EXPERIMENTAL STUDY ON DYNAMIC RESPONSES OF TRUSS SPAR PLATFORM SUBJECTED TO LONG-CRESTED WAVES AND SHORT-CRESTED WAVES WITH CURRENT

by

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is 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 not been undertaken or done by unspecified sources or persons.

NUR AIFA FARIHAH BINTI MAD NOR

ABSTRACT

The environmental conditions e.g. wave and current are the important aspects that shall be considered in the design of offshore structures. Research have been highlighted on the long-crested waves or unidirectional wave. However, the occurrence of such waves are seldom found in the real sea condition [1]. Studies also stated that wave force by long-crested waves would be overestimated or overdesigned [2]. On the other hand, short-crested wave would be better representing the real sea condition. By considering short-crested waves, an optimum design of the offshore structure with cost and time effectiveness could be achieved [2]. Yet, there no experimental studies has been reported comparing the dynamic responses of truss spar platform subjected to long-crested and short-crested wave with current in six degree of freedom. Thus, an experimental study by wave tank test has been performed in order to quantify the effectiveness of the dynamic responses of the truss spar platform subjected to short-crested waves by comparing to the long-crested waves with current. A model of truss spar platform which is fabricated by steel plate with 1:100 ratio scale from the prototype was used in the study of dynamic responses. In wave tank test, long-crested waves with current and short-crested waves with current was generated by wave and current generator. Spreading function, cosine squared ($\cos^2$) was implemented and incorporated with JONSWAP spectrum to produce short-crested wave. Current as well has been considered in this study. Wave probe was adopted to record the wave profile while the Qualisys Track Manager (QTM) was used to record the dynamic motion responses in six degree of freedom. The dynamic motion responses of truss spar platform model were compared among the long and short-crested waves with current. As results, the responses of truss spar considering short-crested waves with current were found to smaller compare to long-crested wave with current. This indicated that offshore structure design considering short-crested waves with current could the optimized and provide an economical design.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

This chapter discussed on the background of study, problem statement, objectives and scopes of study. The problem statement are focusing on the situation of the problem and research questions, which lead to the objectives of the study.

1.1 Background of Study

In general, there are two categories of offshore platforms designed for oil and gas drilling activity, i.e. the fixed platforms and floating platforms. Examples of fixed platforms are Jacket Platform, Gravity Based Structure (GBS) and Compliant Tower. Floating platforms consists of Tension Leg Platform (TLP), Semi-Submersible, Spar Platform and Floating, Production, Storage and Offloading (FPSO).

The applications of spar platforms are acknowledged as an economical and efficient type of floating offshore structure for ultra-deep water region. Spar platform is among the largest platforms in use. Spar generally consist of large vertical cylinder that supporting the deck of the platform. The vertical cylinder is tethered by mooring lines in the mean of cables and lines to the seafloor, to stabilizes platform and allow movement to absorb hurricane impacts [3][4][5][6]. There are 3 types of spar in operation, i.e., the Classic Spar, Truss Spar and Cell Spar. Globally, spar located mainly at the Gulf of Mexico (GOM) and North Sea, except for the Kikeh Spar (truss spar), which located in Malaysia.

In the design of offshore structures, environmental loads e.g. wind loads, wave loads, current, tidal etc. are an important aspect to be considered. Based upon the direction of the wave propagation, the wave can be categorized as long-crested and short-crested waves. Long-crested waves was defined as waves that propagated to only one direction. This type of wave is 2D and normally been called as plane-wave. Short-crested waves was defined as a combination of long-crested waves. Whereby the properties of the short-crested waves are 3D, complex, and cannot be replaced or imitated by plane waves.

1.1.1 Problem Statement

The environmental conditions e.g. wave and current are the important aspects that shall be considered in the design of offshore structures. Even thought, research have been highlighted widely on the long-crested waves or unidirectional wave. But, the occurrence of such waves are seldom found in the real sea condition [7]. Studies also stated that wave force by long-crested waves would be overestimated or overdesigned [3]. On the other hand, short-crested wave would be better representing the real sea condition. By considering short-crested waves, an optimum design of the offshore structure with cost and time effectiveness could be achieved [3]. Yet, there no experimental studies has been reported comparing the dynamic responses of truss spar platform subjected to long-crested and short-crested wave with current in six degree of freedom (6 DOF). Thus, an experimental study is necessary to be performed in order to quantify the effectiveness of the dynamic responses of the truss spar platform subjected to short-crested waves by comparing to the long-crested waves with current.

1.1.2 Objective

Based on the problem statement mentioned in section 1.1.1, the aim of this study is to determine and compare the responses of truss spar platform considering long and short-crested waves with current in six degree of freedom by experimental studies. Following is the objectives that were set to achieve the aim for this study.

a) To determine the dynamic responses of spar platform model subjected to both long-crested and short-crested waves with current in six degree of freedom by wave tank test.

b) To quantify the effectiveness of the dynamic responses of the truss spar platform subjected to short-crested waves by comparing to the response due to long-crested waves with current.

1.1.3 Scope of Study

The scopes of study for this experimental study are involving the four significant aspects:

1.1.3.1 Truss Spar Model

In this experimental study, truss spar is selected as the model. The truss spar model is fabricated using steel plates with scale of 1:100. The model is positioned in the wave tank and restrained by four linear springs connected to the steel wires at each quarter as mooring lines.

1.1.3.2 Degree of Freedom

There are two type of motion which are translation and rotation. For translation, the spar platform is moving up and down (heaving); moving left and right (swaying) and moving forward and backward (surging). On the other hand, the spar platform is tilts forward and backward (pitching); Swivels left and right (yawing) and Pivots side to side (rolling) for rotation.

1.1.3.3 Environmental Condition

There are presence of wave and current in sea condition. Ocean waves are irregular and random in shape, height, length and speed of propagation. A real sea state is best described by a random wave model. Wave conditions which are to be considered for structural design purposes, may be described either by deterministic design wave methods or by stochastic methods applying wave spectra. There are two types of wave condition are taken into account in order to study the dynamic responses of truss spar platform in this study, i.e. the long-crested wave (Unidirectional waves) and short-crested wave (Multi-directional waves) condition.

Current is a movement of seawater which generated by forces acting upon mean flow such as wind, temperature, breaking waves and others. There are several significant mechanisms driving currents, these include: tidal currents, surface wind driven currents, basin response currents derived from tropical storms or strong monsoonal surges and finally density driven currents. Figure 1.1 shows the environmental conditions diagram of wave and current flow.

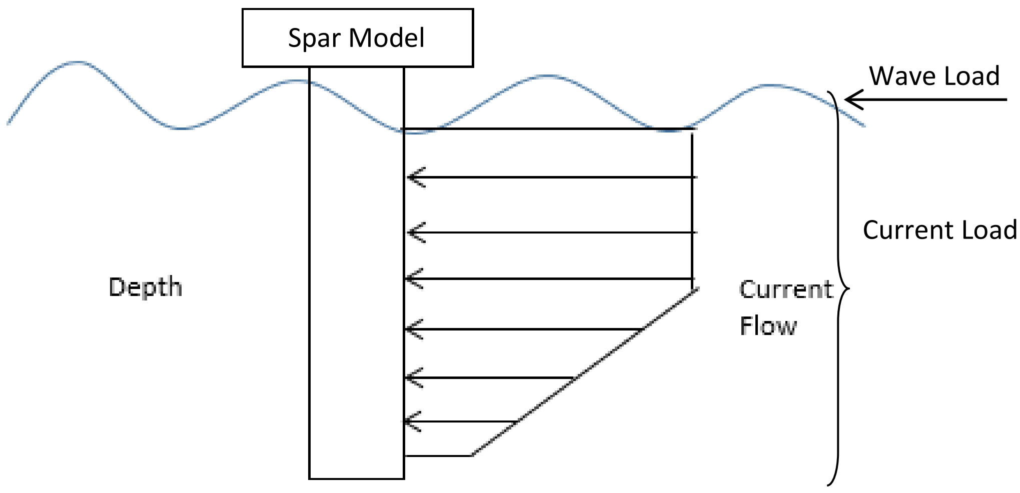

Figure 1.1: Environmental Conditions

1.2 Chapter Summary

Introduction of this study was presented by explaining the background of offshore structure and environmental loads. It was been mentioned that this study are focusing on Truss spar platform while the environmental loads are focusing on waves and current i.e. long and short-crested waves. Finally, the problem statement, objectives and scope of study were presented.

CHAPTER 2

LITERATURE REVIEW

The literature review in this chapter covers the spar platform, long-crested and short-crested waves, dynamic responses of spar platform subjected to long-crested and short-crested wave and current.

2.1 Spar Platform

Numerous researches and studies were found focusing on Spar Platform in order to study the constructive impact on ocean engineering industries. Agarwal and Jain [8] had performed a response analysis in time domain by using the iterative incremental Newmark's Beta approach to solve the dynamic behavior of a moored spar platform as an integrated system. They conducted the numerical studies on spar platform for several regular waves. The outcome showed that modelling of the nonlinear force–excursion (horizontal and vertical) relationship of the mooring lines with different slopes (stiffness) gives the reasonably accurate behaviour of Spar responses. Whereas modelling the force–excursion (horizontal and vertical) relationship of the mooring line with multilinear segments can resulting in unrealistic spar responses. On the other hand, Jeon et al. [9] addressed the numerical investigation of dynamic responses of a spar-type hollow cylindrical floating substructure moored by three catenary cables subjected to irregular wave excitation. Through the numerical stimulations, the time-and frequency-responses of a rigid spar-type hollow cylindrical floating substructure and the tension of mooring cables were investigated with respect to the total length and the connection position of mooring cables. Koo et al. [10] had evaluate damping effects and hull/mooring/riser coupled effects on the principal instability of spar platform. In the simulation, the heave/pitch coupling of the spar platform were considered using the modified Mathieu equation.

Recently, Montasir et al. [6] had studied the effect of symmetric and asymmetric mooring configurations in terms of line azimuth angles on the platform responses. It is essential to find the best possible mooring configuration for a given platform and metocean data, which may reduces the motion responses of the platform to an acceptable level by considering the cost impact of mooring lines on the overall project. Besides that, Ma and Patel [5] had examined the non-linear interaction components for a very deep draft spar platform type that is increasingly being used in the oceans for their research paper. It investigates a formulation for two-linear force components, i.e. the axial divergence force and the centrifugal force.

2.2 Long-Crested and Short-Crested Waves

Similarly, there are some numerical and experimental studies focusing on long-crested and short-crested wave. The research has begun since 1970s concentrating on directional wave force, directional wave spectrum, directional wave kinematics and vertical circular cylinder on short-crested wave [3]. Zhu [2] had come out with the precise solution for the diffraction of short-crested wave's incident on a circular cylinder. The study stated that the design would be over-estimated when the plane incident waves are considered but it may still be a good engineering design criterion.

Zhu's theory has been extended by Zhu and Moule [1] to discuss the wave load on a vertical cylinder of arbitrary cross-section from short-crested incident wave. Zhu and Satravaha [1] had come out with another closed solution to investigate the velocity of non-linear short-crested wave for a vertical cylinder. The solution is presented in closed form for the velocity potential, up to the second-order of wave amplitude, of the non-linear short-crested waves being diffracted by a vertical cylinder. Jian et al. [12] developed an analytical solution for the diffraction of short-crested incident wave on the large circular cylinder with uniform current, which prolonged from Zhu's research. Based on his result, wave load exerted on a cylinder with current would be larger compared wave load exerted by only short-crested wave. This has proven that short-crested wave-current load should be considered on marine construction. This is because the effects of current speeds and current direction are very conspicuous. With the increase of current speed, the water run-up on the cylinder becomes higher, and will exceed that of long-crested plane wave and short-crested wave case without currents even though the current speed is small.

Despite the fact that the short-crested waves represent the real sea condition compared to long-crested waves, abundant studies on the dynamic responses of offshore structure subjected to short-crested wave have been executed. Teigen [13] has conducted a model test on Tension Leg Platform (TLP) in both long-crested and short-crested seas. The experiments point at a considerable reduction in the total energy for the main response modes in short-crested seas compared to long-crested seas. Furthermore, Ong et al. [14] delivered a practical stochastic method by which the maximum equilibrium scour depth around a vertical pile exposed to long-crested and short-crested nonlinear random waves plus current can be derive by using Sumer and Fredsøe's empirical formula for the scour depth. Kurian et al. [15] has conducted a model tests to demonstrate the effect of the short-crested waves on the motions of moored semi-submersible platform. In the tests, model was moored in the head sea with four linear springs fore and aft, and the motion responses subjected to multi-directional waves were measured in three degrees of freedom

2.3 Dynamic Responses on Spar Platform Subjected to Long-Crested and Short-Crested Waves

Common theories used to evaluate the wave force for offshore structures are include the Morison equation, Froude Krylov theory and Diffraction theory. These theories are adopted based upon the type and size of the member of the structures [4]. Studies of dynamic responses on spar platform subjected to long-crested wave and short-crested wave has been started by Kurian et al. [7]. They presented the results of numerical investigation of an offshore classic spar platform subjected to long-crested waves. In this study, two numerical simulations were developed by incorporating the Morison equation and Diffraction theory to obtain the wave forces. Kurian et al. [7] continued their study by investigating numerically on dynamic responses of classic spar platforms subjected to long-crested and short-crested waves by incorporating with Diffraction Theory. Later on, Kurian et at.[3] presented an experimental and numerical study on the truss spar responses subjected to long-crested and short-crested waves and they observed that the response short-crested wave were much lower compared to long-crested waves. This showed that a more economical design would be arrived at by adopting short-crested wave statistic in the design. Ng et al. [16] then extended the study by investigating the dynamic responses on classic spar platform subjected to long-crested and short-crested wave by performing an experimental study. The result had also shown that the responses of classic spar model subjected to short-crested waves on the stretch length are anticipated to be less.

2.4 Current

In the other research, Kurian et al. [4] presented the dynamic responses of the Marlin truss spar in regular waves, current and wind. The current velocity is incorporated in time domain by adding the average current velocity to the horizontal wave velocity in the drag term and carrying out the simulation process. The effect of current and wind forces on motions of truss spar platform is evaluated.   The outcome that focused on the current was stated that the presence of current did not affect the amplitude of the motions. However, it increased the surge mean offset significantly.

Jian et al. [12] developed an analytical solution for the diffraction of short-crested incident wave on the large circular cylinder with uniform current, which prolonged from Zhu's research. Based on his result, wave load exerted on a cylinder with current would be larger compared wave load exerted by only short-crested wave. This has proven that short-crested wave-current load should be considered on marine construction. This is because the effects of current speeds and current direction are very conspicuous. With the increase of current speed, the water run-up on the cylinder becomes more and more high, and will exceed that of long-crested plane wave and short-crested wave case without currents even though the current speed is small.

2.5 Chapter Summary

Based on the accessible studies that has been discussed in the literature, limited experimental studies were found reported about the dynamic responses of spar platforms subjected to short-crested wave. Dynamic responses of spar platforms subjected to short-crested wave with current has not been reported yet. In addition, there are no studies namely experimental study has been reported about the dynamic responses of spar platforms subjected to short-crested wave with current in six degree of freedom and most of the study reported the response in three degree of freedom only. Thus, an experimental study to investigate the dynamic responses of truss spar platform subjected to both long-crested and short-crested waves with current in six degree of freedom is to be performed.

CHAPTER 3

THEORY

There are some theories involved in this study, which will be detail described in the following section.

3.1 Wave Spectrum

There are two approaches considered in selecting the design of wave environment for an offshore structure; single wave method and wave spectrum method [17]. Single wave method represented the design wave by a wave period and a wave height, while the wave spectrum represented the concept of wave energy density spectrum.

3.1.1 Directional Wave Spectrum

The directional spectrum is presented by spreading function and the wave spectra. It measures the distribution of wave energy in wave number or frequency and direction. Directional spectra is spectral representations. This is included both the frequency distribution and the angular spreading of wave energy [17].

The wave generator used for experimental proposed defines the short-crested or multi directional waves as a product of wave spectra and spreading function. One of spreading function idealized is Cosine square ($\cos^2$) [15].

$$D(\theta) = \begin{cases} \frac{2}{\pi} cos^2(\theta - \theta_0), for \left(-\frac{\pi}{2} + \theta_0\right) \\ 0, other\ wise \end{cases} \qquad (1)$$

Where θ = mean wave direction in radians. The cosine-squared formulation is really simple because it is neither a function of frequency nor wide speed. It can be used to parameterize the directional spreading of wind seas. Similar formulations can be derived (cosine-fourth, for example) by changing the value of the exponent and adjusting the coefficient.

The parameter θ is an index describing the degree of directional spreading with $\theta \rightarrow \infty$ representing a unidirectional or long-crested wave field

3.1.2 JONSWAP wave spectrum

JONSWAP (Joint North Sea Wave Project) wave spectrum were considered in this study. This wave spectrum was developed during a joint North Sea wave by Hasselman, et al. [17]. The formula can be written as:

$$S(\omega) = \alpha g^2 \omega^{-5} exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right] \gamma^{exp\left[-\frac{(\omega-\omega_0)^2}{2\tau^2 {\omega_0}^2}\right]} \quad (2)$$

Where γ = peakness parameter

τ = shape parameter $\tau_a \, for \, \omega \leq \omega_0 \, and \, \tau_b \, for \, \omega > \omega_0$

Considering a prevailing wind field with a velocity of U_w and a fetch of X, the average values of these quantities are given by

γ = 3.30	may vary 1 to 7
τ_a = 0.07	considered fixed
τ_b = 0.09	considered fixed
$\alpha = 0.076(X_0)^{-0.22}$	α = 0.0081 (when X is unknown)

3.2 Degree of Freedom

In general, offshore structures are anticipated rigid and experiences six independent degrees of motion which are three translational and three rotational. The definition of six degrees of motion of a tanker are included heave, surge, sway, yaw, roll and pitch. Heave is the vertical motion along Y axis, surge is the longitudinal motion along X axis and sway are transverse motion along Z axis. On the other hand, yaw is angular motion about Y axis, roll is angular motion about X axis and lastly pitch is angular motion about about Z axis. The motion analysis is required for offshore structure included spar platform. Figure 3.1 shows the six degree freedom of a ship.

