Wave-Current Interaction on Offshore Spar Platforms

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Abstract—**Various types of offshore structures have been designed since the beginning of oil and gas discovery. They are conventional fixed platform, compliant tower, tension leg platform, spar, and semi-submersible. The oil and gas exploration is now focusing in the deepwater regions as the natural sources from the shallow water regions are facing depletion. In Malaysia, further studies have to be done in order to develop the technology for oil and gas exploration in deepwater. It is well known that the environmental forces are the main sources of lateral loading acting on offshore structures. When the waves propagate towards the large structure, the existence of the currents in the ocean changes the characteristics of the forces acting on it. So, it is important to know the characteristics of the wave-current interaction on the structure. Some possible interaction mechanisms between waves and currents include surface wind stress, bottom friction, wave climate, wave field, depth and current refraction and modulation of the absolute and relative wave period. The two basics methods of dynamic analysis for offshore floating platforms are the frequency domain and time domain analysis.**

Keywords-Wave-current interaction; Offshore Structure; Frequency Domain Analysis; Time Domain Analysis;

I. Introduction

Rapid development of oil and gas industry has taken place since the last six decades after the first fixed offshore platform was installed in 6 m water depth in Gulf of Mexico in 1947. The total numbers of platforms of various types that have been installed worldwide exceed 10,000 units. The oil and gas sources at the shallow water region have facing depletion fast, therefore leading to the exploration at the deep and ultra deep waters.

Petroleum exploration in Malaysia started at the beginning of the 20th century in Sarawak, where oil was first discovered in 1909 and first produced in 1910. With the rapid development of oil and gas industry in Malaysia, the exploration of oil and gas has expanded to the deep water region and as a result, the construction and installation of Malaysia's first spar was completed in 2007 at Kikeh field located in 1330 m water depth of Sabah Sea. The Kikeh spar is the first spar platform installed outside the Gulf of Mexico.

Further study has to be done in order to develop Malaysia as the leading of oil and gas industry in the future. Further study on design and construction of spar platform is very important for the future deepwater development in Malaysia. For this, the consultants use very costly commercial software and charge huge consultancy fees. It is necessary for us to develop our technology so that we can analyze, design, and maintain the spar and associated mooring components. It is important to mention here that that all our locations have been identified as subjected to significant water currents. Hence wave-current interaction is an important technology to be developed for our Malaysian locations. This involves deriving the required theoretical formulations and generating the strategic transfer function responses for the locations in Malaysia. As many oil and gas companies are operating in our locations, we would be able to use these strategic data for consultancy purposes.

II. Offshore Structure

A. General

An offshore platform, also known as an oil platform or oil rig, is a large structure with facilities including wells drilling, oil and gas extracting and processing and also a facility to export the products to offshore. Depending on the circumstances, the platform may be fixed to the ocean floor or may float. The earliest offshore structure for oil drilling was built off the coast of southern California near Santa Barbara in 1887 [1]. It was built in wooden wharf outfitted with a rig for drilling vertical wells into the sea floor. In order to improve the design, the timber piers were used to support the platforms built for oil drilling, including installations for the mile-deep well n Caddo Lake, Louisiana and Lake Maracaibo, Venezuela. After the innovation of the timber piers, it was found that the lifetime of the piers was limited due to the marine organisms. For this reason, the timber was replaced by the reinforced concrete as the supporting structures for many platforms up to the late 1940s.

Offshore mooring systems have a variety of configurations. The function of the mooring system is to keep the platform structure at a relatively fixed location during the engineering operations. In recent years, engineering efforts in mooring systems have focused in recent years on the development of new anchor configurations with higher pullout loads, larger capacity, and lower cost of installation for deepwater applications.

There are several types of offshore platforms, namely as fixed platforms, compliant tower, tension leg platform, spar, semi-submersibles, and FPSO (Floating production, storage,

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and offloading facility). The jack-up rig, gravity platform, and jacket platforms are designed for depths up to about 500 m, while compliant tower, tension leg platform, and semisubmersible are for depths to 2000 m. In the late 1990s, the first three draft caisson vessels, or spars, were installed for use in 180 m water depths. Spars are floating vertical cylinders that support production decks above storm waves. During drilling and production operations, these structures are kept in place by mooring lines and thrusters.

