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Research Article

An Experimental Investigation of the Responses of Classic Spar Platform Subjected to Bi-directional Waves

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Abstract: The effect of the bi-directional short-crested waves on the dynamic motion responses of the moored classic spar is demonstrated from the results of the models test in this study. Practically in the design of offshore structures, long-crested or 2-dimensional wave properties that propagated to one direction are considered. Even though such long-crested wave is widely used for the design purposes, it is hardly determined in the real sea. The wind generated sea state in the real sea conditions are indeed well represented by the short-crested waves. Short-crested waves are defined as linear summation of long-crested wave series that propagated to different directions. Hence, the motions of the model were investigated experimentally by conducting the wave tank tests in the wave tank of Offshore Laboratory of Universiti Teknologi PETRONAS. Five groups of bi-directional wave series were defined and exerted on the classic spar model, which fabricated by using steel with scaling factor of 1:100. From the results measured, it was found that similar trends of the responses in term of Response Amplitude Operator (RAO) for surge, heave and pitch motions were obtained. Maximum responses of surge, heave and pitch were found due to wave crossing angle 90°, while minimum response was found due to wave crossing angle 135°, respectively. It could be concluded that the wave crossing angle 90° (BD3) gives the widest spreading for short crested waves, while the wave crossing angle 135° (BD4) gives the narrowest spreading for short crested waves.

Keywords: Bi-directional wave, classic spar, experimental investigation, Response Amplitude Operator (RAO)

INTRODUCTION

Wave force calculation is one of the major concerns in the design of offshore structures, where the force constitutes about 70% of the total environmental force. Waves could be classified based upon the propagated direction, for instance long crested and short crested waves. The waves heading to only one direction are defined as uni-directional waves or the long crested waves, while waves that heading to two or more than that are taken as short crested waves.

The long crested waves showed similar wave properties along the Y-axis, as the cross section of X-Z plane was considered. Hence it is also been considered as two-dimensional plane waves. The studies focused on waves have been performed since decades ago. However, majority of it focused on long crested waves. For instance, an expression for regular wave force incorporated with the viscous damping effect and viscous exciting effect that acting on semisubmersible were derived by Sun (1982). Motions of spar due to uni-directional normal and maximum seastate were predicted by Glanville *et al*. (1991). In the same study, the sensitivity of the design of mooring parameters, draft, diameter and the structural mass properties was discussed. Pijfers and Brink (1977) presented a solution for computing the mean and slowly varying drift forces on semisubmersible due to long crested regular and irregular wave and current. Gilrrison *et al*. (1974) performed an experimental and theoretical study of wave forces and overturning moment acting on two geometrical similar gravity based structures. In the prediction, diffraction theory was considered and the results were compared with the model test results for a series of regular waves. Johan (1991) presented a study on regular bi-chromatic wave drift force that inclusive of mean wave drift force, oscillating wave drift force and wave drift damping force acting on a tanker. Mean and low frequency horizontal wave drift force on semisubmersible subjected to regular and irregular waves were studied by Pinkster (1981).

As mentioned, majority of the reported studies were found focused on two-dimensional plane wave or the long crested waves. Yet, long crested waves are hardly found in the real sea conditions. The wind generated sea-state in the real sea are normally short crested and three-dimensional (Zhu, 1993). Hence it is more appropriate to consider the short crested wave properties to represent the real sea conditions. Zhu (1993) performed a study on the short crested waves acting on a circular cylinder by considering the diffraction problem and linear potential wave theory. In

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the study, the hydrodynamic forces were found greater as the spreading of the short crested wave reduced. Zhu and Moule (1994) extended the study to wave loads induced by the short crested waves on a circular cylinder of arbitrary cross section. The study showed that the short crested wave induced force can be larger than that by plane wave with the same total wave number for certain cross section. Again, Zhu's theory was extended by Zhu and Satravaha (1995) to incorporate the effects of the nonlinear wave up to second order of wave amplitude.

