398E+00	5.418E-01	0.8832	53.75	0.0000	0.1169	3.85E-12	5.04E-23	9.203E-05
27	15	0.18	2.512E+00	4.659E-01	0.5066	47.54	0.0000	0.1322	1.64E-13	6.79E-26	3.836E-06
28	16	0.19	1.888E+00	4.039E-01	0.2767	42.34	0.0000	0.1484	5.87E-15	6.51E-29	1.339E-07
29	17	0.20	1.440E+00	3.527E-01	3.5753	37.95	0.0000	0.1656	1.75E-16	4.43E-32	3.908E-09
30	18	0.21	1.113E+00	3.102E-01	2.7928	34.21	0.0000	0.1837	4.37E-18	2.13E-35	9.536E-11
31	19	0.22	8.716E-01	2.744E-01	3.5453	31.00	0.0000	0.2027	9.11E-20	7.23E-39	1.944E-12
32	20	0.24	6.899E-01	2.442E-01	1.9232	28.22	0.0000	0.2227	1.58E-21	1.73E-42	3.309E-14
33	21	0.25	5.518E-01	2.183E-01	5.6763	25.79	0.0000	0.2436	2.30E-23	2.91E-46	4.702E-16
34	22	0.26	4.455E-01	1.962E-01	4.7242	23.67	0.0000	0.2655	2.77E-25	3.43E-50	5.573E-18
35	23	0.27	3.628E-01	1.771E-01	3.0724	21.80	0.0000	0.2883	2.80E-27	2.83E-54	5.509E-20
36	24	0.28	2.979E-01	1.604E-01	0.3681	20.14	0.0000	0.3120	2.35E-29	1.64E-58	4.540E-22
37	25	0.29	2.464E-01	1.459E-01	4.3529	18.66	0.0000	0.3367	1.64E-31	6.63E-63	3.118E-24
38	26	0.30	2.052E-01	1.331E-01	4.0809	17.34	0.0000	0.3623	9.55E-34	1.87E-67	1.784E-26
39											

FD / TS / Chart1 / Chart2 / Chart3 / Chart4 / Chart5 / HEAVE / Sheet1 / Manual

For 10 divisions on the circular bottom profile: (row 40)

41		x	x0	x1	A (m2)
42	1	-9.9	-11	-8.8	19.7836
43	2	-7.7	-8.8	-6.6	34.3391
44	3	-5.5	-6.6	-4.4	41.7908
45	4	-3.3	-4.4	-2.2	46.0775
46	5	-1.1	-2.2	0	48.0754
47	6	1.1	0	2.2	48.0754
48	7	3.3	2.2	4.4	46.0775
49	8	5.5	4.4	6.6	41.7908
50	9	7.7	6.6	8.8	34.3391
51	10	9.9	8.8	11	19.7836
52					380.1328
53					
54			Theoretical A =		380.1327
55				difference	0.0000
56					