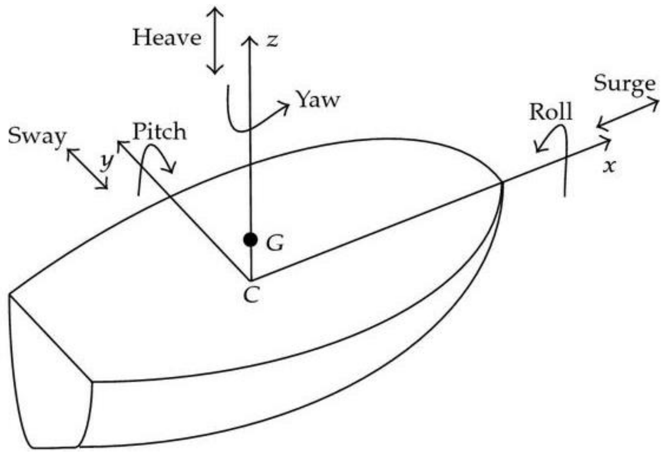

Figure 3.1: The six degree freedom of a ship
(Source: http://www.hindawi.com/journals/mpe/2010/934714/fig1/)

3.3 Wave Directionality

Long-crested wave or unidirectional wave was described as 2-dimensional waves propagated from one direction. The short-crested wave or multidirectional wave was described as groups of long-crested wave in 3-dimensional that propagate to various directions and the wave are randomly varying in the magnitude and direction [3]. Figure 3.2 shows the directions of long-crested and short-crested wave in visualization.

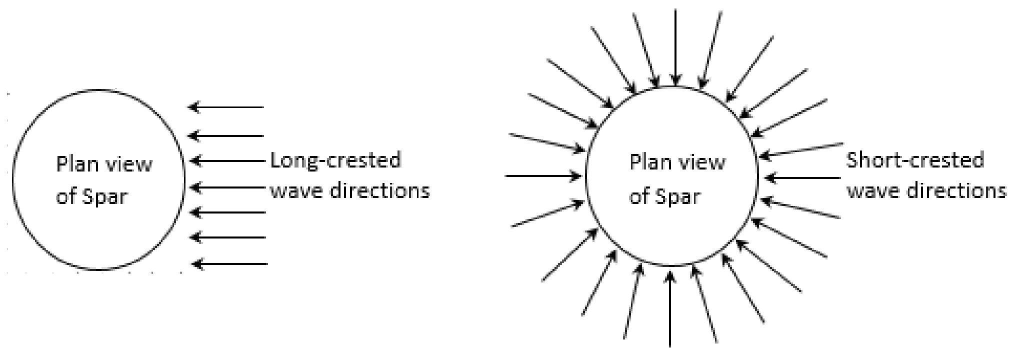

Figure 3.2: The directions of long-crested and short-crested wave

3.4 Response Amplitude Operator

The dynamic motion responses of the classic spar are presented in terms of Responses Amplitude Operator (RAO). Thus, the RAO of six degree of motion for pitch, roll, heave, yaw, sway and pitch were obtained by equation below:

$$RAO = \sqrt{\frac{S_R(f)}{S(f)}} \tag{3}$$

where,

S_R = the motion response spectrum of six degree of motion, S = the wave spectrum, f = the wave frequency [17]

3.5 Spar Platform Physical Modelling

For spar platform, the stability is provided by the hard tank since it is the largest part. In order to estimate the draft (wet height), the following forces should be considered:

a) Weight, which can be calculated as

$$W = \rho m \times V \tag{4}$$

where ρm is the material density (typical value for steel is 7.85 g/cm3) and V is the model volume.

b) Buoyancy, which can be calculated as

$$B = \rho w \times V \tag{5}$$

where ρw is the water density and can be taken as 1000 kg/m3.

c) Mooring line forces.

The dynamic stability of spar is provided if the center of buoyancy B is above the center of gravity CG.

CHAPTER 4

RESEARCH METHODOLOGY

Methodology of this experimental study is covered the model and wave tank description, equipment list, wave tank test, and static offset test.

4.1 Test Planning and Execution

Table 4.1: Test Planning and Execution

Test Planning	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22
Model Set-up	■	■	■	■	■											
Load Cell Calibration						■										
Static Offset Test						■	■									
Free-decay Test							■	■								
Wave probe calibration								■								
Sea-keeping test (long-crested waves without current)								■	■							
Sea-keeping test (short-crested waves without current)									■	■						
Sea-keeping test (long-crested waves with										■	■					

Test Planning	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22
current)																
Sea-keeping test (short-crested waves with current)																
Data Analysis																
Reporting Result																

4.2 Model and Wave Tank Description

The dimension and specification of truss spar model and wave tank are as shown in the Figure 4.1 and 4.2. The scaling factor of the model is 1:100 and was fabricated by using steel plate.

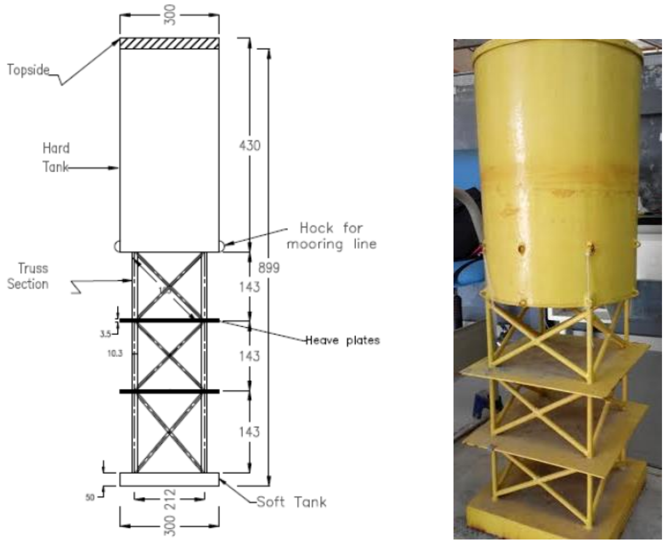

Figure 4.1: Truss Spar Dimension

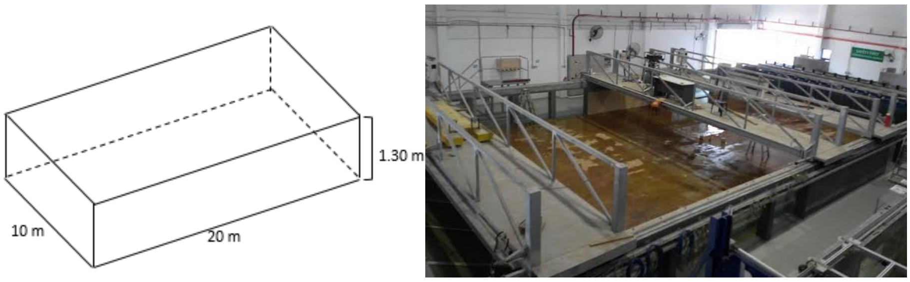

Figure 4.2: Wave Tank Dimension

Table 4.2 shows the structural dimensions of the truss spar model and prototype and Figure 4.3 shows the center of gravity and center of buoyancy of truss spar model.

Table 4.2: Structural dimensions of the truss spar model and prototype

Variable	**Model**	**Prototype**
Total mass, kg	18.18	18.18×10^6
Overall Length, m	0.909	90.90
Draft, m	0.818	81.81
Vertical CG from keel, m	0.435	43.50
Vertical CB from keel, m	0.480	48.00
Water Depth, m	1.00	100
Hull		
Diameter, m	0.300	12.00
Total Length, m	0.430	17.20
Draft, m	0.339	13.56
Wall Thickness, m	0.002	0.08
Truss section		
Diameter, m	0.01	0.40
Diagonal Length, m	0.256	10.24
Nos. of Diagonal members, m	24	24
Wall Thickness, m	0.002	0.08
Vertical Length, m	0.143	5.72
Nos. Vertical Member	12	12
Soft tank		
Nos. Vertical Plate	4	4
Length, m	0.300	12.00
Depth, m	0.050	2.00
Nos. Horizontal plate	2	2
Length, m	0.300	12.00
Depth, m	0.300	12.00
Wall thickness, m	0.002	0.08

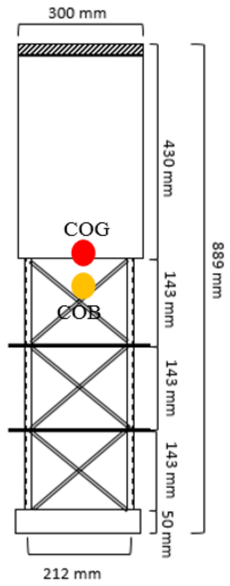

Figure 4.3: Centre of gravity and center of buoyancy of truss spar model

4.3 List of Equipment

Table 4.3 shows the list of apparatus and equipment involved.

Table 4.3: List of Apparatus and Equipment Involved

Equipment	**Function**
Wave Probe	Record the wave profile
Load cell	Measuring the tension of mooring line
Wave generator	Generate short and long-crested wave
Current generator	Generate current
Accelerometers	Measuring acceleration
Velocimeter	Measuring velocity
Qualisys Track Manager	Capture motion to obtain position of the model

Appendix C shows the model testing facilities description.

4.4 Hook up soft mooring in calm water

i. The model is fixed in the basin centre

ii. Mooring lines is attached to fairleads

iii. Pre-tensions is set to specified values by reading load cells

iv. The model is released. It should stay close to centre with Sway, Surge and Yaw~0

v. Mooring stiffness is pre-calibrated to give long surge, sway and yaw natural periods

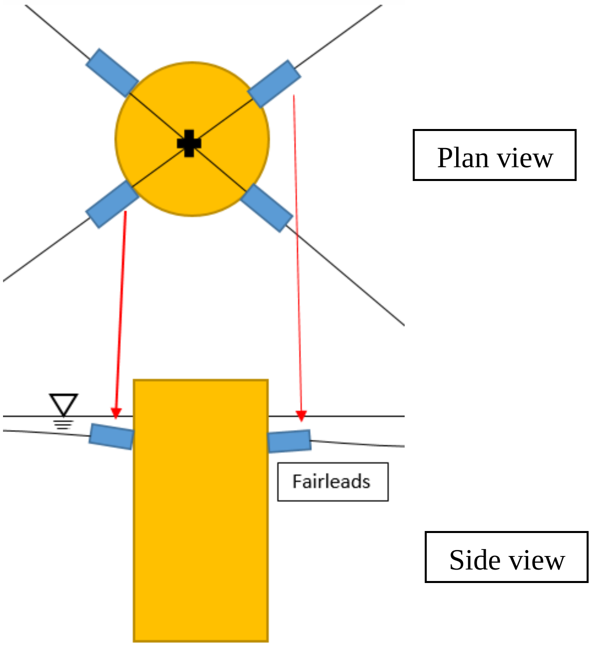

Figure 4.4: Mooring lines attached position

4.5 Types of Tests

4.5.1 Model Calibration Test

Model calibration tests were carried out prior to the sea keeping test. Static offset test is performed to determine the mooring system stiffness while free decay test conducted to determine the natural periods of the system in the considered degrees of freedom [18].

i. **Free decay tests**

Free decay tests were conducted for the purpose to predict the natural period of the system in different conditions. The description of the test procedure as listed below:

- Push the model down a small distance
- Try to make a pure heave motion (no roll, pitch, surge, sway nor yaw)
- Release from rest
- Record motions using QTM cameras
- Repeat for all six motion
- Analyse time signals to determine natural period

ii. **Static offset test**

Static offset test was conducted to estimate the stiffness of the mooring lines in the surge, heave, pitch, sway, roll and yaw direction. As an example, for surge direction, the model was pulled horizontally from the downstream side. Accordingly, static forces were applied and the load cell readings were recorded accordingly. Using this data, the force-displacement relationship was constructed and the stiffness of the mooring line is calculated from the plot [6].

4.5.2 Sea Keeping Test (wave tank test)

Sea keeping test was conducted to measure motions in six degree of freedom and determine RAOs due to random waves.

i. **Equipment Calibration**. The equipment used for the test e.g. load cell, wave probe and trackers need to be calibrated prior to the test to ensure the accurate and precise results obtained (Refer Appendix A).

ii. **Positioning the Model**. The model should be positioned at the test location as shown in Appendix B.

iii. **Collection of data**. The wave probe is used to record the wave profile, velocimeter used for measure current and load cells is used to measure the mooring line tension. QTM will capture the motion of the truss spar to obtain the position of an object.

iv. **Wave and Current Data Details**. The wave data are covered two wave conditions i.e. long-crested wave (random waves condition) and short-crested waves (random waves condition). The current generator consists of three multi-port jet manifolds that can be placed in any direction at variable depths. The maximum current speed is about 0.12 m/s (at surface).

   a. **Long-crested waves**. The wave generator generated long-crested wave in two condition, regular and random wave. Table 4.4 and table 4.5 show the long-crested wave data details and long-crested wave with current data details.

Table 4.4: Long-crested waves without current details

LONG-CRESTED - WITHOUT CURRENT			
RANDOM WAVE TESTS - JONSWAP			
Test Run	Hs (m)	f (Hz)	T (s)
1	0.04	1.190	0.84
2	0.03	1.111	0.9
3	0.05	1.124	0.89
4	0.04	1.064	0.94
5	0.03	1.266	0.79

Table 4.5: Long-crested waves with current details

LONG-CRESTED - WITH CURRENT			
RANDOM WAVE TESTS - JONSWAP			
Test Run	Hs (m)	f (Hz)	T (s)
1	0.04	1.190	0.84
2	0.03	1.111	0.9
3	0.05	1.124	0.89
4	0.04	1.064	0.94
5	0.03	1.266	0.79
Ocean Current			
Current location		Unit	m/s
Current – at surface		m/s	0.124
Current – at mid-depth 0.5D		m/s	0.098
Current – at near seabed 0.01D		m/s	0.027

b. **Short-crested waves**. The generator defined the multi-directional wave as a product of wave spectra (JONSWAP spectrum) and spreading function (cosine squared). It is capable to generate wave due to sea-states condition like multi-directional wave. Custom spectra such as JONSWAP can be added to the software and calibrated [5]. The details of the wave and current data are scaled down by Froude scaling as in Appendix D. The details are based on PTS (Petronas Technical Standard) waves and current data as in Appendix E. Table 4.6 and table 4.7 show the short-crested waves data details and short-crested waves with current data details .

Table 4.6: Short-crested waves without current details

SHORT-CRESTED - WITHOUT CURRENT			
RANDOM WAVE TESTS - JONSWAP			
Test Run	Hs (m)	f (Hz)	T (s)
1	0.04	1.190	0.84
2	0.03	1.111	0.9
3	0.05	1.124	0.89
4	0.04	1.064	0.94
5	0.03	1.266	0.79

Table 4.7: Short-crested waves with current details

SHORT-CRESTED – WITH CURRENT			
RANDOM WAVE TESTS - JONSWAP			
Test Run	Hs (m)	f (Hz)	T (s)
1	0.04	1.190	0.84
2	0.03	1.111	0.9
3	0.05	1.124	0.89
4	0.04	1.064	0.94
5	0.03	1.266	0.79
Ocean Current			
Current location		Unit	m/s
Current – at surface		m/s	0.124
Current – at mid-depth 0.5D		m/s	0.098
Current – at near seabed 0.01D		m/s	0.027

c. **Current.** The current generator consists of three multi-port jet manifolds that can be placed in any direction at variable depths. Theory for current loads is not so well developed compared to the wave loads. However, some reasonable simplifications are often used in modeling current. The assumptions are [6]:

1. Current velocity is steady.
2. Current velocity has the same profile over a reasonable distance.
3. The current and wave kinematics are independent.

v. **Data processing**. Finally, the motion of the model are measured by QTM, which is a motion capture software used to obtain the position of an object by determining the active and passive position through the maker reflections attached on the object. Raw data obtained from the QTM is analysed and the dynamic responses of the model are presented in terms of RAO for all 6 degrees of freedom. Figure 4.5 shows the Project Flow Chart.

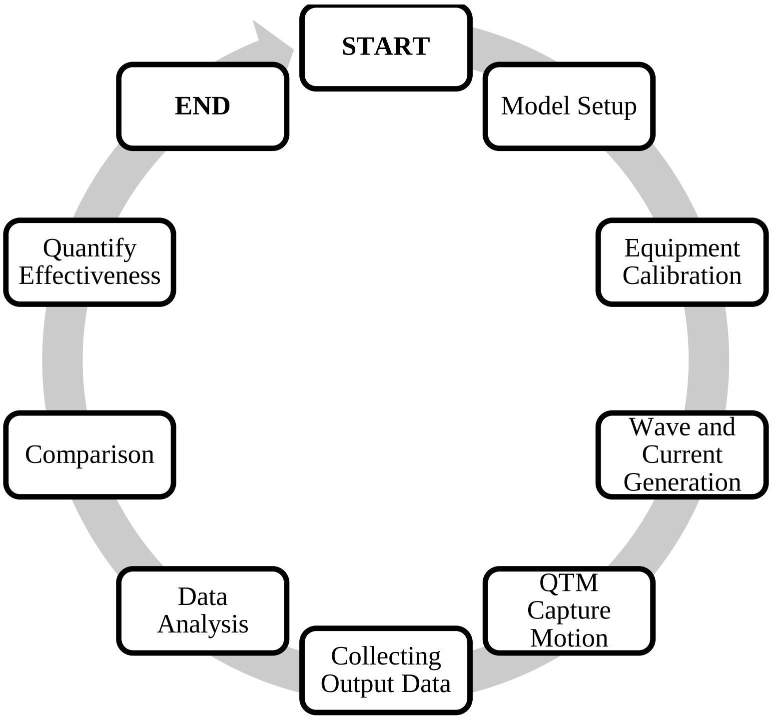

Figure 4.5: Project Flow Chart

4.6 Project key milestone and project timeline

The experimental study is meticulously planned as project timeline and project key milestone as shown in Figure 4.6 and Figure 4.7 respectively.

