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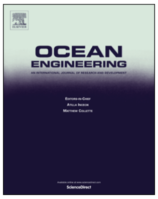

Evaluation of the dynamic responses of truss spar platforms for various mooring configurations with damaged lines

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ABSTRACT

Safe mooring for any platform is of utmost importance and concern because of the number of accidents as well as lack of knowledge due to uncertainties in the mooring lines behavior. This has led researchers to investigate the possible effect on the responses of a floating platform due to mooring line damages. Hence, this paper addresses the responses of a truss spar platform for various symmetric and asymmetric mooring configurations when one and two lines attached are damaged. To investigate this effect, the platform has been modeled as a three degree-of-freedom rigid structure and its motions are analyzed in time-domain. The force–excursion relationship of mooring lines is determined using quasi-static approach. It is observed that the effect of damaged mooring lines on symmetric and asymmetric configurations is nearly same. The migration distance of platform is considerably significant due to the damaged lines. It is more than thrice when two lines are damaged compared to one damaged line condition for symmetric and asymmetric configurations. However, the dynamic motions are not significantly affected.

1. Introduction

In recent years, offshore explorations are increasing more towards deeper waters in order to meet the demand–supply equity. The spar platforms are among the largest offshore platforms in use for deep waters and are kept stationed in the ocean environment by using mooring lines. The mooring systems are intended to keep the platform responses in safe operational zone to ensure the riser system integrity (da Fonseca Monteiro et al., 2013). Thus, primarily it is important to ensure the mooring system integrity. A review on the integrity issues of the mooring systems is presented by Ma et al. (2013). With several incidents in the last decade, the relatively high failure rate of mooring systems is raising a concern in the offshore industry. On a positive note, even though there were multi-line failures, none of them had its mooring system entirely broken which otherwise can allow complete free drifting of the platform or lead to major loss of life. A few incidents are as listed below:

- 2011 – Banff – 5 of 10 lines parted (Upstream Online, 2011; Teekay Petrojarl Production, 2012).
- 2011 – Volve – 2 of 9 lines parted (Moxnes, 2011).
- 2010 – Jubarte – 3 lines parted (Largura et al., 2011).
- 2009 – Nan Hai Fa Xian – 4 of 8 lines parted (CNOOC, 2009a; Wang, 2012).
- 2009 – Hai Yang Shi You – Entire mooring column collapsed (CNOOC, 2009b; Wang, 2012).
- 2002 – Girassol buoy – 3 of 9 lines parted (Jean et al., 2005; Melis et al., 2005; Vargas and Jean, 2005).

Phenomenon like out-of-plane bending of the mooring chains, cracked chain links which are hidden inside the hawse pipes at the top end of the mooring line, low fracture toughness of the shackles, inadequate corrosion protection, can cause mooring line failure (Ma et al., 2013; Gordon et al., 2014). The information on individual mooring failures are provided by Smedley (2009), Wang et al. (2009), L'Hoistis (2011), BOEMRE (2011) and Leeuwenburgh (2012). Therefore, the platform behavior in the case of one or more mooring lines failure has highly concerned the offshore industry. It shall also be noted that replacing a mooring line due to catastrophic failures is a long and expensive exercise. Hence, an early analysis of mooring line damage effects on dynamic responses of floating platforms is extremely essential and valuable.

Among the different types of spar platforms available, the truss spar which has a shallower draft received considerable attention as a more economical design (Kim et al., 2001). For a typical deep water offshore platform such as spar platforms, the ratio of structure dimension to characteristic design wavelength is usually small. Hence, it may be assumed that the wave field is virtually

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undisturbed by the structure and the Morison equation is adequate to calculate the wave exciting forces (Peimin, 1996). As the wave heights in deep waters of Malaysia are usually small compared to the wave length and water depths, the Linear Airy Wave Theory (LAWT) which is considered as most useful of all the wave theories can be considered to predict the incident wave kinematics (Chakrabarti. 1987).

The need to incorporate the dynamic considerations in analysis/design procedure for the deep water mooring systems is addressed in several papers but the quasi-static approach which has been proven to be a proper design tool for the mooring systems is considered a better choice in the first approach as it is almost certain to achieve convergence (Mavrakos et al., 1996; Russel and Colin, 2001; Pascoal et al., 2005, 2006). If desired, further analysis may then be carried out using the output of the static analysis as initial conditions for the dynamic analysis.

Quite a lot of studies have been conducted on the analysis of mooring lines and dynamic responses of truss spar platforms. Nevertheless, no researches were conducted on the damaged mooring systems whose configurations are defined in terms of symmetric and asymmetric azimuth angles. This paper aims to investigate the effect of symmetric and asymmetric mooring configurations in damaged line conditions on the dynamic responses of truss spar platform. The study is intended to aid the industry to optimize mooring configuration of truss spar platforms especially in the preliminary design stage.

