A review of ocean forces interaction model with offshore structures near the free surface

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Abstract

The importance is given for the efficient design of offshore structures which should include economic and safety concerns. The properties of wind-generated (main) surface waves and currents are recognized to play a vital role during design of offshore structures such as windmills, fixed and floating structures. This study looks into the mechanisms of metocean forces, acting on these structures near the continental shelf region of Malaysia. At present, near offshore Malaysia, there is no real behaviour model available for currents and the interaction between waves and current. The free surface flow and rigid body interaction with structural issues of offshore structures such as fatigue, corrosion, and marine growth are also not researched in this region before. Therefore, current and wave-current models need to be developed using the finite volume method. Physics of these forces need to be determined and their free surface flow motions require the development of a framework. Fluid-structure interaction (FSI) is used to model the interfaces such as air-fluid (free surface) and fluid-structure (rigid-body). A Free-surface/rigid body problem fully coupled finite volume model is a preferred method. Six degree of freedom of motion equations are used to define the rigid body. This paper is based on literature review and the expected results due to the effects of wind on wave and currents and the mechanics of current are highlighted along with the seasonal effects of the current. To deal with the moving rigid body and the fluid domain interface an interface-tracking method is used.

Keywords: Ocean current, offshore structures, dynamic forces

Introduction

Oil and gas are one of the main items of revenue generation of the Malaysian economy. Offshore structures are considered to be the backbone of the global renewable and conventional energy in future such as for PETRONAS and Shell. Renewable wind energy is the key focus of the UNO and the Malaysian government such as the offshore windmill. The local oil and gas industry is dealing with various types of offshore structures such as floating production, storage and offloading offshore structures (FPSO), semi-submersibles i.e., SPAR, Tension leg platforms, fixed Jacket platforms. Reduced oil prices in 2015-17, have hampered the development of new structures due to the high design and construction costs. In 2016, the prices of oil had reached between US Dollars 35-45 per barrel. Thus to maintain upstream growth and development of new structures have become a challenge for the oil and gas development sector. Malaysian revenue from oil and gas decreased in the first quarter of 2016 by 26% as compared to the same period in 2015 [1-2]. The design of structures is normally based on estimated load and resistance and thus if estimated loads are higher, the higher resistance is required. This will make the structure economically expensive and unviable which has forced many projects to be shelved or postponed. The main common reason for uneconomical structures is the unavailability of robust real-time data on the behaviour of metocean parameters. The interaction of hydrodynamic forces and surface wave and current also plays a significant role in corrosion and fatigue.

The behaviour of current, which changes during the monsoons, is very significant in the design of structures. Different computer software is available such as SACS, SESAME, but they are based mainly on engineering models using potential-flow theory and Morison's equation and they have inbuilt libraries for codes such as API, ISO, DNV. They are used to evaluate hydrodynamic loads on these structures. Computational fluid dynamics using fluid-structure interaction is proving to be extremely useful when experimental methods are expensive. While these models are computationally expensive, they include many assumptions and approximations [3] and they depend on the behaviour of wind, wave and current model. Unfortunately, these models are still not available for the offshore Malaysian region, especially the role of current in Peninsular Malaysia, Sabah and Sarawak. Thus, it is high time to develop a high- reliability computational fluid dynamics model. Understanding the fundamental current hydrodynamic forces in the offshore environment is crucial to the success of future offshore projects. Current velocity mechanism near free surface close to offshore structures is unidirectional at all heights. Based on the previous research it is clear that this behaviour is not the same throughout the year. The metocean parameters interaction near the structures is not unidirectional as claimed by the simple design approach for these structures.

The cause of fatigue, corrosion and marine growth is related to the effects of metocean mechanism but at present, no one knows the actual behaviour. Previous studies have been conducted on the weather in the North Sea and the Gulf of Mexico. The weather pattern is completely different in the South China Sea. Turbulent flow mixing of metocean parameters and their pressure forces near offshore structures cannot be taken simply by applying the maximum values from each direction. The boundary layer of structure and metocean needs to be understood by using Fluid-structure interaction. This paper will assist in the preparation of ISO 19901 and 19902 codes and in particular an annexe for the wave and current loads. The requirement to compliment this annexe through an extensive survey of wave and current forces estimation procedures have been recognized by the ISO code and this paper makes an effort to meet these requirements. The paper contains more detailed references to the literature for the hydrodynamic data needed in offshore design in Malaysia.