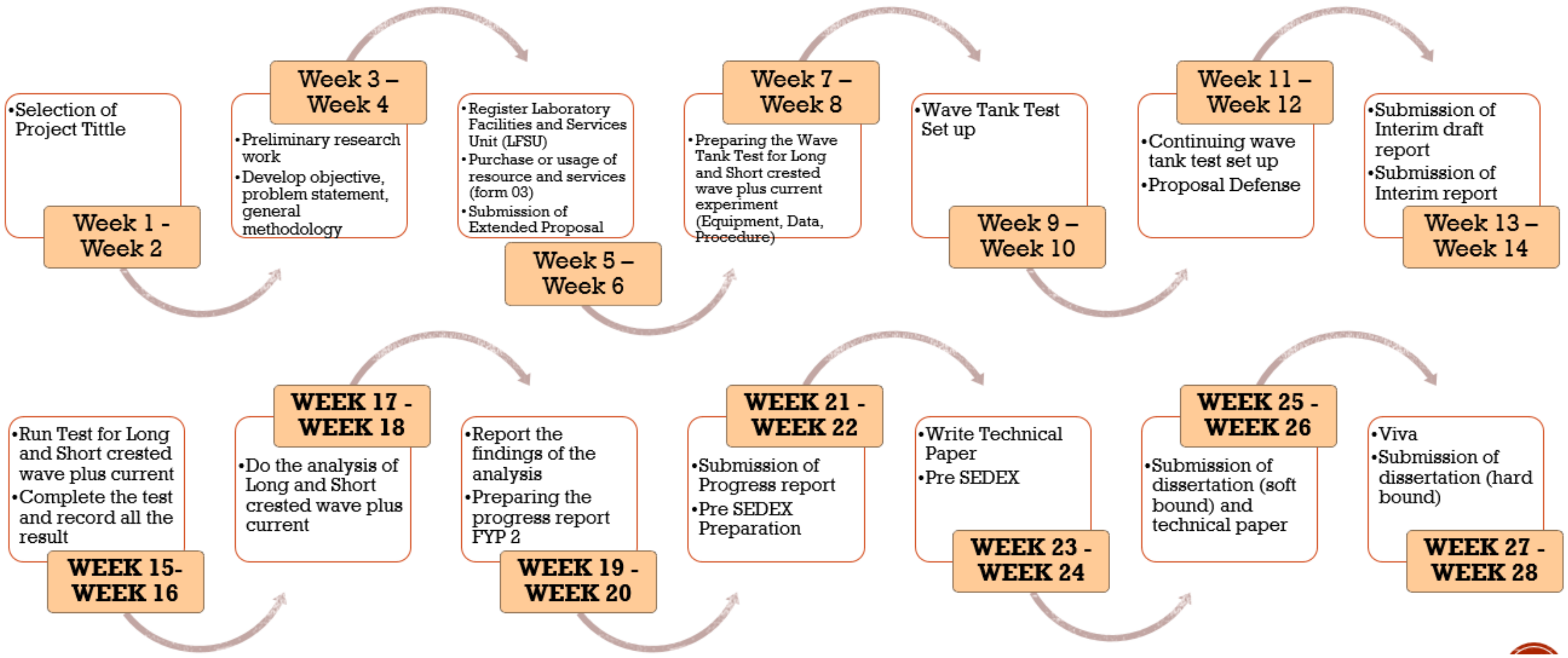

Figure 4.6: Project Timeline

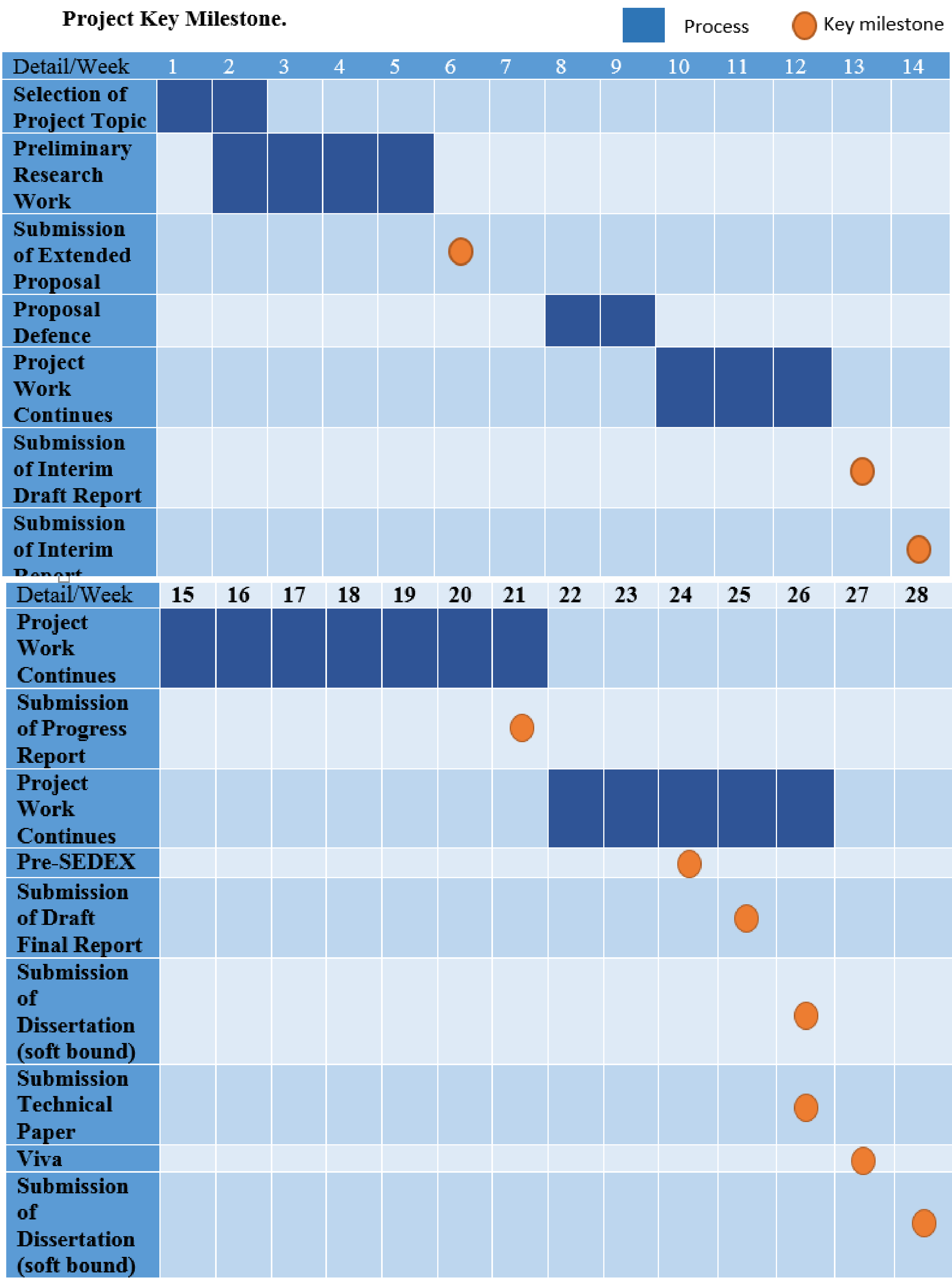

Figure 4.7: Project Key Milestone

4.7 Chapter Summary

In this chapter, the model tests including static offset, free decay and station keeping tests conducted were described. The structural data, lab facilities and the related system were given. The experimental study is also planned as project timeline and project key milestone.

CHAPTER 5

RESULT AND DISCUSSION

Results of this experimental study are covered the results of model calibration tests and sea keeping test. The results will be discussed in this chapter.

5.1 Statistical tables of motions and mooring tensions

5.1.1 Static offset test result – surge direction

Figure 5.1 shows the static offset test results for all load cells reading in surge direction.

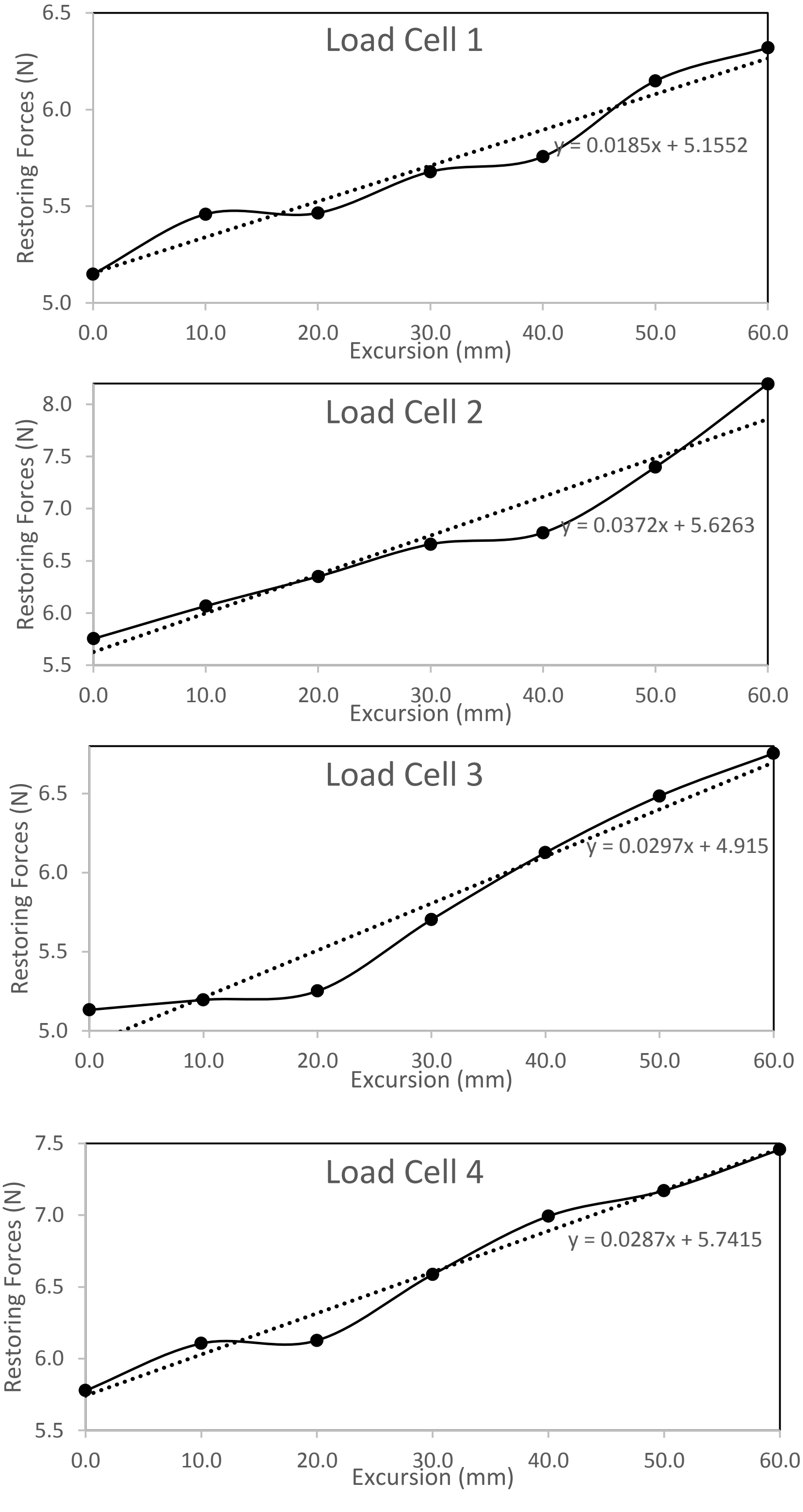

Figure 5.1: Static offset test results

The same procedure used earlier was adopted here to find the mooring line restoring forces or the stiffness. Table 5.1 is the summary of the mooring line stiffness. Due to limitation in calibration works, the stiffness result from Load cell 1 is emitted. In order to design the model with relatively low natural frequencies in all degrees of freedom, soft springs with 0.032 N/mm stiffness (model scale) were used in the experiments to represent the mooring lines system.

Table 5.1: Mooring Line Stiffness

Moring line Label	**Stiffness (N/mm)**
Load cell 2	0.037
Load cell 3	0.030
Load cell 4	0.029
Average Stiffness	**0.032**

5.1.2 Free decay test result

Free decay test results for all six degrees of freedom are as Figure 5.2 to Figure 5.7.

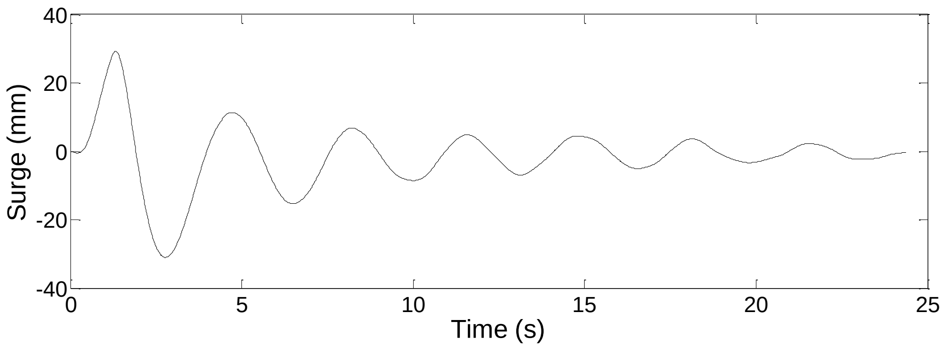

Figure 5.2: Surge free decay test result

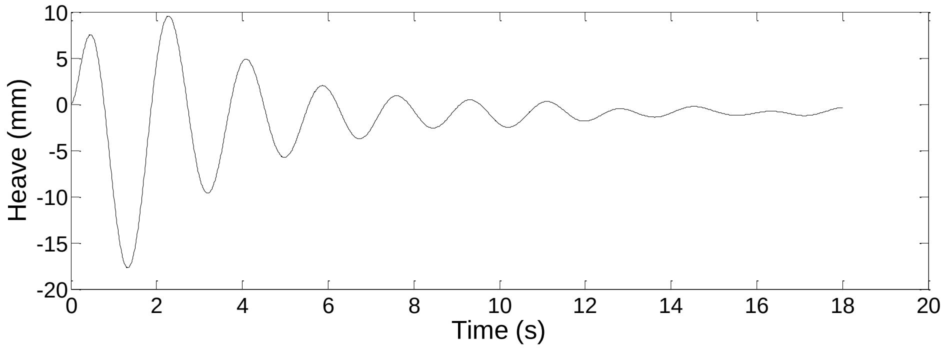

Figure 5.3: Heave free decay test result

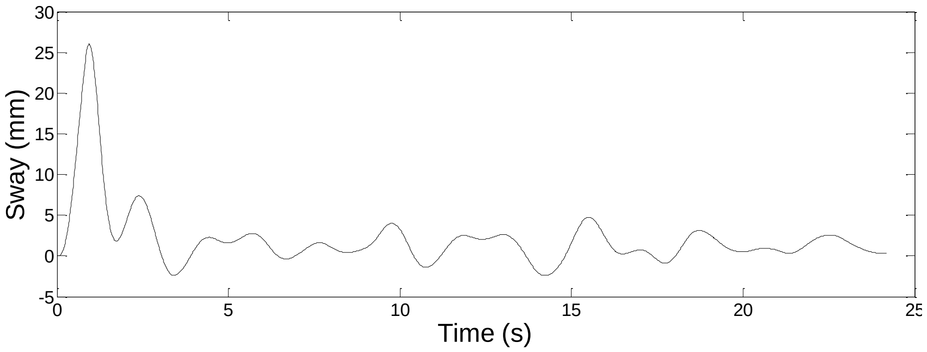

Figure 5.4: Sway free decay test result

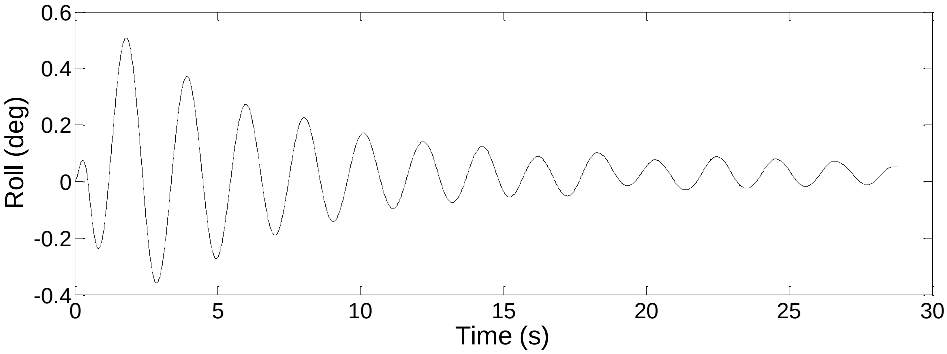

Figure 5.5: Roll free decay test result

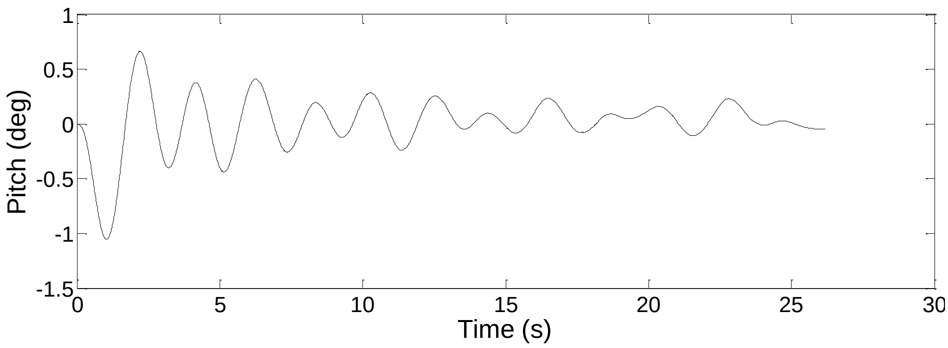

Figure 5.6: Pitch free decay test result

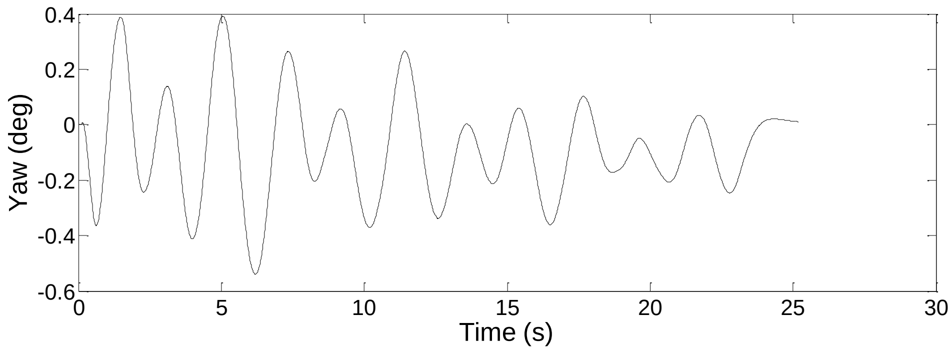

Figure 5.7: Yaw free decay test result

Based on the result of Free-decay test from Figure 5.2 – 5.7, the natural periods of truss spar platform has been summarized in Table 5.2 below.