Hydrodynamic of a moored semisubmersible acted by short crested wave field was investigated by Heidari *et al*. (2004). Frequency domain analysis was developed, by considering the strip theory, the effects of the phase lag on the force and the response amplitude of the structure. Ioualalen *et al*. (2006) presented two methods to compute the short crested wave fields for the two modes of propagation that inclusive of, the resonant propagation, where the significant harmonic resonance appeared; and the non-resonant propagation, which no significant harmonic resonance appeared. Teo *et al*. (2002) investigated the fifth order solution for short crested wave system subjected to a vertical wall. Zhu's theory again been extended by Jian *et al*. (2008) to investigate the effects of a uniform current for different incident angle. Tao *et al*. (2009) performed a study focused on short crested wave interaction with a concentric porous cylindrical structure. Directional wave hybrid models for short crested waves properties were developed by Zhang *et al*. (1999a, b). Noticeable that most of the studies are focused on the short crested wave properties, very few of it focused on response amplitude especially by experimental study. Hence, in this study an experimental study focused on the response amplitude for the classic spar acted by the bi-directional short crested waves are presented.

METHODOLOGY

In order to study the dynamic responses of the classic spar model subjected to bi-directional waves, a series of experimental study was conducted in the wave tank located in the Offshore Laboratory of Universiti Teknologi PETRONAS. The details of the tests performed are elaborated as follow.

Wave tank details: The tests were conducted in the wave tank with dimensions 22 m length, 10 m width and 1 m water depth as shown in Fig. 1. Figure 2 shows the multi-element wave generator with 16 individual paddles that able to generate variety of waves. The importance of having multi-element wave generation system is that by varying the phases between the adjacent paddles, waves can be generated at any angle instead of uni-directional waves that is normal to the wave generator. The wave generator was pre-defined into two modules, where each of it consists of 8 individual paddles that move independently forward

Fig. 1: Wave tank in offshore laboratory of UTP

Fig. 2: Wave maker with 16 individual paddles

Fig. 3: Classic spar model

And backword from left to right and vice versa to generate the bi-directional waves

On the other side of the wave tank was designed with wave absorption beach to prevent waves that reflected back from the model being re-reflected back to the model. Instruments such as optical tracking system, inclinometer, wave probes, load cells, accelerometers and data logger were also used in the test series.

Scale and physical modeling law: The choice of scale of model test is affected by the limitation of the experimental facilities. Hence, a reliable result by minimizing the scale effects and measurement error is preferable. In this study, the Froude's scaling law with factor of 1:100 was adopted.

Model description: The classic spar platform model was fabricated by using steel plates as shown in Fig. 3. Table 1 shows the summary of the general structural data of the classic spar model. The model was held in-place by four 5 mm diameter steel cables with soft springs connected from the fairlead located at each