Background of study

Malaysia a step towards development:

In 2014 crude oil, condensates and gas contributed up to 20% of country's gross domestic product (GDP) and it was reported that since its incorporation PETRONAS has contributed RM 881 billion to the government and majority of these came from offshore regions of Malaysia [2]. It is reported that only 50% of oil and gas resources have been discovered and around 7.0 billion barrel of oil equivalent (BOE) in Malaysia and the rest is expected to come from deepwater offshore areas Malaysia [2]. Thus, there are unlimited benefits for the growth of offshore deep-water structures in Malaysia. The Eleventh Malaysian Plan developed one of the thrust area focusing on 'Strategy E which is related to "encouraging sustainable energy use to support growth is related to offshore oil and gas sustainability". One of the six strategic thrust areas "accelerating human capital development for an advanced nation" reports oil and gas as one of the important areas to be addressed in the 11th Malaysian plan. It shows that in Sabah reliability will be enhanced for the supply of gas pipeline. Further pipeline networks will be laid from offshore fields to FT Labuan, Kota Kinabalu and Kimanis in Sabah. Multiple links will be established for the connectivity of the platforms to provide alternative route options in the event of platform shutdowns. Alternative options will be provided from the offshore platforms for the case of emergency platform shutdown. The new pipeline will be placed by Sabah-Sarawak Gas to facilitate and improve the connectivity for FT Labuan [4].

Design of offshore structures:

The wave, wind and current play a significant role in the design of offshore structures and we need to understand the phenomena that take place during the combined forces on these structures [5]. Many previous studies have shown compressible and incompressible flows, including the structural mechanics with 2D solids and thin shell type of structures. In the industry, small scale model tests are generally fabricated for prediction of wave impacts loads, to examine structural motions, responses and time-dependent behaviour. But small-scale prototypes and experimental tests are time-consuming and costly this paves way for the finite element and finite volume methods [6]. Previous studies in this region have largely focused on the South China Sea as a whole but not specifically the region where the oil and gas reserve is located and without considering the combined effects of wind, wave and current acting near and surrounding the offshore structures [7-13]. Offshore substructures are developed to support structures against complex offshore surroundings.

Offshore structures are always underexposure of flow-induced vibrations, which reduce their durability significantly. The forces produced by environmental loads cause fatigue, due to successive wave current, two most important loads for offshore structures. The effects of turbulent surface waves, due to wind pressure, on ocean currents play an important role in engineering design. This includes wave forces at the surface of the ocean and its interaction with current profiles at sea level, sediment transport and littoral flow [14].

Wave load:

The primary forces on offshore substructures are caused by waves and deformation of waves caused by interactions with the current [15]. For slender structural jacket components, loads due to wave and its response are calculated using Morison equation such as piles, risers of the jacket and its members, Jack up, offshore pipelines. This is due to the consideration that the incident wave kinematics does not vary considerably near structural members. Large structures with having a large span covering a significant portion of the wavelength, the incident waves undergo considerable diffraction or scattering such as FPSO. The wave force evaluation should also take into account this scattering. Thus flow separation is ignored and it can be considered for a complete potential flow and thus a nonlinear issue. Generally, by assuming a small wave height it can be linearized.

Wave theories:

Wave loads are determined based on factors such as water depth, structural dimensions and design wave factors and wave theory. For the probabilistic descriptions of waves and its forces, a linear wave theory is assumed. This theory is used for the deterministic design of wave forces on large structures. Nonlinear wave theory is used for small tubular members. For deep waters, $d/L > 0.01$, Stokes 5th-order nonlinear wave theory is used, here, L = wavelength.

Waves along with currents:

Ocean waves and currents act at the same time on the structures than the wave loads are determined by using the combined flow field. The wave with non-uniform currents interaction is a complex phenomenon. The uniform current influence in the presence of wave is analysed by using a wave theory in a fixed reference frame is related to the conditions in which still water wave and current are analysed together as shown by Eq. (1),

$$c = c_o + U\cos\alpha \qquad (1)$$

U = Current moving in the direction of wave direction α
c = wave speed (in the presence of current)
c_o = wave speed without current

The influences of current on wave height have been demonstrated by Longuet-Higgins and Stewart [16].