2. Numerical modeling

In general, the global responses of a rigid structure have six degrees-of-freedom. The evaluation of structural responses of truss spar platform is a dynamic problem. The water wave forces in the equations of motion are derived from modified Morison equation while the mass, damping and stiffness matrices are obtained from the usual concepts of structural analysis.

In practical situations, waves are always accompanied by current and wind. The study in this paper is concerned with only unidirectional waves, steady current and wind forces. In the case of unidirectional incident waves, only surge, heave and pitch motions are significant and the out-of-plane motions i.e. sway, roll and yaw due to the transverse forces such as Vortex Induced Vibration (VIV) are neglected (Peimin, 1996). Therefore, the platform is modeled as a rigid structure with three degrees-of-freedom.

The structure is supported by an anchor system comprising of spread mooring lines. Mooring lines are modeled as springs and their contribution to the inertia and damping is neglected (Anam, 2000).

2.1. Wave kinematics and force formulations

One of the most useful theories in calculating the kinematics of a progressive wave is linear Airy wave theory which is based on the assumption that the wave height is small compared to the wave length or water depth. This assumption allows the free surface boundary conditions to be linearized by dropping wave height terms which are beyond the first order and also to be satisfied at the mean water level rather than at the oscillating free surface.

The governing equations for the waves and its kinematics are summarized below based on LAWT. Assuming H as wave height, k as wave number, $+x$ as the direction of wave propagation, c as wave velocity, t as the time and substituting $\theta = k(x - ct)$, the wave profile η is given as:

$$\eta = \frac{H}{2}\cos(\theta) \tag{1}$$

Assuming ρ is the density of water, g is the acceleration due to gravity, T is the wave time period, d is the water depth, the wave length L is obtained as:

$$L = \frac{gT^2}{2\pi}\tanh(kd) \tag{2}$$

Substituting $s = y + d$ (where y represents the free surface), the expressions for horizontal water-particle velocity u, vertical water-particle velocity v, horizontal water-particle acceleration du/dt, vertical water-particle acceleration dv/dt are as given below:

$$u = \frac{\pi H}{T}\frac{\cosh(ks)}{\sinh(kd)}\cos(\theta) \tag{3}$$

$$v = \frac{\pi H}{T}\frac{\sinh(ks)}{\sinh(kd)}\sin(\theta) \tag{4}$$

$$\frac{du}{dt} = \frac{2\pi^2 H}{T^2}\frac{\cosh(ks)}{\sinh(kd)}\sin(\theta) \tag{5}$$

$$\frac{dv}{dt} = -\frac{2\pi^2 H}{T^2}\frac{\sinh(ks)}{\sinh(kd)}\cos(\theta) \tag{6}$$

The wave and current forces are formulated using the modified Morison equation viz., relative velocity model (Chakrabarti, 1987) and is composed of two components – inertia and drag. The incremental force f on a small segment ds of the platform, e.g. cylindrical hard tank having diameter D is given as:

$$f = C_m A_I \dot{u} - C_A A_I \ddot{x} + C_D A_D |u + c_v - \dot{x}|(u + c_v - \dot{x}) \tag{7}$$

$$A_I = \rho A_s \left(\text{here, } A_s = \frac{\pi}{4}D^2\right) \text{ and } A_D = \frac{1}{2}\rho D \tag{8}$$

in which C_m, C_A and C_D are inertia, added mass and drag coefficient, u and $\dot{u}$ are instantaneous water-particle velocity and local water-particle acceleration, c_v is the current velocity, $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the cylinder, respectively.

2.2. Equation of motion

The force on the spar platform is the resultant of a number of components including the excitation forces due to wave, hydrostatic pressure, restoring forces due to mooring lines and damping from drag on the structure. The equations for rigid-body motion are derived by applying the conditions of equilibrium in the horizontal and vertical directions and rotation about the CG. They can be most conveniently represented in matrix form in terms of mass, damping and stiffness matrices and force vector. The centroidal displacements in the x–y plane (termed as surge x_G, heave y_G and pitch γ) are given by the equilibrium equations relating the structural motion to the resultant of excitation forces, added forces and spring resistance. As spar is a rigid body, it does not have internal stiffness of its own and derives its static resistance from hydrostatic stiffness and support-systems (mooring lines).

Let M, C, K, and F being the structural mass, damping, stiffness and resultant force matrices respectively, $\ddot{P}$, $\dot{P}$ and P be the structure acceleration, velocity and displacement matrix, then the equilibrium equation is:

$$M\ddot{P} + C\dot{P} + KP = F \tag{9}$$