Run Wave Elevation & Heave Forces

Run Heave Response

```
Function cosh(m)
    cosh = (Exp(m) + Exp(-m)) / 2
End Function
Function sinh(m)
    sinh = (Exp(m) - Exp(-m)) / 2
End Function

Sub WaveElev_Fz()
'Plots Time Series of (i)Wave Elevation and (ii)Heave Forces

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)
```

```
    'Start Looping!
    'for each time step
    For t = 0 To endtime Step dt

        n = 0
        Fheave = 0

        'for each frequency, where i is the frequency index
        For i = 1 To 26 Step 1

        Fheavemax = 0 'Resets Fheavemax at every new frequency calc set

            'Constants
            s = Worksheets("FD").Cells(4, 13)       's
            d = Worksheets("FD").Cells(6, 3)        'Water depth
            rho = Worksheets("FD").Cells(4, 3)      'Density of Water
            dia = Worksheets("FD").Cells(6, 6)      'Spar Diameter

            M0 = Worksheets("FD").Cells(6, 8)       'Total Mass
            C0 = Worksheets("FD").Cells(9, 8)       'Damping Constant
            K0 = Worksheets("FD").Cells(7, 8)       'Surge Stiffness

            'Component Wave Parameters (Frequency Dependent)
            Sf = Worksheets("FD").Cells(12 + i, 3)              'Energy Density
            f = Worksheets("FD").Cells(12 + i, 2)
            w = 2 * Pi * f
            Ti = 1 / f                                          'Wave Period
            H = Worksheets("FD").Cells(12 + i, 4)               'Wave Height
            k = Worksheets("FD").Cells(12 + i, 8)               'Wave Number
            eps = Worksheets("FD").Cells(12 + i, 5)             '2*Pi*Rand()

                'for each x coordinate along bottom cross-section
                For j = 1 To 10 Step 1

                    x = Worksheets("FD").Cells(41 + j, 2)
                    StripArea = Worksheets("FD").Cells(41 + j, 5)

                    'For Time Series:
                    Fheave = Fheave + rho * 9.807 * H / 2 * cosh(k * s) /
cosh(k * d) * Cos(k * x - w * t + eps) * StripArea

                    'For Frequency Series (RAO and Sxf):
                    Fheavemax = Fheavemax + rho * 9.807 * H / 2 * cosh(k *
s) / cosh(k * d) * StripArea

                Next j 'End of bottom-profile finite elements

            RAO = (Abs(Fheavemax) / (H / 2)) / ((K0 - M0 * w ^ 2) ^ 2 + (C0
* w) ^ 2) ^ 0.5

            'List RAO and Sx(f) in Frequency Series
            If t = 0 Then
                Worksheets("FD").Cells(12 + i, 12).Value = Fheavemax
                Worksheets("FD").Cells(12 + i, 10).Value = RAO
                Worksheets("FD").Cells(12 + i, 11).Value = Sf * (RAO ^ 2)
            End If

            'Accumulation of Wave Elevation and Forces
            n = n + (H / 2) * Cos(k * x - w * t + eps)

        Next i 'n and FtotalSF should be the total for entire submerged body
for all frequencies

        'List these in the Time Series
        Worksheets("TS").Cells(5 + t, 1) = t            'Time(secs)
        Worksheets("TS").Cells(5 + t, 2) = n            'Wave Elevation (metres)
        Worksheets("TS").Cells(5 + t, 3) = Fheave       'Total Force (newton)
```

```
    Next t

End Sub

Sub HeaveResponse()
'Plots Time Series of Heave Response

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)

    'START LOOPING!
    'For each time step
    For t = 0 To endtime Step dt

            Zheave = 0

            'for each frequency, where i is the frequency index
            For i = 1 To 26 Step 1

                'Component wave parameters
                f = Worksheets("FD").Cells(12 + i, 2)
                w = 2 * Pi * f
                k = Worksheets("FD").Cells(12 + i, 8)
                eps = Worksheets("FD").Cells(12 + i, 5)
                Sxf = Worksheets("FD").Cells(12 + i, 11)
                df = Worksheets("FD").Cells(7, 11)
                Hz = 2 * (2 * Sxf * df) ^ 0.5


                For j = 1 To 10 Step 1

                x = Worksheets("FD").Cells(41 + j, 2)
                Zheave = Zheave + (Hz / 2) * Cos(k * x - w * t + eps)

                Next j

            Next i

        Worksheets("TS").Cells(5 + t, 4) = Zheave

    Next t

End Sub
```

C.3 PITCH CALCULATIONS FOR NEPTUNE

	A–B	C	D–E	F	G	H	I–J	K	L	M
4	ρ, water (kg/m3)	1025	Drag coeff., Cd	1	Mass (kg)	7.713E+07	Upper freq boundary (Hz)	0.3	x (m)	0
5	Hs (m)	10	Inertia coeff., Cm	2	Added M	7.715E+07	Lower freq boundary (Hz)	0.03	ds (m)	1
6	Water depth, d (m)	590	Spar diameter (m)	22	Total Mass	1.543E+08	No. of components	25		
7	Current V (m/s)	0.5	Draft (m)	198	K (N/m)	1.063E+06	Δf (Hz)	0.0108	dt (s)	1
8			Mass Mom of I (kgm2)	67.36	DampRatio	0.05	Peak ang.freq, ω0 (rad/s)	0.40	Endtime (s)	200
9			KG (CG from base, m)	95	C	1.292E+06	Peak cyclic freq, f0 (Hz)	0.06		

