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Analysis of heave motions of a truss spar platform with semi-closed moon pool

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ABSTRACT

This paper presents the heave motion of a truss Spar platform in regular waves considering the dynamic coupling between the motions of the platform and water in the moon pool. For a spar platform with semi-closed moon pool, water can flow freely through the guide plate at bottom of the moon pool. The mass of water inside the moon pool is comparable to the platform mass itself if the top tension riser system is used. Then the effect of the moon pool water on the motions of the platform should not be ignored. In the study presented in the paper, a 2-DOF (Degree of Freedom) dynamic coupling equations of the heave motions of the spar platform and the vertical motions of water in the moon pool were derived considering that the moon pool is totally closed, or 30% or 70% open. The results show that motions of water in the moon pool significantly affect the heave motions of the spar platform. Parametric study was also carried out to find the effect of the ratio of opening of the bottom plate on the coupled motions. Finally the model experiments were carried out to validate the numerical calculations.

1. Introduction

Spar platforms are one of the platform types used to produce oil and gas from deep-sea fields. Research investigations on Spar platforms mainly focus on wave loading on the hull and its hydrodynamic characteristics, the dynamic response of the platform, stability analysis of coupled heave and pitch motions, simulation of the mooring and the riser system and the vortex-induced vibration (Tang, 2008). Investigators so far have carried out extensive research on the coupled motions between the platform hull and its mooring and riser systems, as well as on the coupling effects of different degrees of freedoms (Kim et al., 2001; Tao et al., 2004; Mohammed et al., 2011; Xu and Jing, 2013). On the other hand the investigations to study the coupled motions between the platform and water inside the moon pool are rare.

Risers and drilling string go through a moon pool which is located in the centre of the hull of a spar platform and extends from the bottom of the hull to the deck. A guide plate is placed at the bottom of the moon pool (Drobyshevski, 2004; Kristiansen and Faltinsen, 2012). According to the design requirements, the moon pool is sometimes designed to be semi-closed, such as Holstein Spar platform, which allows water to flow freely in and out of the moon pool. There are two common ways to deal with the water inside a semi-closed moon pool (Gupta et al., 2008): (1) the moon pool is completely closed and the water inside the moon pool is trapped and thus it moves as a rigid body together with the platform; (2) the moon pool is completely open to the sea and the presence of the water inside the moon pool will not significantly affect the heave motions of the platform. The water in the moon pool has two kinds of natural vibration modes, which are piston-like motion in vertical direction and sloshing motion caused by the free surface (Faltinsen and Timokha, 2009). If the top tension risers are used, the mass of the water inside moon pool is comparable to the mass of the platform. The effect of the motions of water inside the moon pool on the motions of the Spar platform should not be ignored.

Aalbers (1984) assumed that the water column inside a floating vessel can be replaced by a frictionless piston, then the motion equation of water inside the moon pool was derived and the coupled motions were studied. It was found that the water inside the moon pool can decrease the heave amplitude of the vessel. Barreira et al. (2005) treated the motions of water inside a moon pool as a spring-mass system and studied the coupled motions of a mono-column structure and water inside a moon pool. They found that the heave motions of the platform can be decreased by an

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appropriate design of a guide plate. Sphaier et al. (2007) presented the mono-column dynamic behavior in waves as obtained from model experiments. They measured the mono-column vertical motions and the motions of water in the moon pool for different opening ratios of the guide plate. The effect of guide plate opening ratios on the heave motions of the platform was analyzed. Gupta et al. (2008) derived a 2-DOF coupling dynamic model of a spar heave and the vertical motion of water inside the moon pool. This work highlights the importance of the moon pool hydrodynamic characteristics in predicting the heave motions of a spar platform. Spanos et al. (2011) developed a 6-DOF nonlinear model, including surge, heave, and pitch motions of a spar platform; surge and heave motions of risers, and vertical motions of water inside the moon pool. The results indicated that the heave amplitude of the platform is reduced significantly by the coupled motions of the platform and water inside the moon pool.

The study presented in this paper investigated the heave motions of a truss spar platform considering the dynamic coupling between the platform motions and the motions of water in the moon pool. The effect of the motions of water on the heave motions of the platform was investigated. The platform heave and the moon pool motions were discussed as opening ratios of the bottom guide plate varied. Three detachable guide plates were designed for the model tests, with 0% opening ratio (moon pool totally closed, Case 1), 30% opening ratio (Case 2) and 70% opening ratio (Case 3). The results of the experiments were used to validate the numerical analysis.

2. Dynamical modeling

The vertical motion equations of water inside the moon pool of a spar platform were derived based on the work of Gupta et al. (2008) through the following steps: (1) the conservation laws of mass and momentum of water inside the moon pool were applied to find the pressure acting on the top of the guide plate; (2) an empirical formula to calculate the pressure acting on the bottom of the guide plate was used; (3) Newton's second law was applied to the fluid in the guide plate gap, to let the pressure difference between two sides of the guide plate accelerate the fluid. The heave equations of the spar platform was established by applying the rigid body dynamics equations given by Liu et al. (2014), and the wave forces were calculated based on the potential theory.