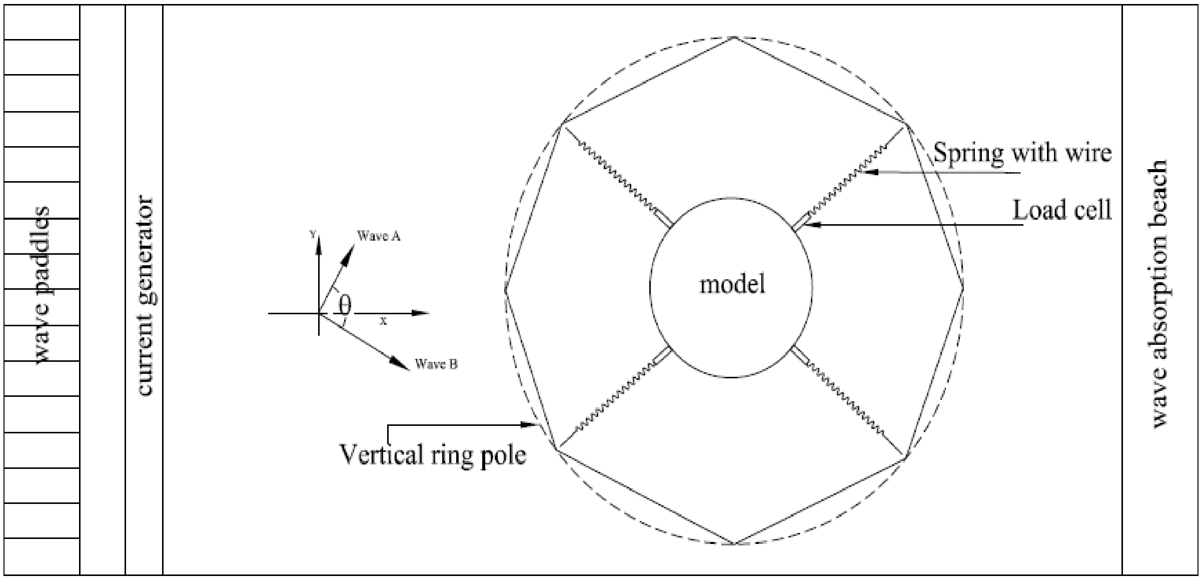

Fig. 4: Model setup-plan view

Table 1: Structural properties of the classic spar model

Variable	Model	Prototype
Diameter, m	0.300	12.000
Total length, m	0.430	17.200
Draft, m	0.225	9.000
Wall thickness, m	0.002	0.080

Table 2: Bi-directional wave series generated

	Wave propagation angle (deg)		
Wave series	Left to right	Right to left	Wave crossing angle (deg)
BD1	15	15	150
BD2	30	30	120
BD3	45	45	90
BD4	15	30	135
BD5	15	45	120
BD6	30	45	105

corner of the model to the steel poles as shown in Fig. 4. In the figure, the wave crossing angles were composed of two uni-directional wave trains, Wave-A and Wave-B with angle θ as shown in Table 2.

The moored model was acted by the bi-directional wave series as stated with wave frequency ranged from 0.8 to 2.0 Hz at 0.2 Hz increment and 0.08 m wave height. The motion amplitude and tension mooring lines were measured by the optical tracking system and load cells, respectively. Data post processing program to transform the response time series to response spectra by the Fast Fourier transformation Technique (FFT) was adopted to filter and transform the data measured. Preliminary tests e.g., the free decay test and static offset test were conducted prior to the sea-keeping test to obtain the natural frequency and stiffness of the system.

Experimental test series:

Static offset test: In order to obtain the stiffness of the mooring system, static offset test was performed. The classic spar model was restrained by four mooring lines with load cells attached on each of it. Measurements were taken for every 2 cm increment and the force applied were recorded for the model.

Free decay test: Free decay test was conducted to obtain the system natural period and damping. The restrained model was initially forced to move to the desired DOF and released to move freely. The surge, heave and pitch motions of the model were then recorded and the natural periods were obtained from the plot.

Sea-keeping test: The sea-keeping characteristics of the model acted by the bi-directional waves were investigated. In the test series, the fore and aft side of the model were restrained by soft spring and steel wires as shown in Fig. 4. Then, series of wave data as discussed above were programmed and generated by the wave generator. In the test, motion responses of the models were recorded by the OptiTrack system. Then, the data were post processed to transform the time series by Fast Fourier Transformation (FFT) to response spectrum. The results of the tests in term of RAO will be discussed in the next section.

RESULTS AND DISCUSSION

Static offset test: From the test carried out for classic spar, the system spring constant was found to be about 140 kN/m. The relationship of the force-excursion for the mooring lines was approximated using multi-linear segments with different slopes as illustrated in Fig. 5.

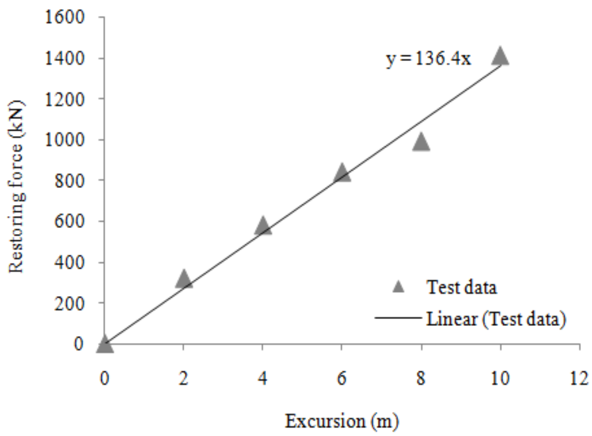

Fig. 5: The force-excursion relationship of classic spar system

Table 3: Measured natural period for classic spar

Motion	Natural period measured, sec	Typical natural period, sec
Surge	188	120~180
Heave	18	25~35
Pitch	25	50~100

Free decay test: In order to measure the natural period of the model, free decay tests were carried out and the findings are shown in Fig. 6 to 8 and the natural periods are summarized in Table 3.