B. Spar Platform

Spar is a floating structure stabilized by mooring lines. There are three types of spars which are classic spar, truss spar, and cell spar. The classic spar consists of one-piece cylindrical hull. The truss spar has the midsection composed of truss elements connecting the upper buoyant hull, also known as a hard tank with the bottom soft tank containing permanent ballast. The cell spar which is built using multiple vertical cylinders. The spar has inherent stability since it has a large counterweight at the bottom and does not depend on the mooring to hold it upright. It also has the ability to move horizontally and to position itself over wells at some distance from the main platform location by adjusting the mooring line tensions.

C. Platforms in Malaysia

In 1969, the first exploration well was drilled and it was the beginning of oil and gas industry in Malaysia. The first deepwater platform in Malaysia is Kikeh spar. It was installed completely with topsides facilities, hull, mooring system, and riser and wellhead systems. It is located in 1,330 m water depth offshore Sabah, Malaysia. This Spar platform was the first one spar ever installed outside the Gulf of Mexico and the first application of tender-assisted drilling on a Spar platform. The Spar hull for Kikeh is 142 m long, with a diameter of 32 m and have a steel weight of 12,000 metric tons. The weight of topsides facilities is 3,000 metric tons and provides a 25-slot wellbay for dry tree wellheads.

III. Wave-Current Interaction On Offshore Structure

A. General

It is well known that in coastal region, wave and current coexist simultaneously that make them being the most important processes controlling the hydrodynamic behavior [2]. Wave and currents are normally the major environmental forces in this region [3]. Determining the hydrodynamic loads is very important for the design stage of offshore platform [4, 5]. Due to the major effects on the design of the offshore platform, various studies on wave and current have been done since the last few decades [2, 5].

B. Previous Study on Wave-Current Interaction

Various studies on the analysis of spars and other platforms such as tension leg platform and semisubmersible have been done. In these studies, frequency domain analysis [6, 7, 8] and time domain analysis [5, 6, 8, 9] have been carried out. Linear Airy wave theory and Morison Equation were used for the estimation of forces. The responses due to random waves known as Response Amplitude Operator (RAO) in surge, heave and pitch are determined [10].

A numerical approach for wave-current interaction around a large structure is investigated, based on the potential flow theory, linear waves and small current velocity approximation. The velocity potential in a wave current coexisting field is separated into steady current potential and an unsteady wave potential. The water surface elevation around a large structure in a wave-current coexisting field can then be obtained by substituting both unsteady wave potential and current velocity into the first-order dynamic surface boundary condition [11]. Another study has used time domain method to observe the effects of a current on the radiation and the diffraction of regular waves around a two dimensional body [5]. The result shows the importance of current or forward speed effects on a large offshore structure in waves. In general, a weak nonlinear relation with the current has been observed for the first and second order results.

To evaluate the effect of waves, it is necessary to employ a consistent formulation of the energy and momentum balance within the airflow, the wave field and the water column [12]. It is desirable to use a coordinate system which can represent vertical variations near the sea surface at scales smaller than the wave height. A number of different approaches, involving changes of variables, have been suggested to remove the failure of the Eulerian approach which are a sigma-coordinate transformation, the generalized Lagrangian mean (GLM) formulation, and a limited time Langrangian approach.

Some possible interaction mechanisms between waves and currents are reviewed which includes surface wind stress, bottom friction, wave climate, wave field, depth and current refraction and modulation of the absolute and relative wave period [13, 14, 15]. The combined current and wave may lead to changes of wave forces, wave run-up, and slow drift motions [16]. The wave and the current generally exist at the same time in practical engineering environments. It is therefore of great importance to predict the slow drift motions generated by the resonance between the wave current and the floating structures, which may involve very large horizontal excursions. It is well known that the overall pattern of the wave current diffraction and radiation by a three-dimensional floating structure are different from those of the pure wave action. A Time Domain Higher order Boundary Element Method was developed for simulating wave current interaction with three-dimensional floating bodies. The result of this study states that the numerical results of wave force, wave run-up and body response are all in a close agreement with those obtained by frequency domain methods.