Table 5.2: Natural periods for dynamic motions of truss spar platform

Dynamic Motions	**Measured Natural Period (s)**	**Typical Natural Period (s)**
Surge	3.6	10.0
Heave	2.6	2.8
Sway	2.8	3.0
Roll	3.1	3.2
Pitch	4.0	5.0
Yaw	3.9	4.0

*Note: Typical Natural Period are based on Kikeh Spar Natural Period [4]

5.2 Time Series Analysis

Time series is a collection of observations of well-defined data items obtained through repeated measurements over time [17]. The irregular wave data are observed by the time series using the single wave method. Single wave method represented the design wave by a wave period and a wave height.

5.2.1 Long-crested random waves without current

Figures 5.8 and 5.9 show the motions of the truss spar platform in 6 DOF and the wave height for long-crested random waves without current.

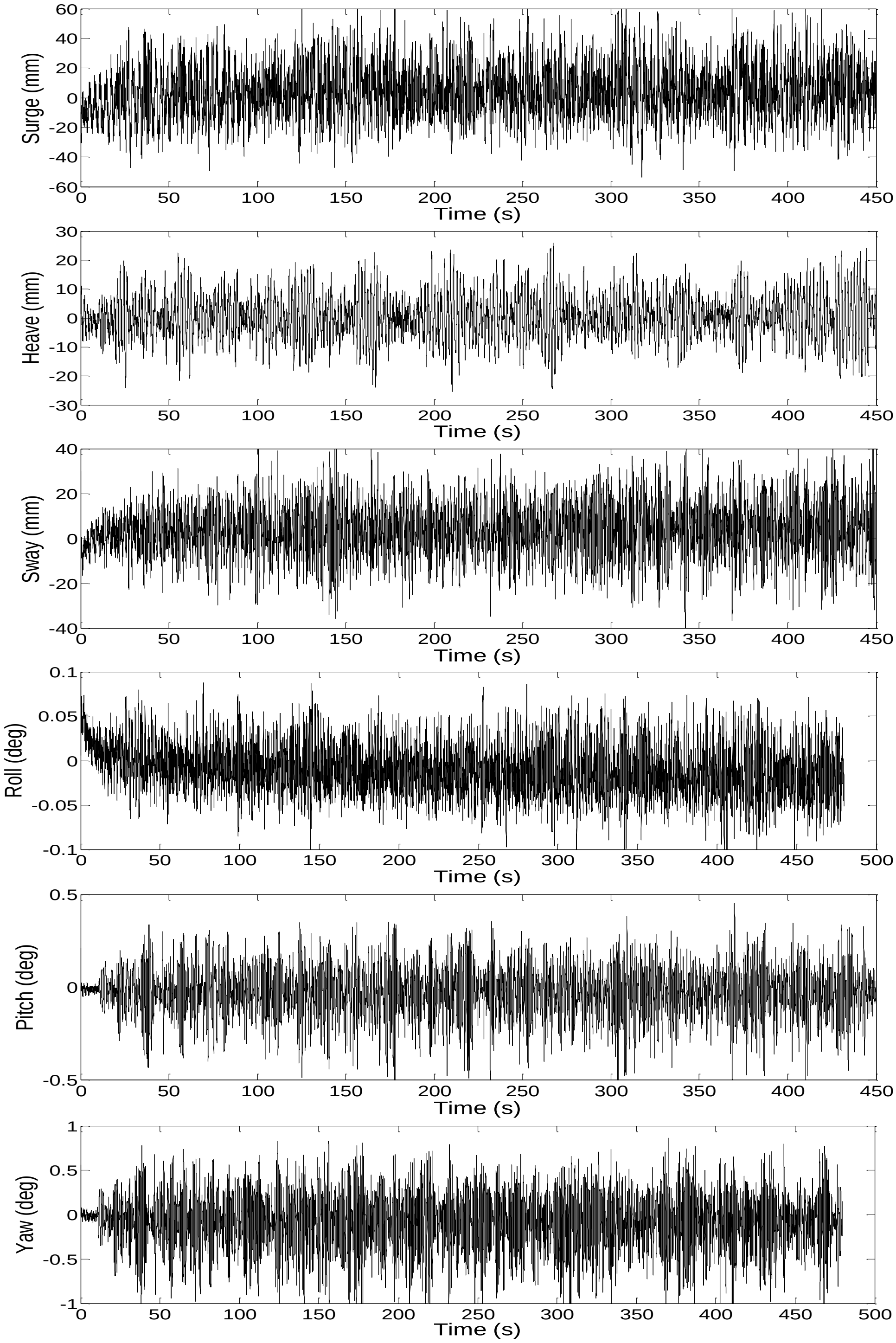

Figure 5.8: Long-crested random waves without current 6 DOF time series

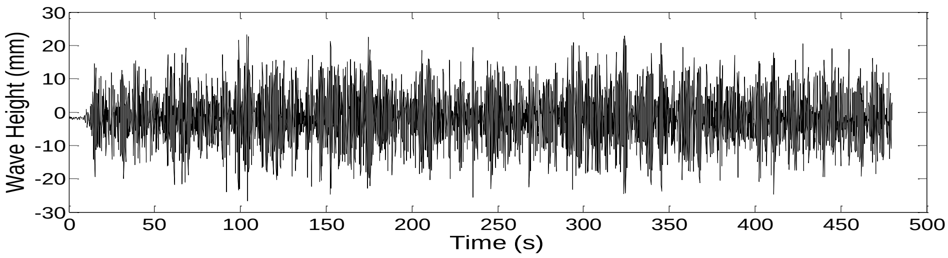

Figure 5.9: Long-crested random waves without current Wave Height

The motions of the truss spar platform in 6 DOF and the wave height for long-crested random waves without current have been observed in Figures 5.8 and 5.9. Table 5.3 summarize the observation.

Table 5.3: Long-crested random waves without current observation

Parameter	**Measured value**
Maximum longitudinal motion (surge)	110 mm
Maximum vertical motion (heave)	50 mm
Maximum transverse motion (sway)	80 mm
Maximum roll angular motion	0.17 deg
Maximum pitch angular motion	0.8 deg
Maximum yaw angular motion	0.17 deg
Maximum wave height	50 mm

5.2.2 Long-crested random waves with current

Figures 5.10 and 5.11 show the motions of the truss spar platform in 6 DOF and the wave height for long-crested random waves with current.

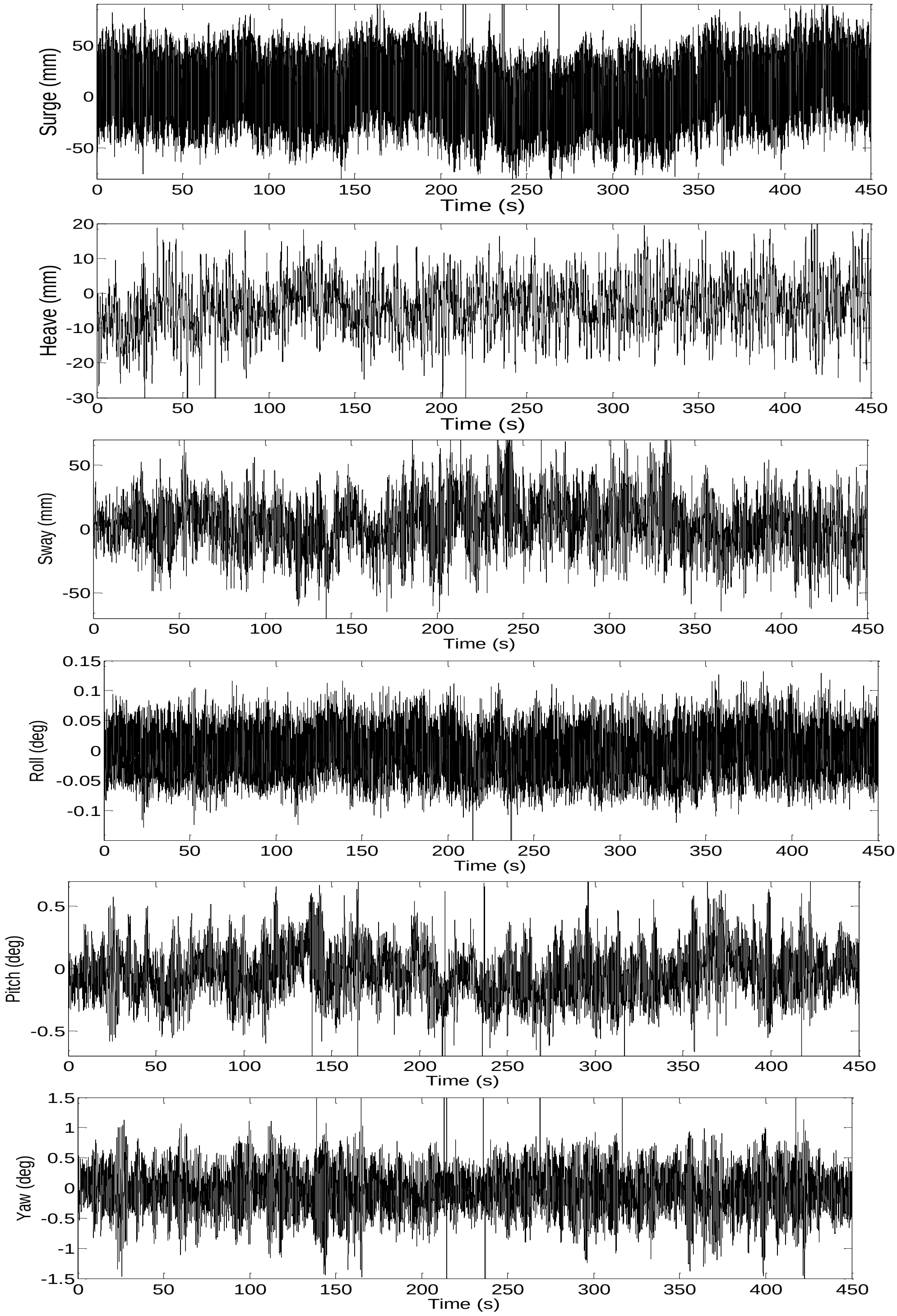

Figure 5.10: Long-crested random waves with current 6 DOF time series

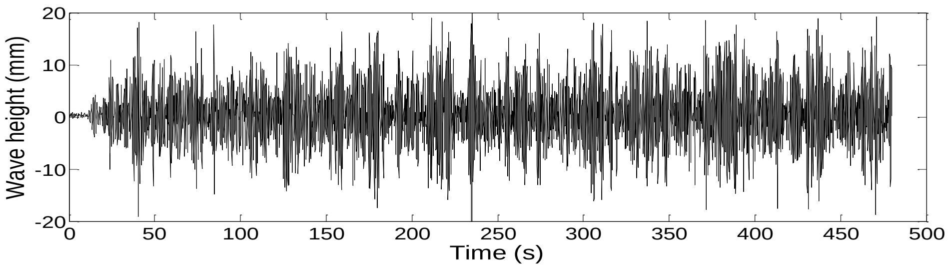

Figure 5.11: Long-crested random waves with current Wave Height

The motions of the truss spar platform in 6 DOF and the wave height for long-crested random waves with current have been observed in Figure 5.10 and 5.11. Table 5.4 summarize the observation.

Table 5.4: Long-crested random waves with current observation

Parameter	Measured value
Maximum longitudinal motion (surge)	110 mm
Maximum vertical motion (heave)	43 mm
Maximum transverse motion (sway)	110 mm
Maximum roll angular motion	0.25 deg
Maximum pitch angular motion	1.2 deg
Maximum yaw angular motion	2.5 deg
Maximum wave height	40 mm

Based on the observation between motions of truss spar model due to both long-crested waves with and without current, there are a little bit differences in motions as summarizes in Table 5.5.

Table 5.5: Percentage differences of truss spar model motions due to long-crested waves

Parameter	**Measured value of truss spar model motions due to long-crested waves**		**Differences (%)**
	Without current	**With current**	
Maximum longitudinal motion (surge)	110 mm	110 mm	-
Maximum vertical motion (heave)	50 mm	43 mm	-14%
Maximum transverse motion (sway)	80 mm	110 mm	+27%
Maximum roll angular motion	0.17 deg	0.25 deg	+32%
Maximum pitch angular motion	0.8 deg	1.2 deg	+33%
Maximum yaw angular motion	0.17 deg	2.5 deg	+93%
Maximum wave height	50 mm	40 mm	-20%

Note:

Positive sign (+) represent the increase of the motions value and negative sign (-) represent the decrease of the motions value.

Due to the effect of current loads, the motions of truss spar model increases in sway, roll, pitch and yaw direction.

5.2.3 Short-crested random waves without current

Figures 5.12 and 5.13 show the motions of the truss spar platform in 6 DOF and the wave height for short-crested random waves without current.

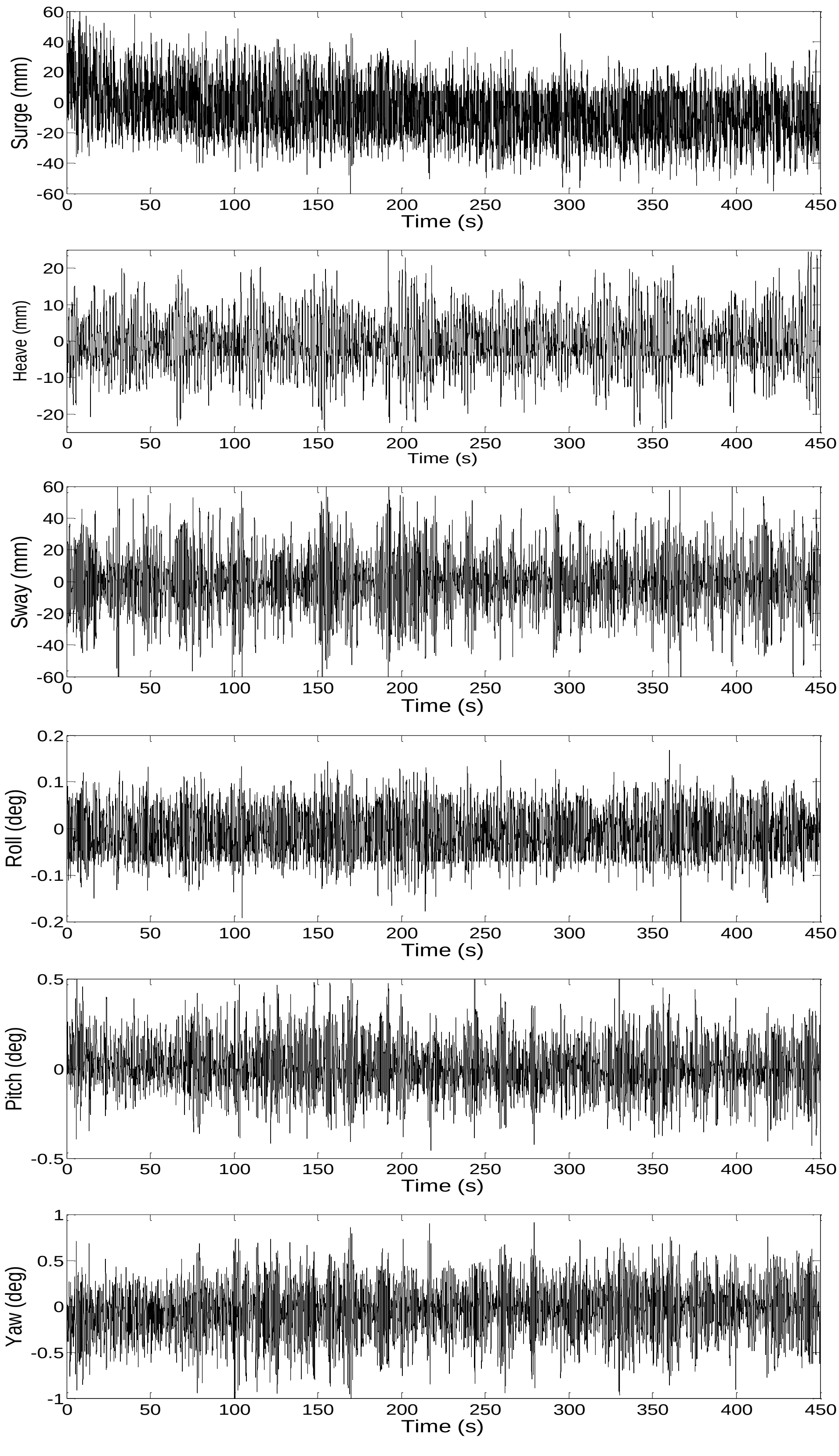

Figure 5.12: Short-crested random waves without current 6 DOF time series

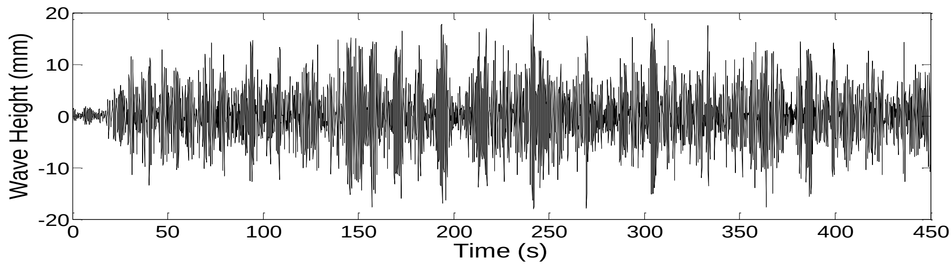

Figure 5.13: Short-crested random waves without current Wave Height

The motions of the truss spar platform in 6 DOF and the wave height for short-crested random waves without current have been observed in Figures 5.12 and 5.13. Table 5.6 summarize the observation.