FREQUENCY DOMAIN

	No.	f (Hz)	S(f)	H(f) (m)	ε=2πRn	L (m)	L solver	k (/m)	Fmax (N)	AOx (m/m)	Sx(f)
13	1	0.03	0.0000	0.0002	0.8159	1691.49	0.0000	0.0037	-1.9594E+06	0.86	0.00
14	2	0.0408	3.2496	0.5299	6.1598	936.95	0.0000	0.0067	-4.1026E+07	0.00	0.00
15	3	0.0516	81.4124	2.6522	5.4409	586.21	0.0000	0.0107	-3.4436E+08	0.00	0.00
16	4	0.0624	141.3093	3.4942	5.5488	400.85	0.0000	0.0157	-6.4869E+08	0.00	0.00
17	5	0.0732	118.5310	3.2002	1.5037	291.30	0.0000	0.0216	-7.4622E+08	0.00	0.00
18	6	0.084	79.9884	2.6289	3.8001	221.21	0.0000	0.0284	-7.0941E+08	0.00	0.00
19	7	0.0948	50.9662	2.0984	1.1806	173.68	0.0000	0.0362	-6.2291E+08	0.00	0.00
20	8	0.1056	32.4107	1.6734	3.1777	139.97	0.0000	0.0449	-5.2969E+08	0.00	0.00
21	9	0.1164	20.9783	1.3463	5.9116	115.20	0.0000	0.0545	-4.4577E+08	0.00	0.00
22	10	0.1272	13.9070	1.0962	0.2632	96.47	0.0000	0.0651	-3.7507E+08	0.00	0.00
23	11	0.138	9.4515	0.9037	0.8759	81.96	0.0000	0.0767	-3.1699E+08	0.00	0.00
24	12	0.1488	6.5783	0.7539	5.2470	70.49	0.0000	0.0891	-2.6963E+08	0.00	0.00
25	13	0.1596	4.6805	0.6359	4.7587	61.28	0.0000	0.1025	-2.3100E+08	0.00	0.00
26	14	0.1704	3.3977	0.5418	3.7121	53.75	0.0000	0.1169	-1.9935E+08	0.00	0.00
27	15	0.1812	2.5118	0.4659	0.1548	47.54	0.0000	0.1322	-1.7325E+08	0.00	0.00
28	16	0.192	1.8877	0.4039	3.0863	42.34	0.0000	0.1484	-1.5157E+08	0.00	0.00
29	17	0.2028	1.4400	0.3527	3.4644	37.95	0.0000	0.1656	-1.3344E+08	0.00	0.00
30	18	0.2136	1.1134	0.3102	5.5748	34.21	0.0000	0.1837	-1.1817E+08	0.00	0.00
31	19	0.2244	0.8716	0.2744	4.4220	31.00	0.0000	0.2027	-1.0522E+08	0.00	0.00
32	20	0.2352	0.6899	0.2442	5.8582	28.22	0.0000	0.2227	-9.4161E+07	0.00	0.00
33	21	0.246	0.5518	0.2183	2.8672	25.79	0.0000	0.2436	-8.4662E+07	0.00	0.00
34	22	0.2568	0.4455	0.1962	1.9508	23.67	0.0000	0.2655	-7.6454E+07	0.00	0.00
35	23	0.2676	0.3628	0.1771	1.9762	21.80	0.0000	0.2883	-6.9324E+07	0.00	0.00
36	24	0.2784	0.2979	0.1604	0.0705	20.14	0.0000	0.3120	-6.3098E+07	0.00	0.00
37	25	0.2892	0.2464	0.1459	1.3114	18.66	0.0000	0.3367	-5.7635E+07	0.00	0.00
38	26	0.3	0.2052	0.1331	3.0186	17.34	0.0000	0.3623	-5.2819E+07	0.00	0.00