Another study has been done in order to observe the effect of wave-current interaction on the mean steady current profile for different conditions according to the angle of propagation between waves and currents [2]. The conditions are the following waves and current, the opposing waves and currents, and the perpendicular waves and currents. In the perpendicular cases, a reduction of the flow velocity was observed. While for the following cases reduction of the velocity was observed just below the wave trough level, intensification occurred in the opposing one. These changes became more evident as the wave height increased and as the wave period decreased.

There are different technologies available and presently adopted in wave and current measurement [17]. Understanding of coastal and oceanic processes is mostly based on field measurement and laboratory experiments. Most coastal processes occur over relatively long time spans and have large spatial extends. Measurement of waves, both site and in wave flumes, are carried out using different techniques. Different instruments for wave and current and measurement have its own advantage depending on the application and needs. As conclusion, wave rider buoys have proven to be a cost effective means of collecting ocean current observations. However buoys report only near surface currents and a Langrangrian technique does not provide a means of activity targeting and monitoring a specific site or area. Acoustic Doppler Current Profilers mounted on moorings and platforms can provide real time current information but not always optimally located. High Frequency Radar provides data for a wider area but only of the surface waves/currents perspective. Synthetic Aperture Radar data provide wider spatial coverage through satellite sensors. It is essential to choose the type of application based on the needs and importance. A thorough knowledge of the particular instrument to be used is essential before it is deployed. Cost may be an issue, depending on funding availability and duration of project. Table 1 shows the devices with their functions.

TABLE I. WAVE AND CURRENT MEASUREMENT DEVICES AND THEIR FUNCTIONS

Devices	Function
Wave Rider Buoy	To measure near surface waves and current.
Acoustic Doppler Current Profilers	To provide a robust means of determining wave heights and direction in shallow and deep water.
High Frequency Radar	To measure ocean surface wave and current Electromagnetic waves sent to the ocean are backscattered on surface waves of exactly half the radio wavelength.
Remote Sensing	Synthetic Aperture Radar: a microwave instrument producing high resolution imagery regardless of clouds, dusty condition and solar illumination.

Some studies on wave-current interaction also have been done in the Southern North Sea [18] and in the River Pearl Estuary [3]. At the Southern North Sea, it was observed that along the Belgian coast, the current induced by the radiation stress was as same as the excess current obtained by a wave-dependant sea surface stress and highly controlled by bathymetric features. At the River Pearl Estuary, the study found that waves propagating from the open sea would be attenuated significantly when they entered into the estuary, with their energy dissipating due to the sheltering by islands and the shallow water depth in it. The tidal flow increased the wave heights generally. The effect of the ebbing flow on waves was significant. The waves came from the south had a great influence on the flow and mass transport in the estuary.

IV. HYDRODYNAMIC ANALYSIS OF OFFSHORE PLATFORM

A. General

There are two basic approaches that are considered in the floating structure dynamic problem using frequency domain or time domain analysis [19]. Frequency domain analysis is performed for the simplified solution and it is useful for long term response prediction. It can estimate responses due to a random wave input through spectral formulations. The limitation of this analysis is that all nonlinearities in the equation of motion must be replaced by linear approximations. On the other hand, it is simpler to interpret and always being used for the preliminary design stage.

Time domain analysis utilizes the direct numerical integration of the equations of motion allowing the inclusion of all system nonlinearities which are nonlinear fluid drag force, nonlinear mooring line force and nonlinear viscous damping. The limitations of this analysis are increased computer time and difficulyt to interpret and apply.