Sea-keeping test: The response amplitudes of the classic spar model subjected to bi-directional short-crested waves are shown in Fig. 9 to 11. Comparison of the surge amplitude due to series of bi-directional waves as stated is presented in Fig. 9. From the figure it could be observed that trend of the surge amplitude generally yield the same. The greatest amplitude was found due to BD4 where the spreading of the incident short crested waves are wide. Vice versa, the smallest amplitude was found due to BD3 where the spreading of the incident short crested waves are small. It could be understand that when two waves travelling in opposite directions through the same medium collide, the amplitude of the resulting wave height was found reduced. Maximum wave heights of crossing waves decrease with the increasing difference with the wave propagation angles. It could also be observed that maximum discrepancy of 77% at 0.056 Hz wave frequency was found by comparing the BD4 to the BD3.

In Fig. 10, similar trend was found for heave amplitude due to the bi-directional wave series. It could be observed that the narrowest spread bi-directional wave, BD3 resulted smaller response amplitude and vice versa for BD 4 that gives the largest response amplitude. It is also noticeable that the maximum different of about 71% was found at 0.06369 Hz.

Figure 11 showed the comparison of the pitch RAOs due to bi-directional wave series. From the figure, it is noticeable that the narrowest spread of the short crested waves, BD3, yielded the smallest response amplitude. On the other hand, the greatest pitch amplitude for the classic spar model was found due to BD4. Maximum discrepancy of 60% was found at 0.032 Hz by comparing the amplitude due to BD3 and BD4.

Generally, it was shown that the spreading of the bi-directional short crested waves affects the response amplitude of the classic spar mode. This case is