Table 5.6: Short-crested random waves without current observation

Parameter	Measured value
Maximum longitudinal motion (surge)	100 mm
Maximum vertical motion (heave)	45 mm
Maximum transverse motion (sway)	120 mm
Maximum roll angular motion	0.32 deg
Maximum pitch angular motion	0.9 deg
Maximum yaw angular motion	1.8 deg
Maximum wave height	40 mm

5.2.4 Short-crested random waves with current

Figures 5.14 and 5.15 show the motions of the truss spar platform in 6 DOF and the wave height for short-crested random waves with current.

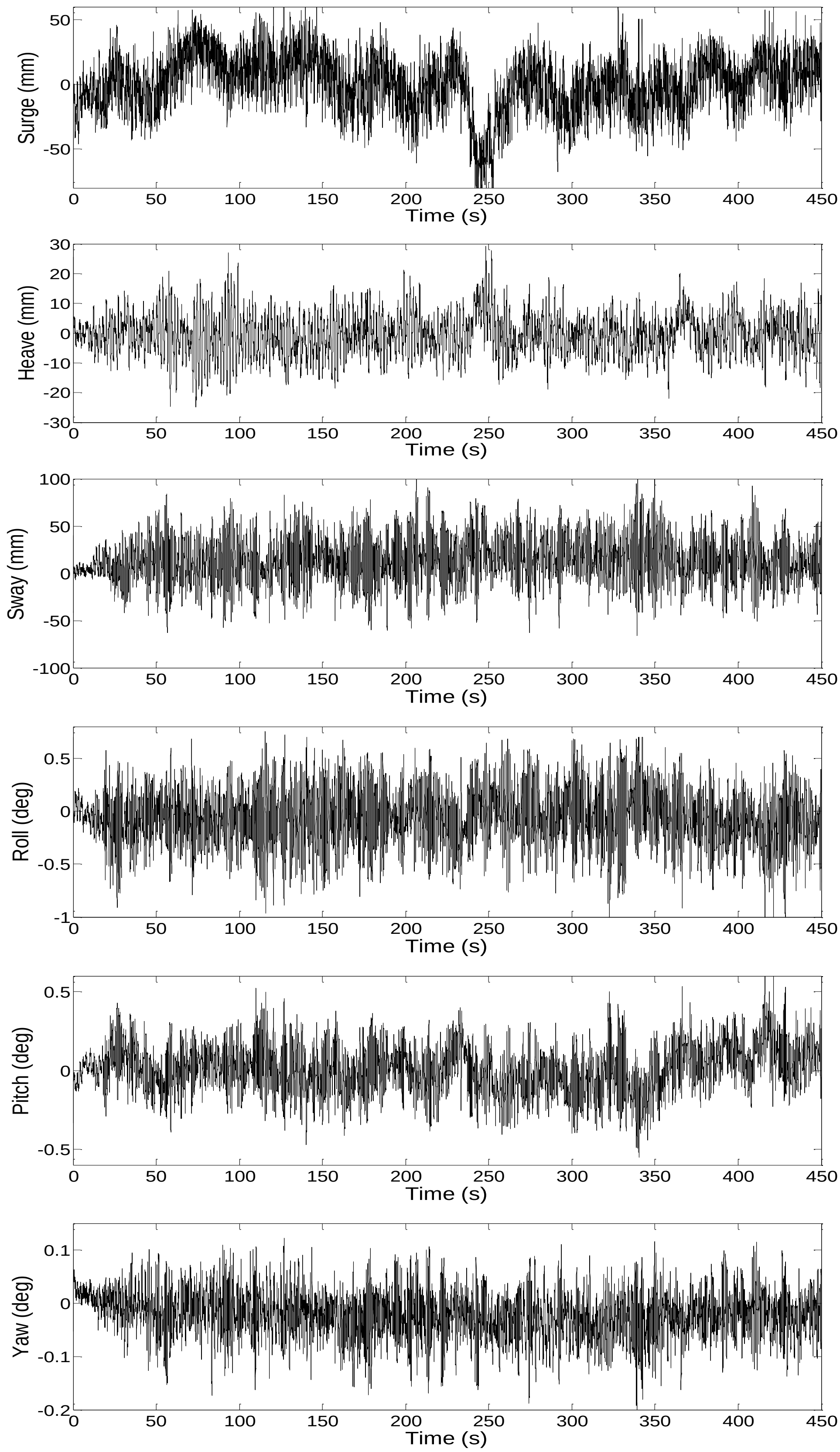

Figure 5.14: Short-crested random waves with current 6 DOF time series

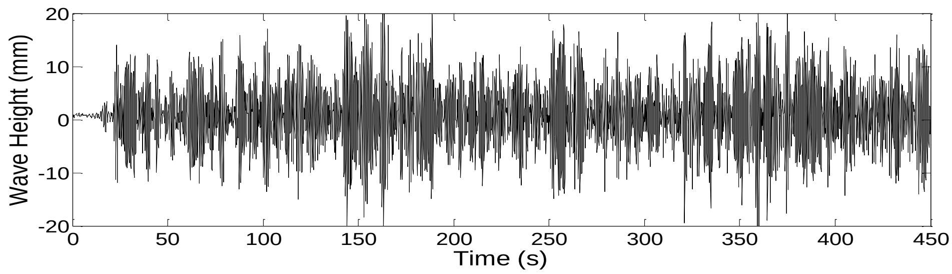

Figure 5.15: Short-crested random waves with current Wave Height

The motions of the truss spar platform in 6 DOF and the wave height for short-crested random waves with current have been observed in Figures 5.14 and 5.15. Table 5.7 summarize the observation.

Table 5.7: Long crested random waves with current observation

Parameter	**Measured value**
Maximum longitudinal motion (surge)	110 mm
Maximum vertical motion (heave)	45 mm
Maximum transverse motion (sway)	140 mm
Maximum roll angular motion	1.8 deg
Maximum pitch angular motion	0.9 deg
Maximum yaw angular motion	0.3 deg
Maximum wave height	40 mm

Based on the observation between motions of truss spar model due to both long-crested waves with and without current, there are a little bit differences in motions as summarizes in Table 5.8.

Table 5.8: Percentage differences of truss spar model motions due to short-crested waves

Parameter	Measured value of truss spar model motions due to long-crested waves		Differences (%)
	Without current	With current	
Maximum longitudinal motion (surge)	100 mm	110 mm	+9%
Maximum vertical motion (heave)	45 mm	45 mm	-
Maximum transverse motion (sway)	120 mm	140 mm	+14%
Maximum roll angular motion	0.32 deg	1.8 deg	+80%
Maximum pitch angular motion	0.9 deg	0.9 deg	-
Maximum yaw angular motion	1.8 deg	0.3 deg	-83%
Maximum wave height	40 mm	40 mm	-

Note:

Positive sign (+) represent the increase of the motions value and negative sign (-) represent the decrease of the motions value.

Due to the effect of current loads, the motions of truss spar model increases in surge, sway and roll direction.

5.3 Response Spectra Analysis

Wave spectrum represented the concept of wave energy density spectrum. JONSWAP wave spectrum were considered as mentioned in section 3.1.2. MATLAB Program was used to transform the wave data to wave energy density spectrum.

5.3.1 Long-crested random waves without current

Six DOF Spectrum of long-crested waves without current was filtered and the results are shown in Figure 5.16. Figure 5.17 shows the wave spectrum of long-crested waves without current.

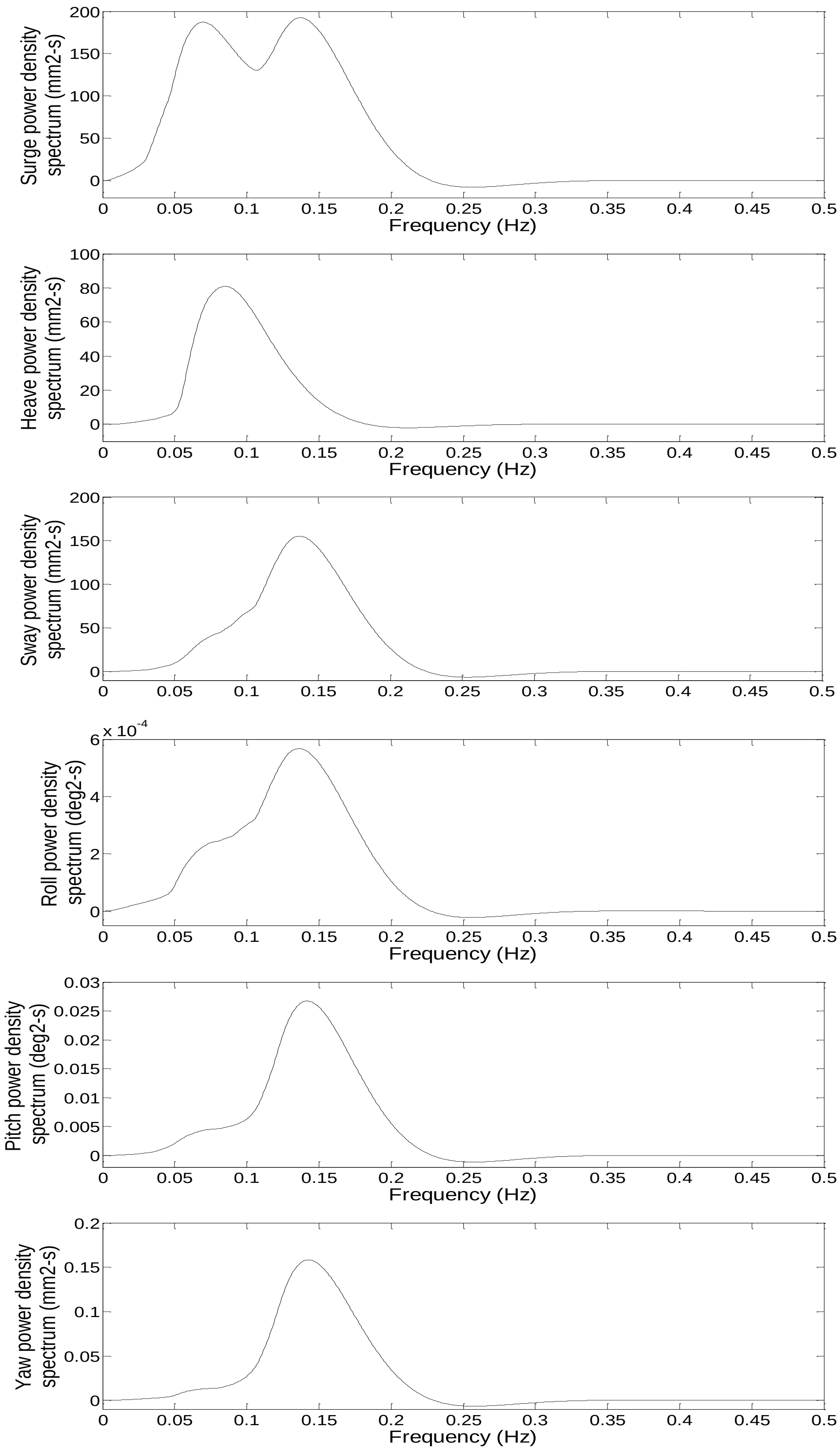

Figure 5.16: Six DOF spectrum of long-crested waves without current

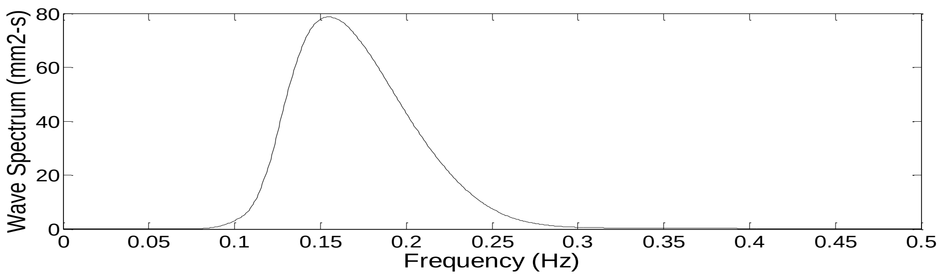

Figure 5.17: Wave spectrum of long-crested waves without current

The six DOF responses spectra due to long-crested waves are shown in Figure 5.16. It was noticed that the six DOF response are as summarizes in Table 5.9.

Table 5.9: Six DOF responses spectra due to long-crested waves

Six DOF	**Responses spectra**
Surge	180 mm^2-s
Heave	80 mm^2-s
Sway	150 mm^2-s
Roll	0.00058 deg^2-s
Pitch	0.027 deg^2-s
Yaw	0.16 deg^2-s

5.3.2 Long-crested random waves with current

Six DOF Spectrum of long-crested waves with current was filtered and the results are shown in Figure 5.18. Figure 5.19 shows the wave spectrum of long-crested waves with current.

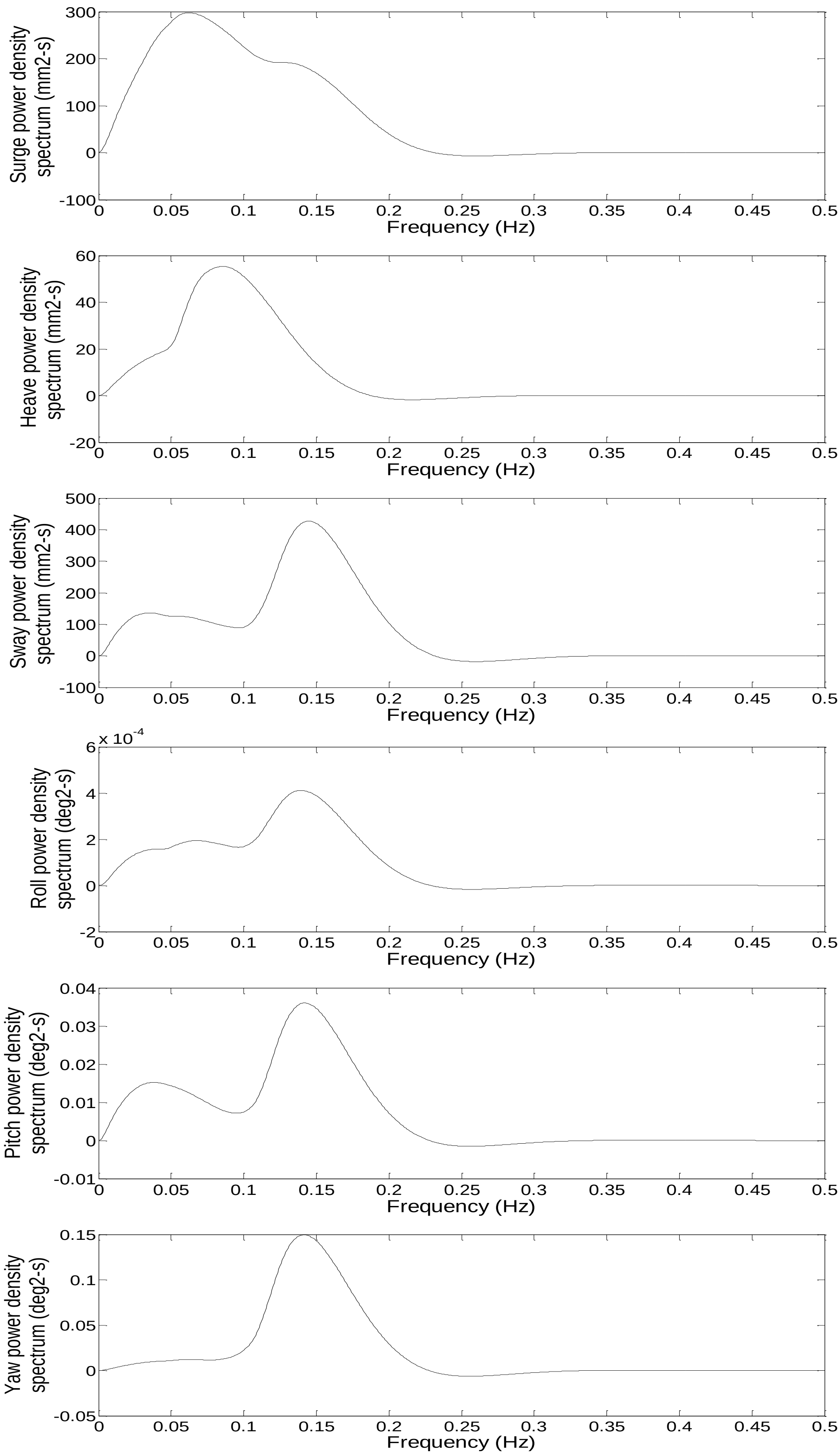

Figure 5.18: Six DOF spectrum of long-crested waves with current

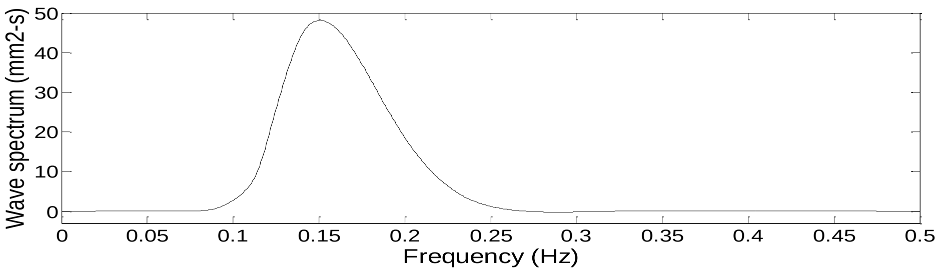

Figure 5.19: Wave spectrum of long-crested waves with current

The six DOF responses spectra due to long-crested waves are shown in Figure 5.18. It was noticed that the six DOF response are as summarizes in Table 5.10.