B. Linear Airy Theory

By using linear wave theory, with a wave height and wave period chosen according to the location of the structure, the corresponding horizontal and vertical components of wave particle velocity and acceleration are determined. The kinematics of the wave water are determined by the following equations:

Water particle velocity:

Horizontal: $$u = \frac{\pi H}{T}\frac{\cosh ks}{\sinh kd}\cos\theta \quad (1)$$

Vertical: $$v = \frac{\pi H}{T}\frac{\sinh ks}{\sinh kd}\sin\theta \quad (2)$$

Water particle acceleration:

Horizontal: $$\dot{u} = \frac{2\pi^2 H}{T^2}\frac{\cosh ks}{\sinh kd}\sin\theta \quad (3)$$

Vertical: $$\dot{v} = -\frac{2\pi^2 H}{T^2}\frac{\sinh ks}{\sinh kd}\cos\theta \quad (4)$$

In which $s = y + d$, $\theta = kx - \omega t$, wave number $k = \frac{2\pi}{L}$, natural frequency $\omega = \frac{2\pi}{T}$, T is wave period, y is height of the point of evaluation of water particle kinematics, x is point of evaluation of water particle kinematics from the origin in the horizontal direction, t is time instant at which water particle kinematics is evaluated, L is wave length, H is wave height, and d is water depth. Figu1 shows the definitions of wave parameters.

C. Morison Equation

The computation of the water wave forces on an offshore structure is one of the primary tasks in the design of the structure. It is also one of the difficult tasks since it involves the complexity of the interaction waves with the structure. There are many types of offshore structures such as piled jacket type of platform, large volume gravity platforms, tensionlegged platform, and semisubmersibles. Based on the type and size of the members in an offshore structure, different formulations for wave forces are applicable and one of them is Morison equation. The Morison equation assumes the force to be composed of inertia and drag forces. It is applicable when the drag force is significant. This is usually the case when a structure is small compared to the water wave length.

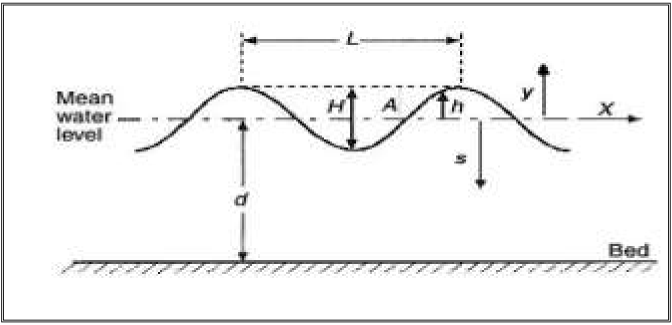

Figure 1. Definitions of wave parameters.

Combining the inertia and drag component of force, the Morison equation is written as

$$f = f_D + f_I \tag{5}$$

In which f is total force per unit length, f_D is drag force per unit length, and f_I is inertia forces per unit length.

The principle involved in the concept of the inertia force is that a water particle moving in a wave carries a momentum with it. As the water particle passes around the circular cylinder, it accelerates and then decelerates. This requires that work to be done through the application of a force on the cylinder to increase this momentum. The incremental force on a small segment of a cylinder, ∂s, needed to accomplish this is proportional to the water particle acceleration at the center of the cylinder.

$$\partial f_I = \rho C_M \frac{\pi D^2}{4} \dot{U}\, \partial s \tag{6}$$

In which ∂f_1 is inertia force on the segment ∂s of the vertical cylinder, ρ is a mass density of sea water, D is cylinder diameter, $\dot{U}$ is local water particle acceleration at the center line of the cylinder, and C_M is inertia coefficient.

The principle cause of the drag force component is the presence of a wake region on the downstream side of the cylinder. The wake is a region of low pressure compared to the pressure on the upstream side and thus a pressure differential is created by the wake between the upstream and downstream of the cylinder at the given instant of time. As the water particle motion under a wave is oscillatory within a given wave period, the downstream side of the cylinder reverses every half cycle and a mirror image is created after half a cycle. The pressure differential causes a force to be exerted in the direction of the instantaneous water particle velocity. In a steady flow, downstream side is fixed and the drag force is proportional to the square of the water particle velocity. In an oscillatory flow, the absolute value of the water particle velocity is inserted to ensure that the drag force is in the same direction as the velocity.

$$\partial f_D = \rho C_D \frac{D}{2} |U| U\, \partial s \tag{7}$$

In which ∂f_D is drag force on the segment ∂s of the vertical cylinder, U is local water particle acceleration at the center line of the cylinder, and C_D is drag coefficient.