Currents:

Current magnitudes include three components such as tidal current U_t. At the surface level, this part of the current can be obtained from tide tables or by hindcast data using a mathematical model. The other one is called low-frequency U_c this is obtained from accompanying with long-term circulation patterns. The last one is caused by wind at ocean surface i.e. drift U_w near free surface and is about 3% of the wind speed of 10 min mean measured at 10 m height. The current velocity U(z) vertical distribution is shown by Eq. (2),

$$U(z) = (U_t + U_c)\left(\frac{z+d}{d}\right)^{1/7} + U_w\left(\frac{z+d_o}{d_o}\right) \qquad (2)$$

z = Sea water level vertical ordinate

d_o = the depth of the temperature gradient / 50 m, whichever is less

A major vertical gradient in ocean water can give rise to the internal waves due to the long period it can produce an extra component of current. Large amplitude internal current surges can occur near the continental shelf due to density stratification. Table 1 shows the variations of water depth in offshore Malaysia along with maximum and minimum currents in critical directions.

Table 1: Ocean mud level Depths for three regions of Malaysia

Region	Ocean depth (m)		Extreme design current at surface level (m/sec)		
	Minimum	Maximum	Minimum	Maximum	Platform specific
PMO	60.0	79.2	0.68	1.50	1.47
SBO	36.9	59.1	0.66	2.23	0.94
SKO	46.0	95.0	0.40	1.80	1.2

Fluid-structure interaction (FSI):

Motions of fluid and solid are coupled such as when leaves flap in the wind, the beating of hearts, the vibration of wings of the aeroplane, rocking motion of ships and under the sea, risers or pipes are acted upon by waves and currents. Fluid-Structure Interaction (FSI) can be seen everywhere in our daily life. Thus, we can say that it plays a significant part in the design of modern-day offshore structures [17]. As practical problems become more difficult and expensive to conduct therefore understanding the basic phenomenon by using finite volume method and then conducting the practical will be more viable. FSI has to deal with load and structural issues which are fundamentally non-linear and time-dependent. Thus the analytical approaches are difficult to use. The main difficulty in real flows scale has been the accurate modelling of turbulence.

The contour of the offshore structure and its dynamic motion define the behaviour of flow near it. Fluid forces acting on the offshore structure will cause its motion and deformation. Computational fluid dynamics model are developed for flow-induced vibrations. It helps to predict and mitigate phenomenon such as flutter, sloshing, vortex induced vibration and added mass for ocean engineering. Fluid-structure interaction (FSI) is a robust, efficient and capable to model accurately computational model, with geometrically complex configurations. Differential equations of fluid and solid mechanics, coupled at the fluid-solid interface are used to define the boundary between fluid and structure. Fundamentals of computational fluid and solid mechanics are used for the computation of fluid-structure behaviour. This is a vital physical phenomenon for offshore structures i.e., semisubmersibles, wind platforms, risers, platforms and floating structures. It provides the solution to real-world problems.

Fluid only or offshore jacket only problem is called as a single phase mechanics problem. In this case, problem domain is defined by the governing differential equations and boundary domain is defined by the boundary conditions which could be in motion or not. In FSI, the differential equation and boundary conditions of water and solid must be solved simultaneously. They should not overlay and the two systems are coupled near the interface [17]. The material properties of the structure will define its movement. Thereafter the fluid will change to adjust the movement of the structure. The differential equations and boundary conditions will define the water motion. The non-moving and moving grids are the two important discrete methods. Here motion of the fluid is the third unknown which is a function of structural displacement. The discretization of the fluid-structure interface needs accuracy, stability and dealing with the intricate geometry. The separate fluid and structure discretization will result in creating a mesh at the interface. Despite this, it must be ensured that fluid and the structure are coupled through kinematics and tractions such as matching discretisation at the interface of fluid and structure. As the interface of fluid-structure becomes complex flexibility becomes important.