Run Wave Elevation & Pitch Moments | Run Pitch Response

FD / TS / S(f) / Pitch RAO / Pitch Spectrum / n / Moment / PITCH / Sheet2

```
Function cosh(m)
    cosh = (Exp(m) + Exp(-m)) / 2
End Function
Function sinh(m)
    sinh = (Exp(m) - Exp(-m)) / 2
End Function

Sub WaveElev_Mx()
'Plots Time Series of (i)Wave Elevation and (ii)Pitch moments calculated by
Morison Equation

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)

    's loop configuration
    Depth = Worksheets("FD").Cells(6, 3)
    Draft = Worksheets("FD").Cells(7, 6)
    ds = Worksheets("FD").Cells(5, 13)
    s0 = Depth - Draft + (ds / 2)
    s1 = Depth - (ds / 2)

    'Start Looping!
    'for each time step
    For t = 0 To endtime Step dt

        n = 0
```

```
        Mtotal = 0

        'for each frequency, where i is the frequency index
        For i = 1 To 26 Step 1

        Mmaxtotal = 0

            'Constants
            d = Worksheets("FD").Cells(6, 3)      'Water depth
            rho = Worksheets("FD").Cells(4, 3)    'Density of Water
            Cd = Worksheets("FD").Cells(4, 6)     'Drag Coefficient
            Cm = Worksheets("FD").Cells(5, 6)     'Mass Coefficient
            dia = Worksheets("FD").Cells(6, 6)    'Spar Diameter
            x = Worksheets("FD").Cells(4, 13)     'Horizontal Coord.
            v = Worksheets("FD").Cells(7, 3)      'Current Velocity
            KG = Worksheets("FD").Cells(9, 6)     'Distance of CG frm sparbase
            sCG = s0 + KG                         'Elevation of CG from seabed


            ds = Worksheets("FD").Cells(5, 13)

            Mass = Worksheets("FD").Cells(4, 8)  'Structural Mass
            Ry = Worksheets("FD").Cells(8, 6)     'PITCH Radius of Gyration
            Iy0 = Mass * (Ry) ^ 2                 'MassMoment ofInertia(PITCH)

            AddedMass = Worksheets("FD").Cells(5, 8)


            Iy = Iy0 + (Iy0 * AddedMass / Mass) 'Total Mass Mom of I (PITCH)

            C0 = Worksheets("FD").Cells(9, 8)     'Damping Constant
            K0 = Worksheets("FD").Cells(7, 8)     'Surge Stiffness

            'Component Wave Parameters (Frequency Dependent)
            Sf = Worksheets("FD").Cells(12 + i, 3)          'Energy Density
            f = Worksheets("FD").Cells(12 + i, 2)
            w = 2 * Pi * f
            Ti = 1 / f                                      'Wave Period
            H = Worksheets("FD").Cells(12 + i, 4)           'Wave Height
            k = Worksheets("FD").Cells(12 + i, 8)           'Wave Number
            eps = Worksheets("FD").Cells(12 + i, 5)         '2*Pi*Rand()


                'for each s coordinate along the draft
                For s = s0 To s1 Step ds

                    'For Time Series:
                    u = v + (Pi * H / Ti) * cosh(k * s) / sinh(k * d) *
Cos(k * x - w * t + eps)
                    udot = 2 * Pi ^ 2 * H / (Ti ^ 2) * cosh(k * s) / sinh(k
* d) * Sin(k * x - w * t + eps)
                    Fd = 0.5 * Cd * rho * dia * Abs(u) * u * ds
                    Fi = Cm * rho * Pi / 4 * dia ^ 2 * udot * ds
                    Mtotal = Mtotal + (Fd + Fi) * (sCG - s)

                    'For Frequency Series (RAO and Sxf):
                    umax = v + (Pi * H / Ti) * cosh(k * s) / sinh(k * d)
                    udotmax = 2 * Pi ^ 2 * H / (Ti ^ 2) * cosh(k * s) /
sinh(k * d)
                    FDmax = 0.5 * Cd * rho * dia * Abs(umax) * umax * ds
                    FImax = Cm * rho * Pi / 4 * dia ^ 2 * udotmax * ds
                    Mmaxtotal = Mmaxtotal + (FDmax + FImax) * (sCG - s)

                Next s

            RAO = (Abs(Mmaxtotal) / (H / 2)) / ((K0 - Iy * w ^ 2) ^ 2 + (C0
* w) ^ 2) ^ 0.5
```

```
            'List RAO and S-pitch(f) in Frequency Series
            If t = 0 Then
                Worksheets("FD").Cells(12 + i, 9).Value = Mmaxtotal
                Worksheets("FD").Cells(12 + i, 10).Value = RAO
                Worksheets("FD").Cells(12 + i, 11).Value = Sf * (RAO ^ 2)
            End If


            'Accumulation of Wave Elevation and Forces
            n = n + (H / 2) * Cos(k * x - w * t + eps)

        Next i

        'List these in the Time Series
        Worksheets("TS").Cells(5 + t, 1) = t          'Time(secs)
        Worksheets("TS").Cells(5 + t, 2) = n          'Wave Elevation (metres)
        Worksheets("TS").Cells(5 + t, 3) = Mtotal     'Total Moment (Nm)

    Next t

End Sub

Sub PitchResponse()
'Plots Time Series of Surge Response

    Pi = 3.14159265358979

    'get user-defined time step and limit of time series
    dt = Worksheets("FD").Cells(7, 13)
    endtime = Worksheets("FD").Cells(8, 13)

    'START LOOPING!
    'For each time step
    For t = 0 To endtime Step dt

        Pitch = 0

        'for each frequency, where i is the frequency index
        For i = 1 To 26 Step 1

            'Component wave parameters
            f = Worksheets("FD").Cells(12 + i, 2)
            w = 2 * Pi * f
            k = Worksheets("FD").Cells(12 + i, 8)
            x = Worksheets("FD").Cells(4, 13)
            eps = Worksheets("FD").Cells(12 + i, 5)
            Spitch = Worksheets("FD").Cells(12 + i, 11)
            df = Worksheets("FD").Cells(7, 11)
            Hpitch = 2 * (2 * Spitch * df) ^ 0.5

            Pitch = Pitch + (Hpitch / 2) * Cos(k * x - w * t + eps)

        Next i

      Worksheets("TS").Cells(5 + t, 4) = Pitch

    Next t

End Sub
```