Table 5.10: Six DOF responses spectra due to long-crested waves with current

Six DOF	**Responses spectra**
Surge	300 mm^2-s
Heave	58 mm^2-s
Sway	420 mm^2-s
Roll	0.0004 deg^2-s
Pitch	0.025 deg^2-s
Yaw	0.15 deg^2-s

The heave, roll, pitch and yaw responses spectra due to combined random waves and current shown were noticed that the presence of current substantially decreased the heave, roll, pitch and yaw resonant responses. This is because adding current to the wave results in additional damping.

5.3.3 Short-crested random waves without current

Six DOF Spectrum of long-crested waves with current was filtered and the results are shown in Figure 5.20. Figure 5.21 shows the wave spectrum of short-crested waves without current.

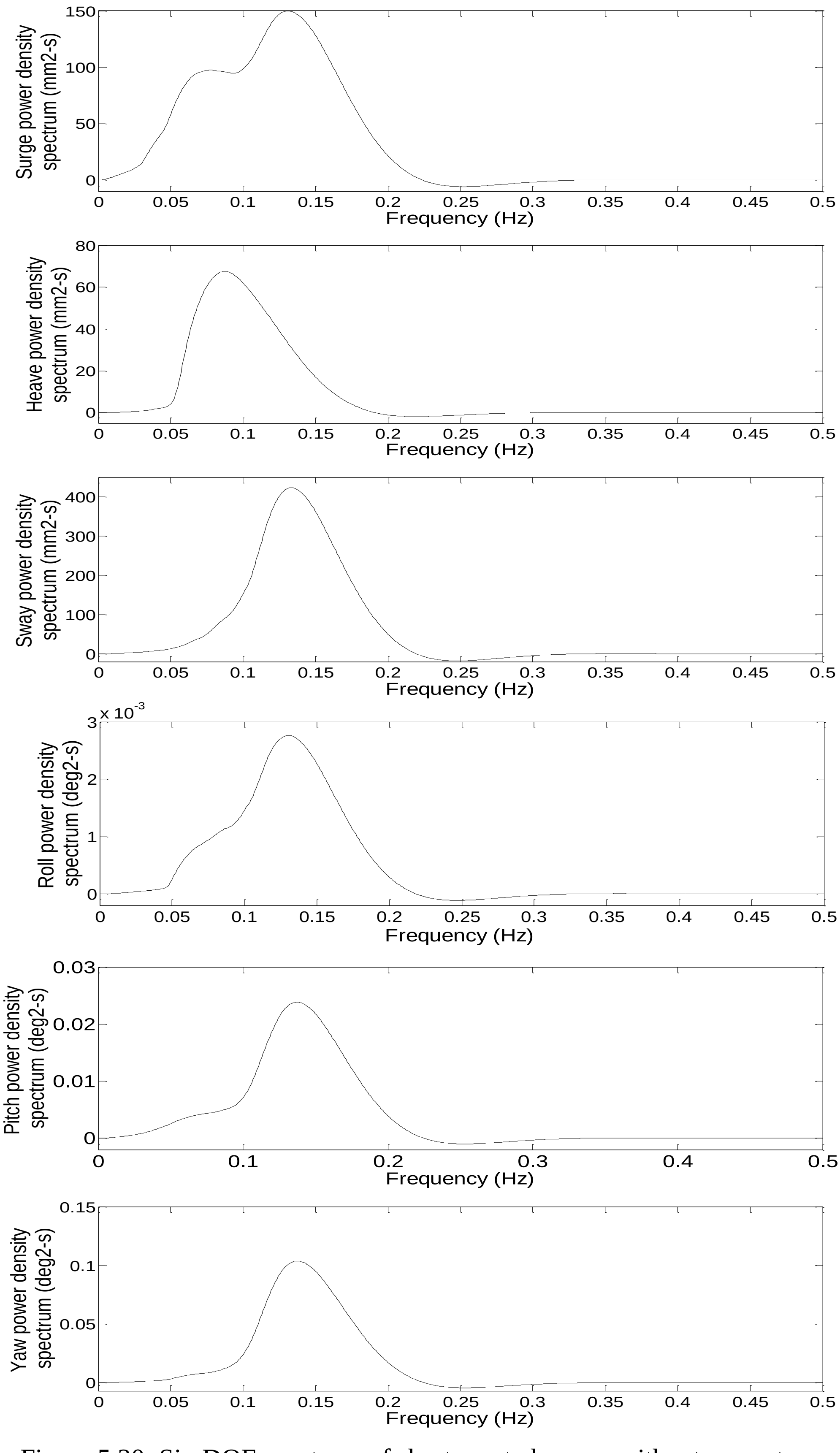

Figure 5.20: Six DOF spectrum of short-crested waves without current

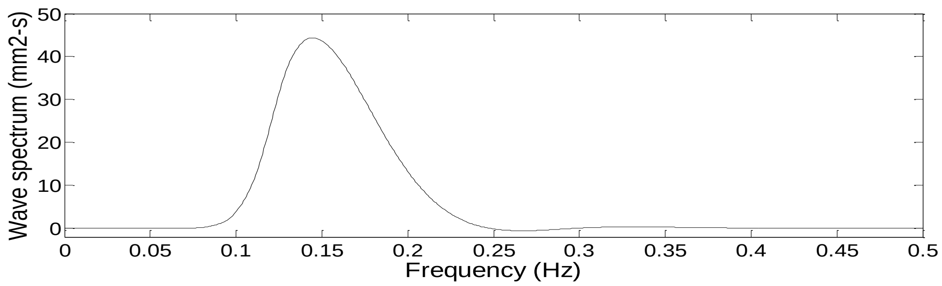

Figure 5.21: Wave spectrum of short-crested waves without current

The six DOF responses spectra due to long-crested waves are shown in Figure 5.20. It was noticed that the six DOF response are as summarizes in Table 5.11.

Table 5.11: Six DOF responses spectra due to short-crested waves without current

Six DOF	**Responses spectra**
Surge	150 mm^2-s
Heave	70 mm^2-s
Sway	410 mm^2-s
Roll	0.0028 deg^2-s
Pitch	0.025 deg^2-s
Yaw	0.12 deg^2-s

5.3.4 Short-crested random waves with current

Six DOF Spectrum of long-crested waves with current was filtered and the results are shown in Figure 5.22. Figure 5.23 shows the wave spectrum of short-crested waves with current.

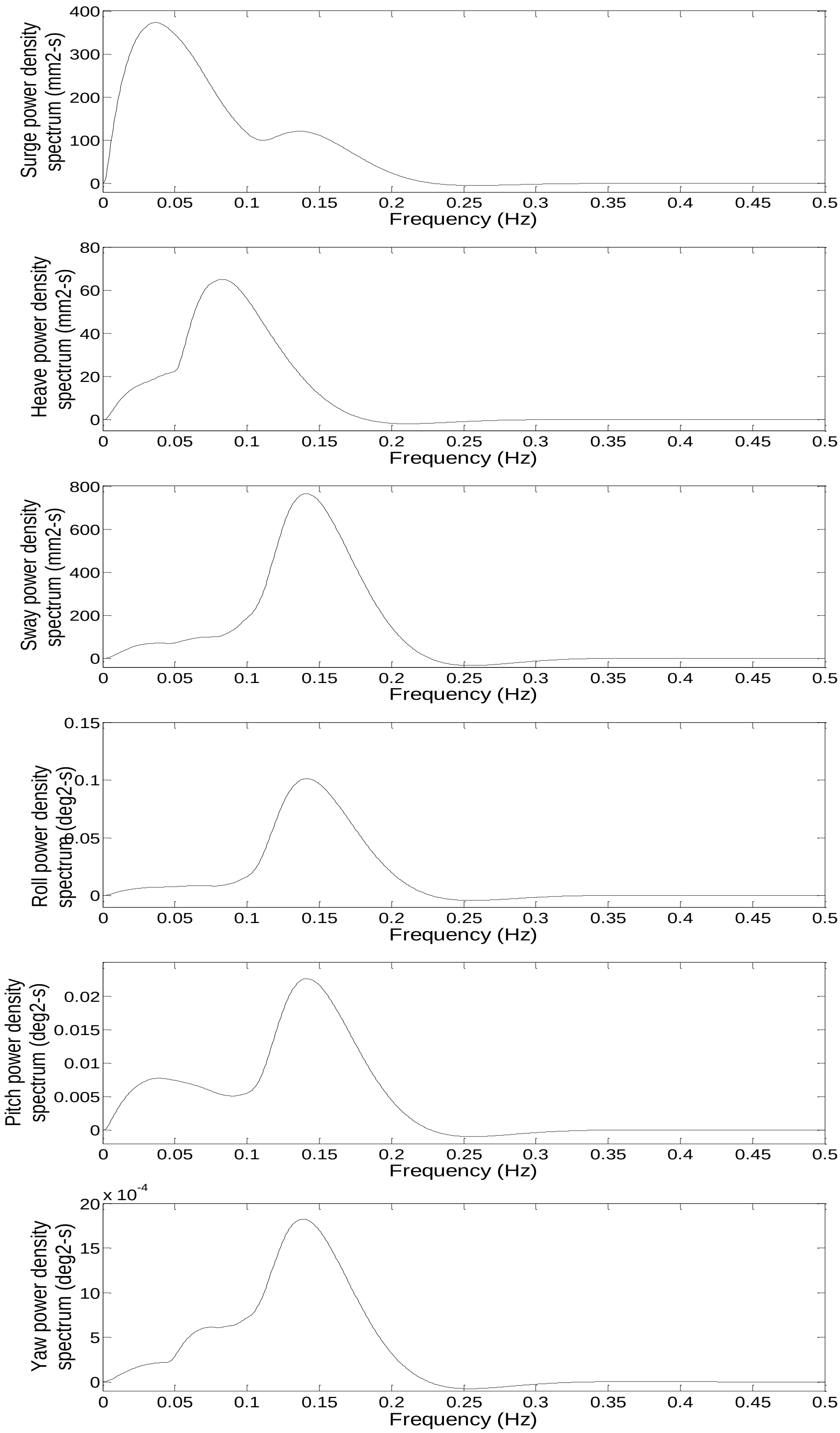

Figure 5.22: Six DOF spectrum of short-crested waves with current

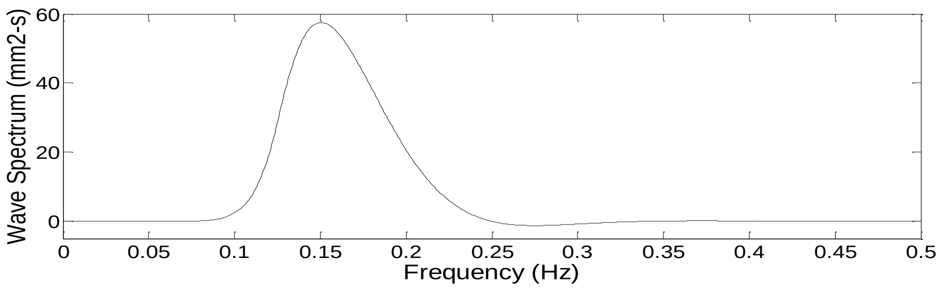

Figure 5.23: Wave spectrum of short-crested waves with current

The six DOF responses spectra due to long-crested waves are shown in Figure 5.22. It was noticed that the six DOF response are as summarizes in Table 5.12.

Table 5.12: Six DOF responses spectra due to short-crested waves with current

Six DOF	**Responses spectra**
Surge	380 mm^2-s
Heave	65 mm^2-s
Sway	780 mm^2-s
Roll	0.0018 deg^2-s
Pitch	0.023 deg^2-s
Yaw	0.01 deg^2-s

The heave, roll, pitch and yaw responses spectra due to combined random waves and current shown were noticed that the presence of current substantially decreased the heave, roll, pitch and yaw resonant responses. This is because adding current to the wave results in additional damping.

5.4 Response Amplitude Operator (RAO)

Laboratory result shows the Response Amplitude Operator (RAO) against Frequency graphs on six degree of motions consist of Surge, Heave, Sway, Yaw, Pitch and Roll are represented in this section.

5.4.1 Long-crested waves without current and long-crested waves with current

Figure 5.24 shows the motions responses of truss spar platform model due to long-crested waves with and without current for all six DOF.

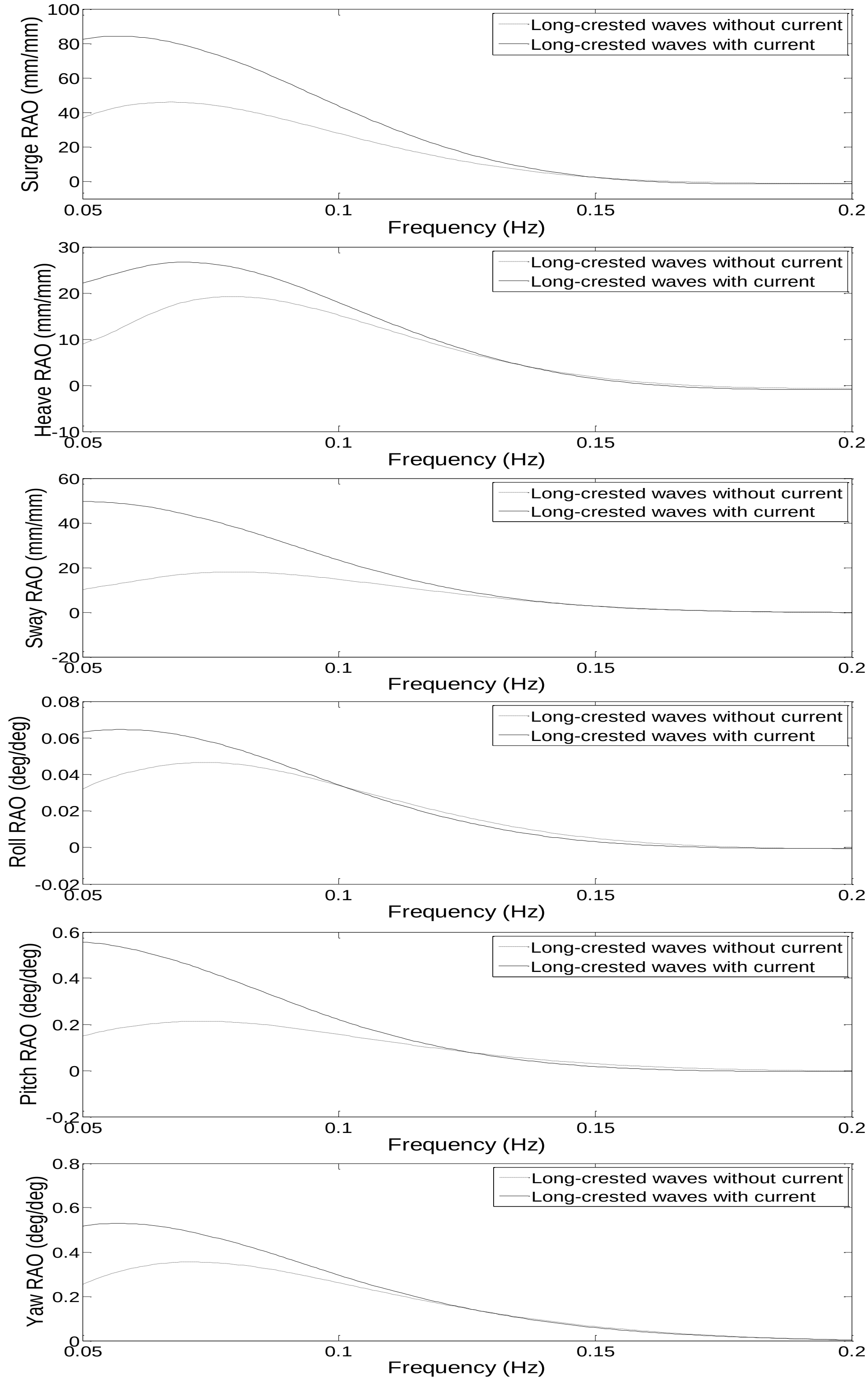

Figure 5.24: RAO due to long-crested waves with and without current

From the observation, the motion of responses is decreased when the frequency is increased. Figure 5.24 show that RAO of truss spar model due to long-crested waves with current are greater than RAO due to long-crested waves without current for all six degree of freedom. This shows that the combined long-crested wave and current load give a higher effect of motions and this could be considered on offshore structure construction. The effects of current speeds and current direction are very noticeable. With the adding of current speed, the water run-up on the truss spar platform model becomes higher, and this causing the increase of truss spar model motion responses due to short-crested wave without currents even though the current speed is small.