The coordinate system and cross section of the platform hull are shown in Fig. 1. In Fig. 1(a), x axis is in the horizontal plane of the still water, z axis is vertically upward and through the gravity center of the platform, $-z_0$ is the hull static draft, z_1 is the moon pool water surface elevation in the moon pool relative to the horizontal plane of the still water. In Fig. 1(b), S_g is the open area at the bottom of the moon pool, S_o is the area of the guide plate and S_p is the sectional area of the hard tank. The moon pool sectional area can be written as $S_{mp}=S_o+S_g$ and the moon pool opening ratio can be written as S_g/S_{mp}.

First, the motion equation of water in the moon pool in vertical direction is derived. Taking the moon pool water as a deformable control volume, the mass conservation equation is

$$\int_{S_g}\rho(\vec{v}_1-\vec{v}_b)\times\vec{n}dA=-\frac{dM_{mp}}{dt} \tag{1}$$

where ρ is the water density, $\vec{v}_1$ is the velocity of water flowing through the guide plate gap, the magnitude is v_g, $\vec{v}_b$ is the velocity of the spar platform heave, the magnitude is $\dot{z}$, $\vec{n}$ is unit outward normal vector, $M_{mp}=\rho S_{mp}(z_1-z-z_0)$ is the mass of the moon pool water. Substituting above parameters into Eq. (1) leads to

$$v_g=\frac{\dot{z}+S_{mp}}{S_g\times(\dot{z}_1-\dot{z})} \tag{2}$$

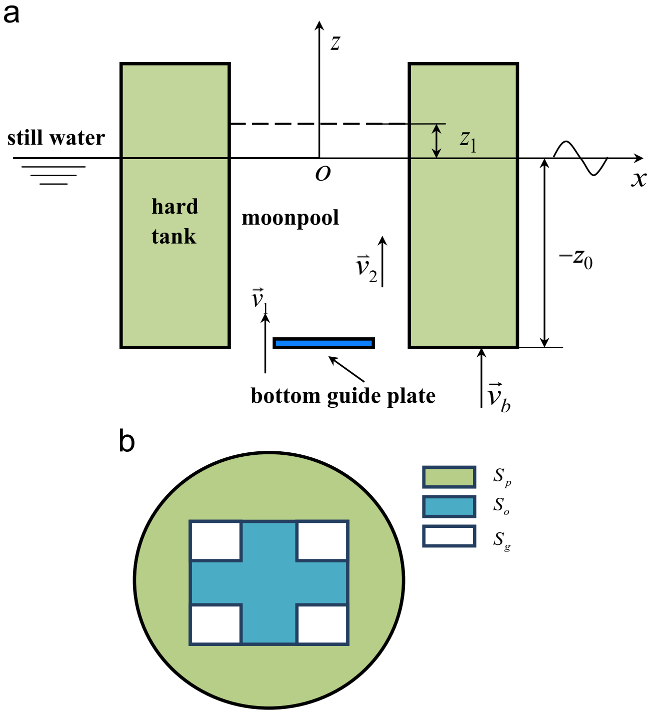

Fig. 1. Coordinate system and cross section of the hull of the platform: (a) coordinate system, (b) cross section.

The linear momentum equation of the deformable control volume can be written as Hansen (1967)

$$\sum\vec{F}=\frac{d}{dt}\left(\int_{CV}\vec{V}\rho d\forall\right)+\int_{CS}\vec{V}\rho(\vec{V}_r\times\vec{n})dA \tag{3}$$

where $\vec{V}$ is fluid velocity vector in the control volume CV, $\vec{V}_r$ is the fluid velocity vector cross the control surface CS.

To simplify the analysis, assuming the flow properties over the cross section and those inside the control volume are uniform, respectively (White, 2003), the right hand side of Eq. (3) can be further written as

$$\frac{d}{dt}\left(\int_{CV}\rho\vec{v}_2 d\forall\right)+\int_{S_g}\rho\vec{v}_2(\vec{v}_1-\vec{v}_b)\times\vec{n}dA=\frac{d}{dt}\{\rho\dot{z}_1S_{mp}(z_1-z-z_0)\}-\rho\dot{z}_1\left(v_g-\dot{z}\right)S_g \tag{4}$$

where $\vec{v}_2$ is the velocity of the water particle inside the moon pool, the magnitude is $\dot{z}_1$.

The left hand side of Eq. (3) includes surface force acting on the control surface and mass force acting on the water particles inside the moon pool. The forces can be written as

$$\sum\vec{F}=-\rho gS_{mp}(z_1-z-z_0)+p_1S_{mp} \tag{5}$$

where p_1 is the pressure on the upper side of the guide plate, g is the acceleration of gravity.

Substituting Eqs. (4) and (5) into Eq. (3) yields the relation

$$\rho\ddot{z}_1S_{mp}(z_1-z-z_0)=-\rho gS_{mp}(z_1-z-z_0)+p_1S_{mp} \tag{6}$$

From Eq. (6), p_1 can be derived as

$$p_1=\rho(\ddot{z}_1+g)(z_1-z-z_0) \tag{7}$$

The pressure on the lower side of the guide plate includes the static pressure, the inertia force due to vertical acceleration, the dynamic pressure due to velocity and the incident wave pressure.