D. Wave Spectrum- Pierson-Moskowitz Spectrum

The mathematical spectrum models are generally based on one or more parameters such as significant wave height, wave period, and shape factors. The most common single-parameter spectrum is the Pierson-Moskowitz model based on the significant wave height or wind speed. The new formula for an energy spectrum distribution of a wind generated ea state is commonly known as P-M model. This model has since been extensively used by ocean engineers as one of the most representative for waters all over the world.

$$S(f) = \frac{\alpha\, g^2}{(2\pi)^4} f^{-5} \exp\left[-1.25 \left(\frac{f}{f_0}\right)^{-4}\right] \tag{8}$$

In which $\alpha = 0.0081$, $f_0 = {}^{\omega_0}/_{2\pi}$, and $\omega_0^2 = 0.161\, g\, /H_s$.

E. Simulation of Wave Profile From Spectra

It is sometimes necessary to calculate the height of a wave at a particular frequency from an energy density spectrum curve. At frequency, f_1, the energy density is $S(f_1)$. The wave height at this frequency is obtained as follows:

$$H(f_1) = 2\sqrt{2S(f_1)\Delta f} \tag{9}$$

Then, for a given horizontal coordinate, x, which is the location at which the wave profile is desired, and time, t, which is incremented, the wave profile is computed from

$$n(x,t) = \sum_{n=1}^{N} \frac{H(n)}{2} \cos[k(n)x - 2\pi f(n)t - \varepsilon(n)] \tag{10}$$

In which $k(n) = 2\pi/L(n)$ and $L(n)$ corresponds to the wave length for the nth frequency, $f(n)$. The quantity, N, is the total number of frequency bands of width, Δf, dividing the total energy density . Sometimes, $f(n)$ is chosen randomly within each Δf for more randomness.

F. Motion-Response Spectrum

The first phase of the theoretical study consists of performing dynamic analysis using frequency domain analysis. This study involves calculation of Response Amplitude Operator (RAO) based on the forces acting on the structures, the total mass, the stiffness and the damping coefficient. This is done for both regular and random wave analysis. RAO can be expressed as:

$$RAO = \frac{(\frac{F_I}{H/2})}{\sqrt{(k-m\omega^2)^2+(C\omega)^2}} \quad (11)$$

in which F is the inertia forces acting on the body, H is the wave height, K is the stiffness of the structures, m is the total mass of the submerged body and C is the damping coefficient.

V. Summary And Conclusion

Oil and gas industry highly contributes on the economical and sociological aspects of human The oil and gas exploration is now focusing in the deepwater regions as the oil sources from the shallow water regions have facing depletion. The expansion of the oil and gas industry leads to various studies to observe the environmental responses on the offshore structure.

Wave and current are very significant in Malaysia water and they highly contribute to the hydrodynamic forces action on the structures. When the waves propagate towards the large platform, the existence of the currents in the ocean has changed the characteristics of the forces acting on it. Further studies on design and construction of spar platform are very important for the future deepwater development in Malaysia. For this, the consultants use very costly commercial software and charge huge consultancy fees. It is necessary for us to develop our technology so that we can analyze, design, and maintain the deepwater offshore structures.

The two basic methods of dynamic analysis for offshore floating platforms are frequency domain analysis and time domain analysis. Dynamic analysis is very important to determine the responses in surge, heave, and pitch. This involves deriving the required theoretical formulations and generating the strategic transfer function responses for the locations in Malaysia. We would be able to use these strategic data for consultancy purposes as many oil and gas companies are operating in our locations

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References

[1] Wilson, J. F. (2002). *Dynamics of Offshore Structures.* USA: John Wiley & Sons, Inc., Hoboken, New Jersey.