Loosely coupled and strongly coupled are the two important FSI classes. In the first one sequential solutions are carried out for fluid and structural mechanics and mesh issues [18-33]. For each step, time displacement rate at the interface, the equations of the fluid mechanics and the velocity is solved using the boundary conditions of the structure. Then the structural mechanic's equations are solved with the updated fluid mechanics interface traction. Finally, the mesh moving equations is solved with the structural displacement at the boundary of two interfaces. the staggered approach is preferred as it is deemed efficient [17].

Large eddy simulation:

The large eddy method (the separation of scales) is one of the methods to analyse FSI behaviour. Turbulence scales are resolved directly which are larger than the filter width. The smaller scales are parameterised by a turbulence model of sub grid-scale (SGS) [34]. As the major part of the energy is in large eddies the most of the turbulence energy is resolved by the eddy. Grid resolution defines the width of the filter which can range between 50 to 100 m and reduced to 0.5-2 m respectively. For incompressible Navier–Stokes flows coupled with tubular members, Detached eddy approach is used. Combined turbulence model using eddy method is used. The Reynolds average Navier-Stokes equation is used for modelling at high Reynolds number flows near free oscillating tubular members. Near-wall flow features are modelled using wake dynamics along with Navier-Stokes.

Methodology

The structural design will also need to consider some other factors also like nonlinear (steep) coexisting and breaking waves, vortex shedding. Due to the oil field requirements, this may also include the interference effects between neighbouring structures and innovative structural configurations. The wave and current may also affect tow out or installation and fatigue and for this, a motion response analysis may be required to be done. Mooring analysis of a fixed and floating structure could be used by FSI methods along with the intact and damaged reliability analyses may also be required [38].

Loads acting on offshore structures:

Malaysia offshore structures are located in shallow and deep waters. Regional oceanic modelling system is necessary for the high turbulent flows near offshore structures. The currents in this region change directions at different depths and act on these structures in a complex way. At present during design, many assumptions are made to simplify the design. This simplification results in an extreme increase in costs. The strong and persistent currents, with changing directions and coupled with waves creates an extreme mechanics of force. If these forces are combined with wind direction, the problem becomes more complex. Besides that, there is no existing model of free surface waves and issues related to corrosion, fatigue and marine growth in this region. The physical explanation of the underlying mechanism for metocean forces is to be researched. This will involve the analysis of some of the climate data available with NASA.

The resonant response of the offshore structures in extreme environmental conditions should be evaluated. As compared to the design wave frequency, the natural frequency of vibrations of the offshore structure is generally very high. The linear wave theory does not show dynamic amplification for analysing the wave load. The nonlinear waves contain significant energy; near the natural frequency of the vibration with higher harmonics will produce resonance and significant wave loads which will amplify the structural dynamic response. Eddy method has been used since the early 1970s for research subjects on turbulent flows at large Reynolds numbers in the atmospheric boundary layer [34].

This research will include flow model around a circular cylinder of large diameter. Ocean hindcast data through NASA website will be analysed for the current, wave and wind. Then, the parameters such as grid density and the time step size are determined. The behaviour of current and surface waves for different waves and amplitudes will be analysed. Similarly, the effects of wind on the structure will also be explored. Thereafter, the developed model will be used to determine wave and current loads on a vertical face of the structure.

Wave forces:

Wave forces on tubular structural components give rise to separation of flow. Wave forces on floating offshore structures such as FPSO the incident waves are diffracted. The short-term changes in waves are considered for operating conditions and they are counted during a sea state of a return period whereas the long term variation is determined for specific sea states such as hurricanes. The longwave are defined by sea states, (6 h duration), and characterized by wave spectrum, significant wave height its direction, the degree of directional spreading of the waves and wave period (peak period). The metocean data is obtained from the offshore platform or hindcast using wind data and the probability distribution is used to define the wave parameters. the short-term distribution of individual significant wave heights is considered to follow Rayleigh probability distribution. During a sea state individual wave height is shown by the Eq. (3),

$$\frac{H_m}{H_s} = \sqrt{\frac{1}{2}\ln N} \quad (3)$$

H_m = largest individual wave height
H_s = significant wave height
N= number of waves

N = $\frac{\tau}{T}$, where τ = duration taken and T = zero-crossing wave period. $\frac{H_m}{H_s}$ = it is in range of 1.8-2.0.
S(*f*) = wave spectrum (distribution of wave energy). The most common form of wave spectra is Pierson- Moscowitz spectrum or Bretschneider spectrum can determine the wave frequency or period as shown in Eq. (4),

$$s(f) = \frac{5{H_s}^2}{16f_o}\frac{1}{(f/f_o)^5}exp\left[-\frac{5}{4}\left(\frac{f}{f_o}\right)^{-4}\right] \quad (4)$$