Current load affect the dynamic responses of truss spar model. Table 5.13 shows the percentage differences of truss spar model responses between responses due to long-crested waves without current and long-crested waves with current.

Table 5.13: Percentage differences of truss spar model responses between responses due to long-crested waves with and without current

Degree of Freedom	RAO percentage differences (%)
Surge	45
Heave	33
Sway	60
Roll	27
Pitch	65
Yaw	32

Based on the observation, the responses due to long-crested waves with current are higher about 32% to 65% compared to long-crested waves without current loads.

5.4.2 Short-crested waves without current and short-crested waves with current

Figure 5.25 shows the motions responses of truss spar platform model due to short-crested waves with and without current for all six DOF.

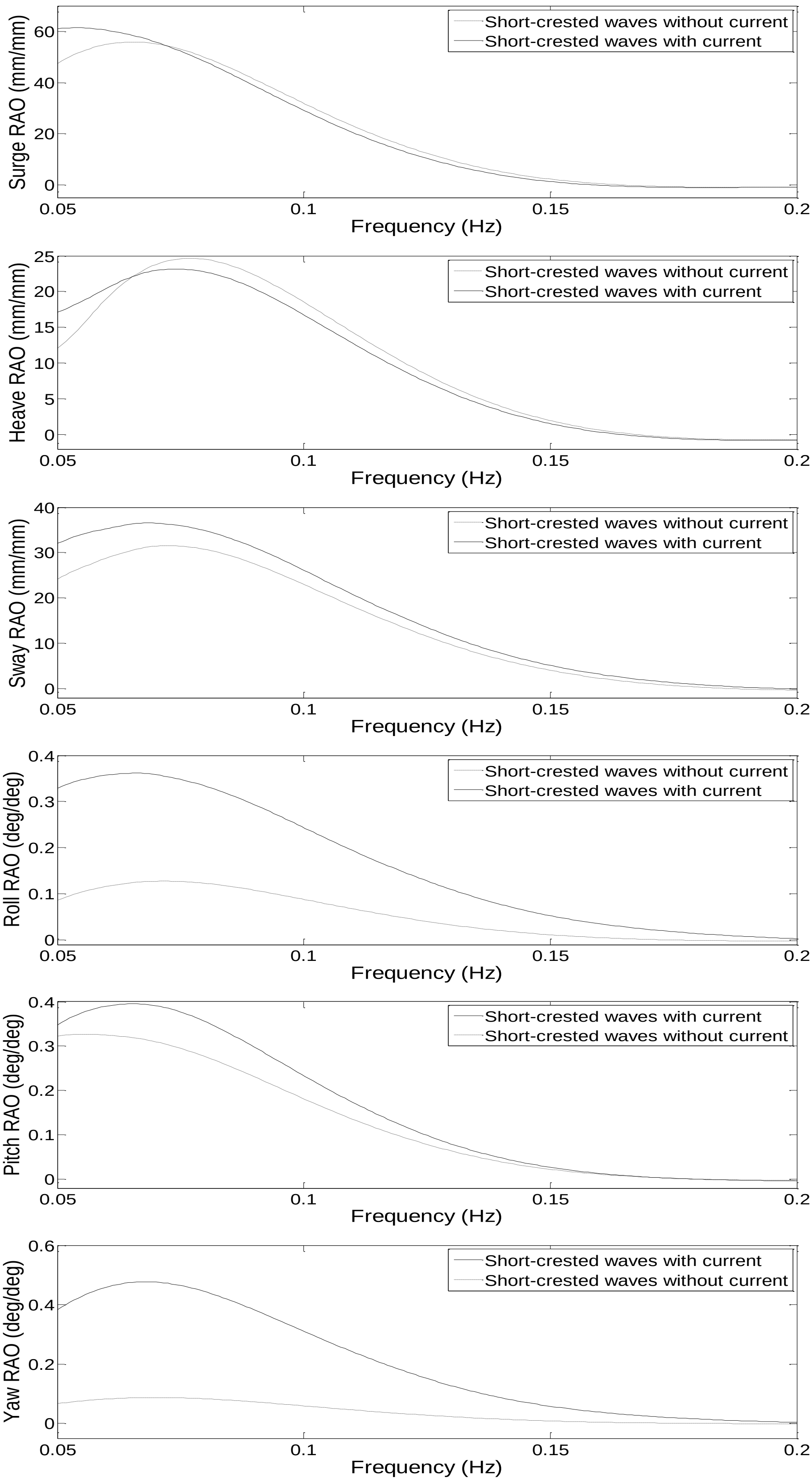

Figure 5.25: RAO due to short-crested waves with and without current

Same cases here, the motion of responses is decreased when the frequency is increased. Figure 525 shows that RAO of truss spar model due to short-crested waves with current are greater than RAO due to short-crested waves without current for surge, sway, roll pitch and yaw direction. This shows that the combined short-crested wave and current loads give a greater effect of motions and this could be considered on offshore structure construction. The effects of current speeds and current direction are very noticeable. With the adding of current speed, the water run-up on the truss spar platform model becomes higher, and this causing the increase of truss spar model motion responses due to short-crested wave without currents even though the current speed is small.

On the other hand, the current loads did not affected the motions responses of heave direction. The responses are about 4% smaller when adding current to the environmental conditions. This is because the direction of current flow are from horizontal direction, thus, vertical motion are not affected.

Current loads affect the dynamic responses of truss spar model other degree of freedom. Table 5.14 shows the percentage differences of truss spar model responses between responses due to short-crested waves without current and short-crested waves with current.

Table 5.14: Percentage differences of truss spar model responses between responses due to short-crested waves with and without current

Degree of Freedom	**RAO percentage differences (%)**
Surge	3
Heave	4
Sway	17
Roll	63
Pitch	18
Yaw	79

Based on the observation, the responses due to short-crested waves with current are higher about 3% to 79% compared to short-crested waves without current load.

5.4.3 Long and short-crested waves without current

Figure 5.26 shows the motions responses of truss spar platform model due to long-crested and short-crested waves without current for all six DOF.

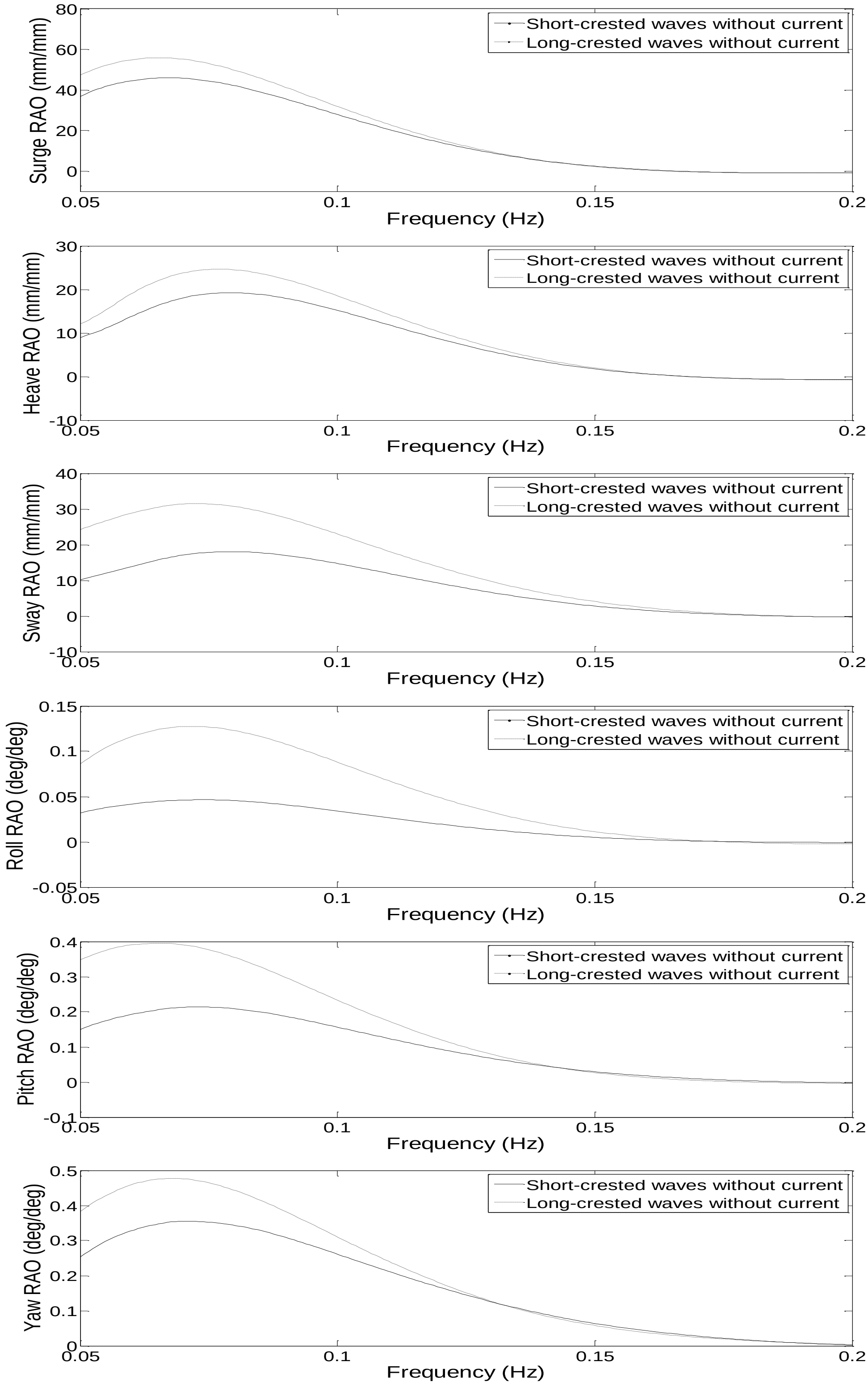

Figure 5.26: RAO due to long-crested and short-crested waves without current

The responses in surge, heave, sway, roll, pitch and yaw motion of truss spar platform model due to short-crested waves is smaller compared those long-crested waves in the absences of current load. Figure 5.26 shows the comparison between the responses of truss spar platform due to long and short-crested waves without current. From the figure, percentage differences between both wave conditions could be summarized as Table 5.15.

Table 5.15: RAO percentage differences between responses due to long and short-crested waves without current

Degree of Freedom	**RAO percentage differences (%)**
Surge	27
Heave	24
Sway	33
Roll	62
Pitch	49
Yaw	25

From the observation, the trend of responses agreed quite well where the responses decreased substantially from 0.06Hz to 0.14Hz for about 24% to 62%. This is might due to the assumption of large offshore platform stretch acted up on by long-crested waves [7]. Thus, the design considering long-crested waves would be overestimated. On the other hand, by considering the short-crested waves, the net effect are quite likely to be less when the waves hitting the stretch length of the truss spar in different angle. Thus, it shows that a more economical design would be arrived by adopting short-crested wave statistic in the design.

5.4.4 Long-crested waves with current and short-crested waves with current

Figure 5.27 shows the motions responses of truss spar platform model due to long-crested and short-crested waves with current for all six DOF.

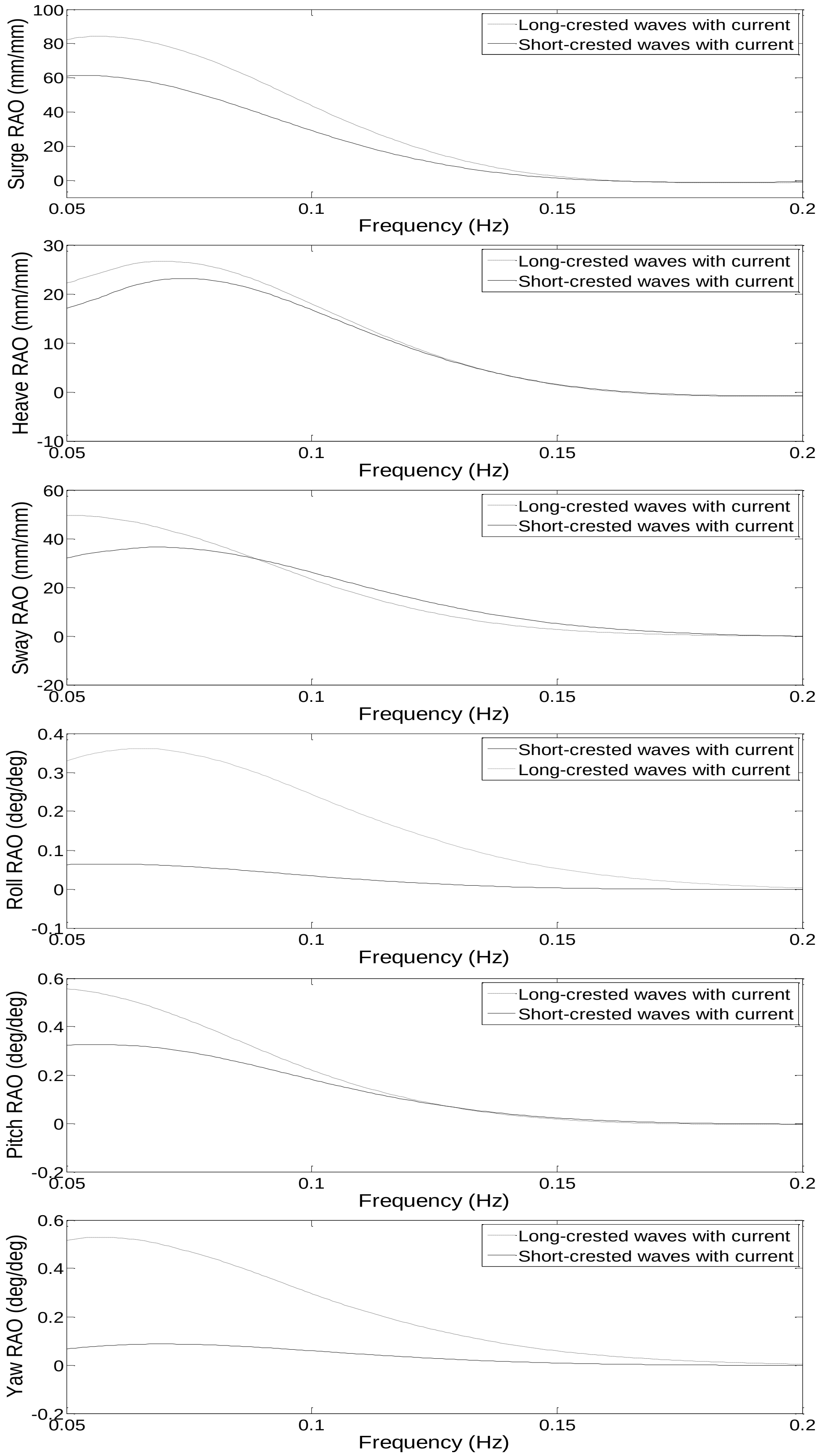

Figure 5.27: RAO due to long-crested and short-crested waves with current

It can be observed that the trend of the six DOF RAOs agreed fairly well with the RAOs decreasing as the frequency increases.

The RAOs due to long and short-crested waves with current are compared in Figure 5.27. It was found that the trends due to both waves are similar. However, significant variation could be observed in the magnitudes. The RAO due to short-crested waves are lower responses compared to the long-crested waves with current for all six DOF. From the figure, percentage differences between both wave conditions has been summarized as Table 5.16.

Table 5.16: RAO percentage differences between responses due to long and short-crested waves with current

Degree of Freedom	**RAO percentage differences (%)**
Surge	26
Heave	22
Sway	32
Roll	75
Pitch	45
Yaw	83

From the observation, the trend of responses agreed quite well where the responses decreased substantially from 0.06Hz to 0.14Hz for about 22% to 83% as the frequency decreased. This is also might due to the assumption of large offshore platform stretch acted up on by long-crested waves. Thus, the design considering long-crested waves would be overestimated. On the other hand, by considering the short-crested waves, the net effect of the waves responses when the waves hitting the stretch length of the spar in different angle are less. Thus, it shows that a more economical design would be arrived by adopting short-crested wave statistic in the design.

From the study, the trends agreed for the surge, heave, sway, roll, pitch and yaw responses. The responses for all six DOF due to short-crested waves with current were much lower compared to the responses for long-crested waves with current. Further studies on this can confirm the same. If this fact is very well established, it can lead to much more economical design of offshore structure.

5.5 Chapter Summary

In this chapter, the results of model tests including static offset, free decay and station keeping tests was presented and discussed. It is expected that in long-crested wave the design of offshore structure would be overestimated. Hence, the results considering short-crested wave statistic in the design of offshore structure is expected to provide a more economical design. The combined short-crested wave and current load also should be considered on offshore structure construction since the effect of current to the dynamic responses are noticeable.

CONCLUSION AND RECOMMENDATION

This experimental study on dynamic responses of classic spar platform subjected to long-crested wave and short-crested wave with current are performed. The dynamic motion response of the truss spar model with 1:100 scaling factor restrained by mooring lines is to be captured and measured by Qualisys Track Manager. In this study, spreading function, cosine squared ($\cos^2$) is implemented and incorporated with JONSWAP spectrum to produce short-crested wave. Current as well will be considered in this study.