[2] Olabarrieta, M., Medina, R., & Castanedo, S. (2010). *Effects of Wave-Current Interaction on the Current Profile*. Coastal Engineering , 643-654.

[3] Wang, C. H., Wai, W. H., Li, Y. S., & Chen, Y. (2006). *Modelling of the Wave-Current Interaction in the Pearl River Estuary*. Conference of Global Chinese Scholars on Hydrodynamics, (pp. 159-165). Hong Kong, China.

[4] Popescu, M., & Simbotin, A. (2002). *Hydrodynamic Loads on Offshore Platform Structures*. Ovidius University Annals of Construction (pp. 433-438). Romania: Ovidius University Press.

[5] Isaacson, M., & Cheung, K. F. (1993). *Time Domain Solution for Wave-Current Interactions with a Two Dimensional Body*. Applied Ocean Research , 39-52.

[6] Kurian, V. J., Gasim, M. A., & Narayanan, S. P. (2009). *Frequency and Time Domain Analyses for TLP Responses.* 7th Asia Pacific Structural Engineering & Construction Conference 2009, (pp. 555-560). Pulau Langkawi.

[7] Kurian, V. J., Wong, B. S., & Montasir, O. A. (2008). *Frequency Domain Analysis of Truss Spar Platform.* International Conference of Construction and Building Technology, (pp. 235-244). Kuala Lumpur.

[8] Roitman, N., Andrade, R. F., & Batista, R. C. (1992). *Dynamic Responses Analysis of a Small-Scale Model Tension Leg Platform.* Marine Structures , 491-513.

[9] Anam, I., Roesset, J. M., & Niedzwecki, J. M. (2003). *Time Domain and Frequency Domain Analysis of Spar Platform*. The Thirteenth International Offshore and Polar Engineering Conference, (pp. 240-247). Honolulu, Hawaii, USA.

[10] Montasir, O. A., Kurian, V. J., & Shafiq, N. (2009). *Numerical and Model Test Results for Truss Spar Platform Subjected to Random Waves.* 2nd International Conference on Engineering Technology, (pp. 1-6). Kuala Lumpur.

[11] Lin, M. C., & Hsiao, S. S. (1994). *Boundary Element Analysis of Wave-Current Interaction Around A Large Structure.* Engineering Analysis with Boundary Elements , *14*, 325-334.

[12] Jenkins, A. D., & Ardhuin, F. (2004). *Interaction of Ocean Waves and Currents: How Different Approaches May be Reconciled.* Proc. 14th Int. Offshore & Polar Engng Confn, 3, pp. 105-111. Toulon, France.

[13] Wolf, J., & Prandle, D. (1999). *Some Observation of Wave-Current Interaction.* Coastal Engineering , 471-485.

[14] Tayfun, M. A., Dalrymple, R. A., & Yang, C. Y. (1976). *Random Wave-Current Interactions in Water of Varying Depth*. Ocean Engineering , 3, 403-420.

[15] Gudmestad, O. T., & Karunakaran, D. (1990). *Wave Current Interaction.* Environmental Forces on Offshore Structures and Their Prediciton, (pp. 81-110). Netherlands.

[16] Liu, Z., Teng, B., Ning, D.-z., & Gou, Y. (2009). *Wave-Current Interactions with Three-Dimensional Floating Bodies*. Journal of Hydrodynamics , 229-240.

[17] Pandian, P. K., Emmanuel, O., Ruscoe, J. P., Side, J. C., Harris, R. E., Kerr, S. A., et al. (2010). *An Overview of Recent Technologies on Wave and Current Measurement in Coastal and Marine Application.* Journal of Oceanography and Marine Science , 1, 001-010.

[18] Osuna, P., & Monbaliu, J. (2004). *Wave-Current Interaction in the Southern North Sea.* Journal of Marine Systems , 52, 65-87.

[19] Chakrabarti, S. K. (1987). *Hydrodynamics of Offshore Structures*. USA: WIT Press.