H_s = significant wave height and f_o = peak frequency of the spectrum

Finite volume method:

The spatial and time scale of flow is usually large. The spacing of grid points and time step are used to resolve dissipation of scales by dividing flow region into cubes and its order is smaller in length for large-scale flow. A fraction of turbulent fluctuation can be resolved to get the mean flow and turbulent stresses. The filtered flow of this scale can represent the overall characteristics of simulated flow [30-33]. Finite volume method, with Smagorinsky subgrid scale (SGS) model, will be applied to simulate the ocean flow. LES has the ability to resolve fine structures in the turbulent wake of the spar. Velocity profiles in the shell cylinder wake, hydrodynamics values, and pressure distribution on spar wall will be investigated at and around the free surface to give a better understanding of the physics.

Risk assessment:

For offshore structures, risk due to failures from fatigue, corrosion, and marine growth can be measured by loss of life, property and production, environmental pollution all these losses are directly related to the costs of the project. These risks can be minimised by reducing the probability of accident occurrence and/or minimizing the consequences of such accidents. In this study, it is to be investigated that if a wave and current influenced wind field will affect the offshore structural loads, fatigue, corrosion and marine growth. This will be made by the use of computational fluid dynamic (CFD) and by introducing a moving wave coupled with a response of the structure.

Expected outcomes and conclusions:

It is well known that the current force plays a significant role in the design of offshore structures and this study will provide a real current model based on the most recent data. The interaction of surface waves and current forces to be used for the design of offshore structures will also be determined. The models for current, wave-current and wind-wave will be the main outcome of this study. The development of this model will provide a tool for oil and gas engineers with the actual behaviour of wind, wave and current. Truly predictive fluid-structure interaction method is in high demand for offshore industry is moving towards deeper waters in general and ship industry in particular. The behaviour of free surface flow and its effect on fatigue, corrosion, and marine growth will have a significant impact on existing and new offshore structures. Thus the effect of surface environmental forces on Fatigue, corrosion and marine growth will also be determined.

Impacts on Economy

The accurate information current, wave and wind will make future structures economical. This will benefit the oil and gas industry of Malaysia for their offshore installations. It will be good for society and the nation for safe and economical structures. This study is expected to show a great potential of the planned approach for the analysis and design of the structures subjected to flow-induced vibrations due to metocean parameters. Fig. 1 shows the offshore Malaysia region.

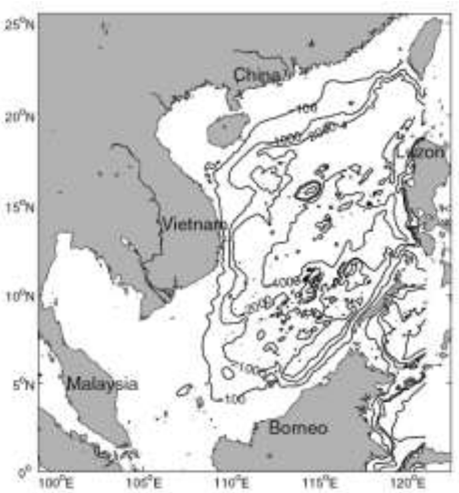

Fig. 1 Offshore Malaysia [37]

Offshore oil and gas sector acts as a backbone of the Malaysian economy. The design of the offshore structures is very significant from the cost and environment point of view. This study will have significant impacts on the economic and safe design and their effects after construction. This study can provide guidance on Malaysian annexe to ISO 19901 and 19902 codes. Current as a force plays a significant role in the design of offshore structures. The movement and behaviour of current in offshore Malaysia during different seasons has never been modelled previously. This study will develop a model based on realistic oceanic current flows such as sheared currents with variable temperature, density and direction at the free surface. The models for the wave-current interaction and wind, wave and current at free surface acting on the offshore structures will also be developed. This study will determine the effects of wave, current and wind load on offshore structures and it will enhance our understanding of fatigue, corrosion and marine growth in this region.

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