Based on the problem statement and literature review elaborated earlier, the significant of this study to compare the dynamic responses of the truss spar due to short-crested waves and long-crested wave with current is necessary to be carried out. From this study, the results of dynamic response in six degree of freedom motion are presented and compared among long-crested and short-crested wave with current.

Based on the observation, the responses due to long-crested waves with current are higher about 32% to 65% compared to long-crested waves without current loads and the responses due to short-crested waves with current are higher about 3% to 79% compared to short-crested waves without current load. This shows that the combined wave and current loads give a higher effect of motions and this should be considered on offshore structure construction. The effects of current speeds and current direction are very noticeable. With the adding of current speed, the water run-up on the truss spar platform model becomes higher, and this causing the increase of truss spar model motion responses due to short-crested wave without currents even though the current speed is small.

In addition, the responses in surge, heave, sway, roll, pitch and yaw motion of truss spar platform model due to short-crested waves is smaller compared those long-crested waves both in the present and absence of current loads. From the observation, the trend of responses agreed quite well where the responses due to short-crested wave compared to long-crested waves decreased substantially from 0.06Hz to 0.14Hz for about 24% to 62% in the absence of current loads. Similarly, the trend of responses agreed quite well where the responses due to short-crested wave compared to long-crested waves decreased substantially from 0.06Hz to 0.14Hz for about 22% to 83% in the present of current loads as the frequency decreased

This is might due to the assumption of large offshore platform stretch acted up on by long-crested waves. Thus, the design considering long-crested waves would be overestimated. On the other hand, by considering the short-crested waves, the net effect are quite likely to be less when the waves hitting the stretch length of the truss spar platform in different angle. Hence, the results considering short-crested wave statistic in the design of offshore structure is expected to provide a more economical design.

Lastly, for the future work, it is recommended that to take care of the calibration works. It is to confirm that the equipment or machines that we used are conformed to the standard. Calibration is very important, as it ensures that facilities are working properly. Without a good calibration test, our results for the experiment will be effected.

Besides that, the following future studies are recommended to perform for a better understanding of this topic:

i. Besides the current loads, considering the wind loads in the design of offshore structure are also would be good in the design considerations. Thus, experimental study on dynamic responses of truss spar platform subjected to long and short-crested waves with current and wind loads should be perform in future.
ii. Investigation of the mooring line and risers effects on the dynamic responses of truss spar platforms subjected to long and short-crested waves with current and wind loads.

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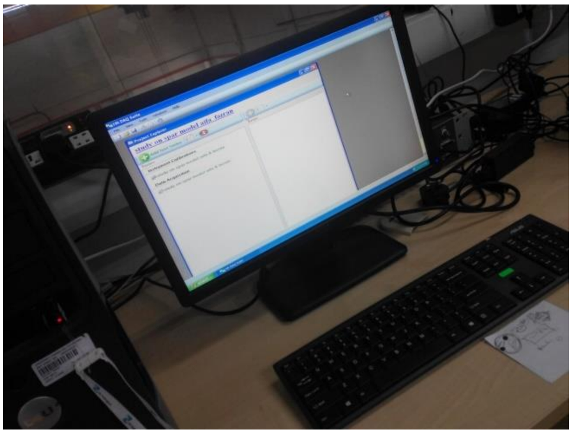
APPENDIX A

EQUIPMENT CALIBRATION

Load Cell Calibration

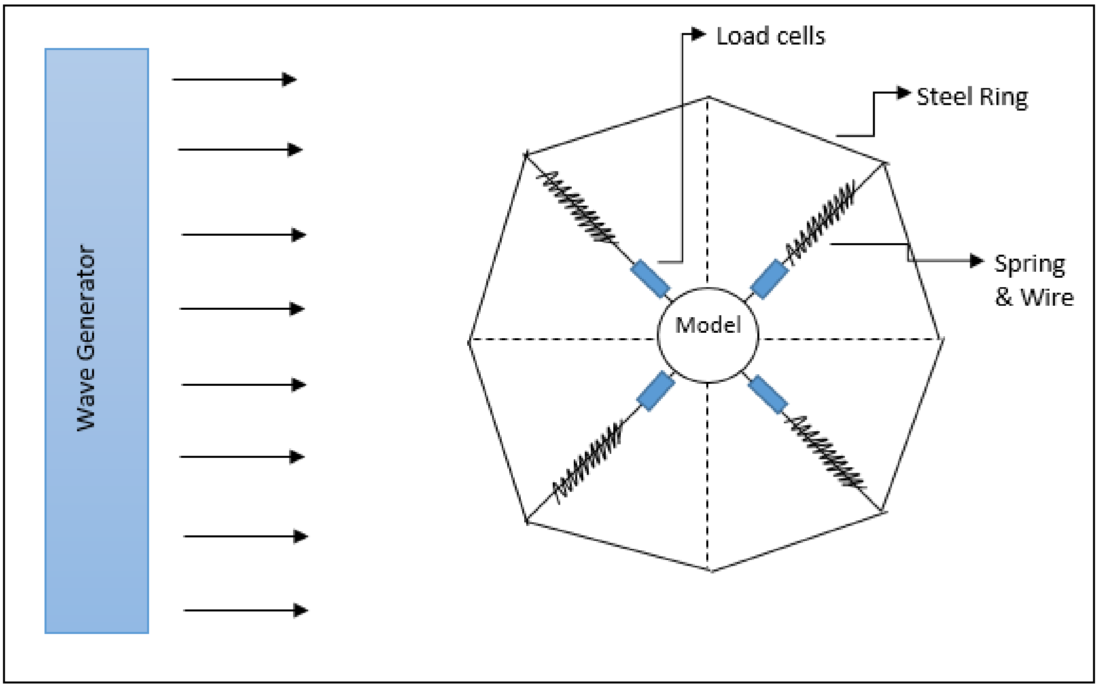


Wave Probe Calibration

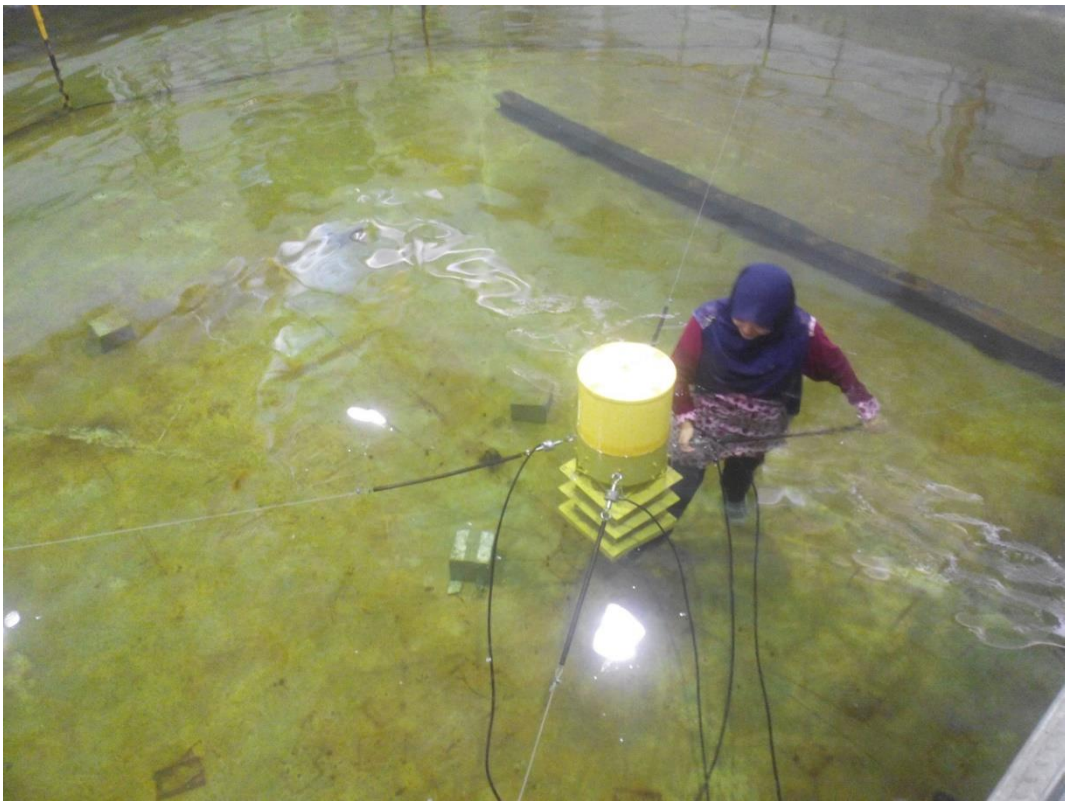
Wave Probe Calibration

APPENDIX B

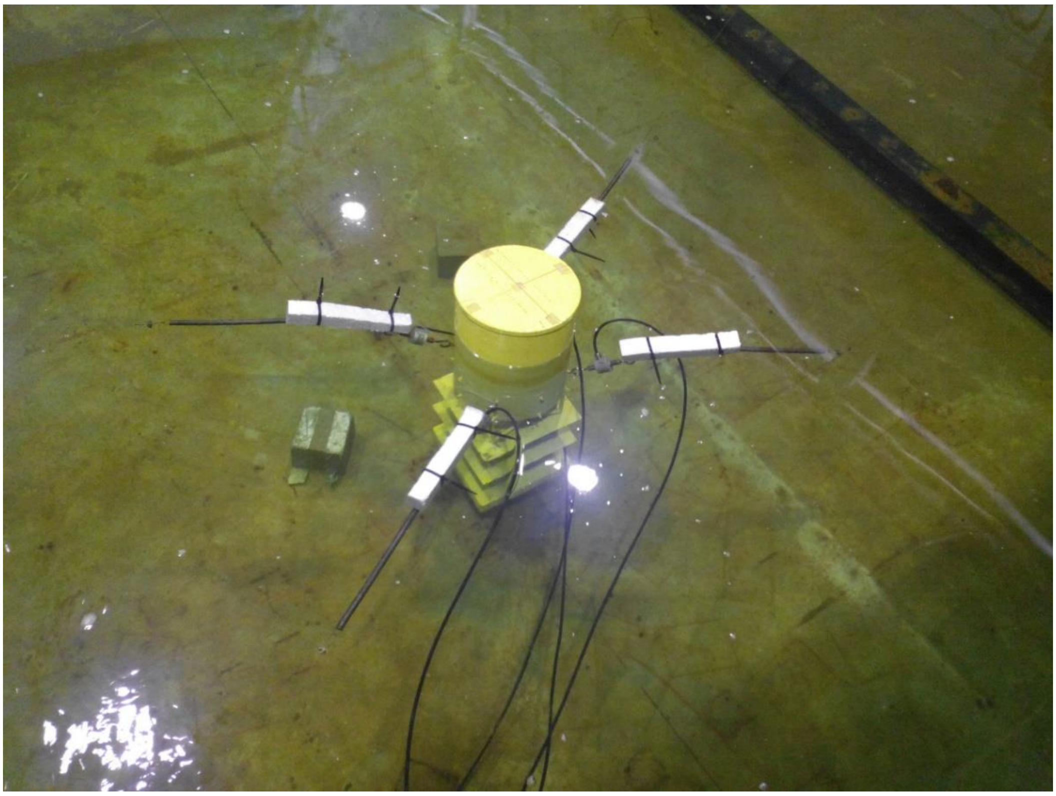
POSITION OF TRUSS SPAR MODEL IN THE WAVE TANK



Position of Truss Spar model in wave tank



Truss Spar model is positioned in the center of wave tank



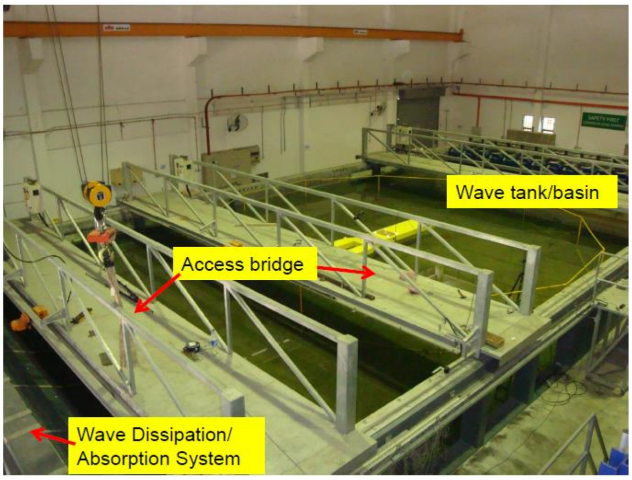
The view of Truss Spar model after Setting up

APPENDIX C

MODEL TESTING FACILITIES: MAIN FACILITIES DESCRIPTION

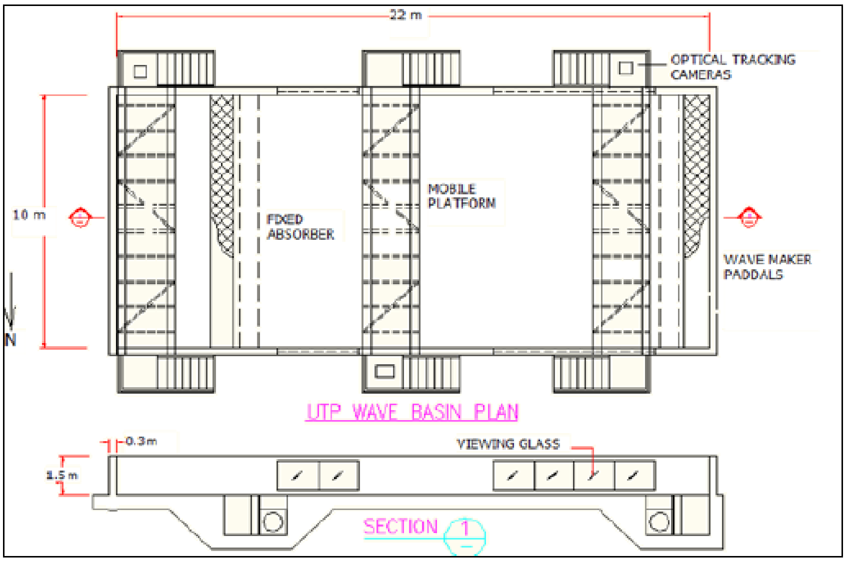
Wave Tank

No.	Name of facility	Quantity	Dimension	Properties
1	Wave tank	1	20 m (L) x 10 m (W) x 1.5 (D)	✓ Multi-element wave maker containing 16 paddles and wave dissipation. ✓ System of pumps to generate a) Regular waves (normal and obligue angles b) Bi-directional (regular and irregular waves) c) Irregular long crested and short crested waves ✓ Sea states available: a) JONSWAP b) Moskowitz c) User-defined ✓ Max wave height: 0.15 m in 1m water depth ✓ Max current velocity: 0.3 m/sec for 1 m depth



Other Facilities

No.	Name of facility	Quantity	Properties
1	Wave Probe	26	Range of wave heights: 5mm to 300mm
2	Vectrino	7	✓ Velocity range: 0.01 – 4 m/s ✓ Accuracy: 0.5% of measured values +/- 1 mm/s
3	TCLP-10KNB Load Cell 10kN TML (Japan) Tension/Compression Load cell	2	Capacity: 10 kN
4	TCLK-5KNA TML (Japan) Tension/Compression Load cell	2	Capacity: 5 kN
5	DDEN 250N Submersible Load Cell	9	Capacity: 250N; Submersible
6	ARH 10A Waterproof Accelerometer	15	Capacity: 10 m/s^2
7	Qualisys Tracking System	1 set	✓ Consist of 4 cameras ✓ Camera: 4MP ✓ Capture rate: Max 179Hz
8	DC 204R Dynamic Data Logger	6	4 Channel
9	MC1250 –AMTI Load Cell MC1250 – 6DOF	5	Rate maximum loads: 1 kN, 5.65 Nm
10	GEN-5 – 6DOF-Dataloggers	3	6 Channels
11	Desktop PCs	3	HR Wavemaker, HR DAQ Suite, Qualysis Tracking Manager



UTP WAVE BASIN

APPENDIX D

MODEL TO PROTOTYPE MULTIPLIERS FOR THE VIARIBLE

UNDER FROUDE SCALING

(*Source: Offshore structure modeling, Chakrabarti, 1994*)

Variable	**Unit**	**Scale factor**
	Geometry	
Length	L	λ
Area	L^2	λ^2
Volume	L^3	λ^3
Angle	None	1
Radius of gyration	L	λ
Area moment of inertia	L^4	λ^4
Mass moment of inertia	ML^2	λ^5
CG	L	λ
	Kinematics and dynamics	
Time	T	$\lambda^{0.5}$
Acceleration	LT^{-2}	1
Velocity	LT^{-1}	$\lambda^{0.5}$
Displacement	L	λ
Angular acceleration	T^{-2}	λ^{-1}
Angular velocity	T^{-1}	$\lambda^{0.5}$
Angular displacement	None	1
Spring constant (linear)	MT^{-2}	λ^2
Damping coefficient	None	1
Damping factor	MT^{-1}	$\lambda^{3/2}$
Natural Period	T	$\lambda^{0.5}$
Displacement	L	λ
	Wave mechanics	
Wave height	L	λ
Wave period	T	$\lambda^{0.5}$
Wave length	L	λ
Celerity	LT^{-1}	$\lambda^{0.5}$
Particle velocity	LT^{-1}	$\lambda^{0.5}$
Particle acceleration	LT^{-2}	1
Water depth	L	λ
Wave pressure	$ML^{-1}\,T^{-2}$	λ

APPENDIX E

PETRONAS TECHNICAL STANDARD (PTS) METOCEAN DATA