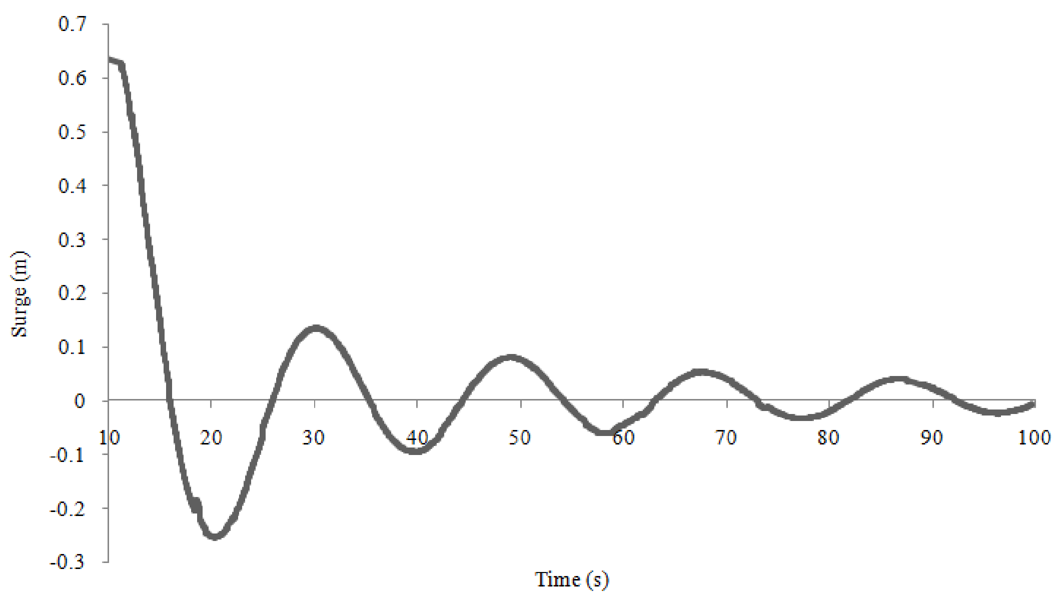

Fig. 6: Free decay test result for classic spar in surge motion

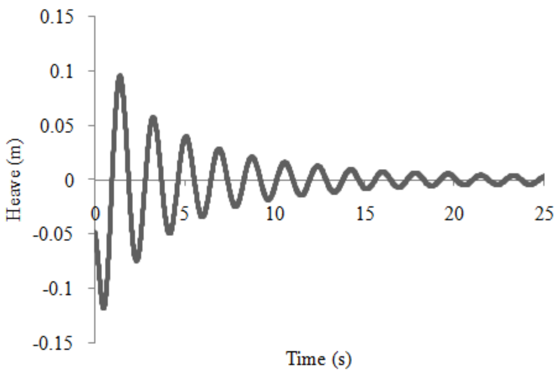

Fig. 7: Free decay test result for classic spar in heave motion

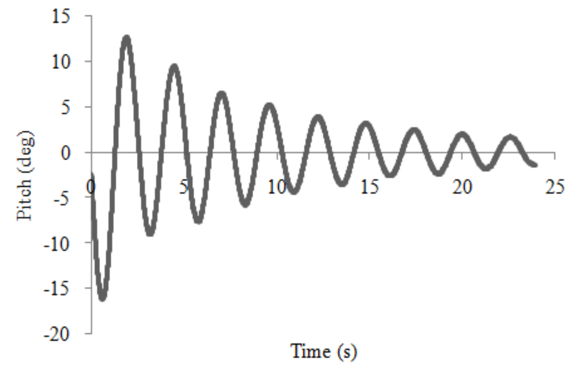

Fig. 8: Free decay test result for classic spar in pitch motion

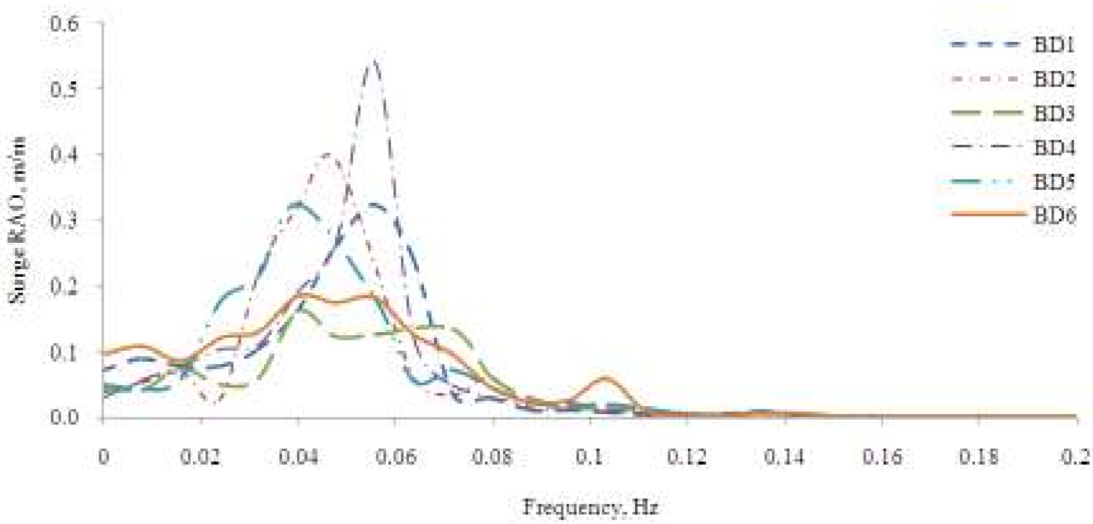

Fig. 9: Surge RAO for classic spar model

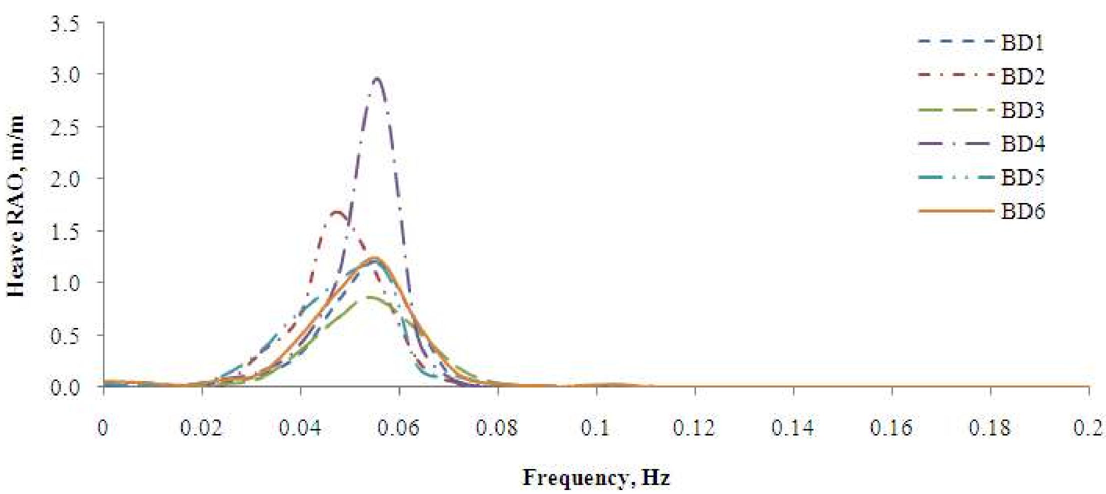

Fig. 10: Heave RAO for classic spar model

noticeable, especially for the narrow spread short crested wave such as BD3 that formed a wave crossing angle of 90° by a 45° wave from left to right and 45° wave from right to left. All the three degree-of-freedom of the classic spar model subjected by BD3 yielded the smallest responses compared to the other wave series.

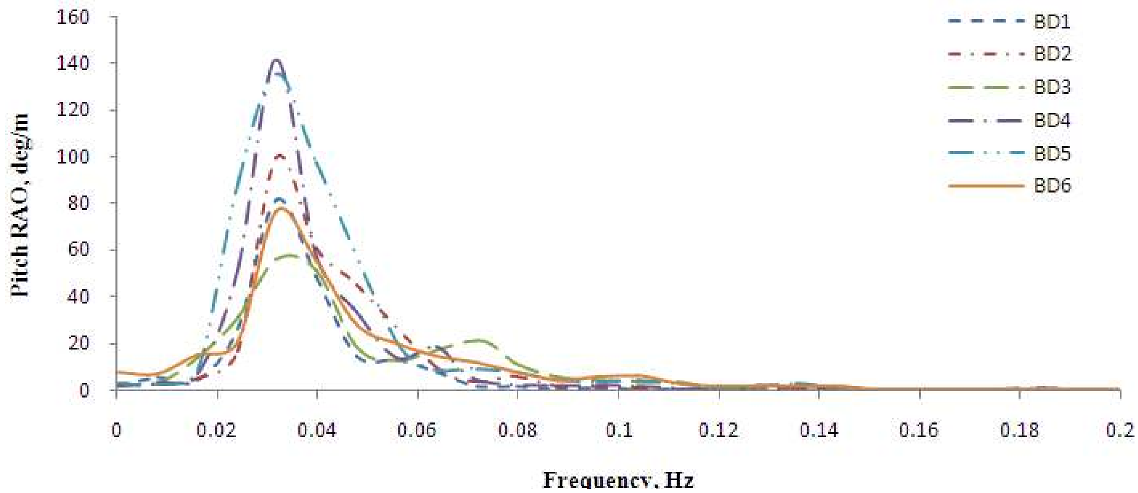

Fig. 11: Pitch RAO for classic spar model

Vice versa was found for BD4, where the crossing angle 135° was formed by a 15° wave heading from left to right and 30° wave heading from right to left.

CONCLUSION

In this study, a series of bi-directional waves were generated and acted on a steel-made classic spar model with scale of 1:100. The response amplitudes of the model were recorded in time series during the experiments. Data post-processing were performed, to filter and transform the time series responses to the response spectrums. Comparisons of the response amplitude were presented. Following are the conclusion drawn:

- The smallest response amplitude was found due to BD3 with the wave crossing angle 90°. BD3 was found to have the narrowest spreading among the bi-directional wave series generated.
- The highest response amplitude was found acted by BD4 with wave crossing angle 135°, where the widest spreading for short crested waves was generated.
- The spreading of the short crested waves might not affected by the wave crossing angle. The study showed that the greatest wave crossing angle (150°) does not yield greatest response, where the most significant response was found due to BD4, wave crossing angle = 135°.

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