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Numerical study of hydrodynamic coefficients of multiple heave plates by large eddy simulations with volume of fluid method

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ABSTRACT

Hydrodynamic coefficients of multiple heave plates are studied for offshore structures to reduce heave responses in oscillating flows. Large eddy simulations with volume of fluid method are performed to predict the hydrodynamic force on a forced oscillated model with multiple heave plates. Predicted added mass and drag coefficients are validated by a water tank test. Then, flow pattern around the multiple heave plates is investigated to clarify the mechanism of hydrodynamic forces on each plate, and a systematic study on the effects of geometric parameters, such as spacing ratio, diameter ratio and aspect ratio on the hydrodynamics of octagonal heave plate are conducted. Finally, formulas of added mass and drag coefficients for a single and double heave plates with circular, octagonal and square cross-sections are proposed to cover a wide range of application of the heave plate.

1. Introduction

Floating offshore wind turbine (FOWT) is a promising innovation. The world's first full-scale 2.3 MW spar FOWT in Hywind project was installed in Norway by Statoil Hydro in 2009 (Hywind Demo), and the second prototype was the 2 MW semi-submersible FOWT in WindFloat project deployed in Portugal by Principle Power in 2011 (WindFloat). In Japan, a 2 MW spar FOWT in GOTO-FOWT project was built off the coast of Kabashima in 2013 (GOTO FOWT). In addition, another 2 MW semi-submersible FOWT and a 7 MW V-shape semi-submersible FOWT in Fukushima FORWARD project were completed off the coast of Fukushima in 2013 and 2015, respectively (Fukushima FORWARD). In the semi-submersible and advanced spar FOWTs, heave plates are commonly used to reduce heave motions and to shift heave resonance periods out of the first-order wave energy range (Lopez-Pavon and Souto-Iglesias, 2015, Fukushima FORWARD). Some new concepts of floating platform have been adopted. A substation and a 5 MW FOWT constructed in Fukushima FORWARD project (Fukushima FORWARD) adopt an advanced spar consisting of multiple heave plates. The hydrodynamic characteristics of multiple heave plates is one of the key factors for the structural design of platforms.

Morison's equation and potential theory are widely used to predict hydrodynamic loads on the platform of FOWT (Phuc and Ishihara, 2007; Waris and Ishihara, 2012; Jonkman, 2007; Browning et al., 2014; Kvittem et al., 2012). The hydrodynamic coefficients, namely added mass and drag coefficients of heave plates (hereinafter referred to as C_a and C_d, respectively) have to be determined to evaluate hydrodynamic loads on them. The hydrodynamic coefficients of the heave plates can be attained by means of water tank tests (Lopez-Pavon and Souto-Iglesias, 2015; Li et al., 2013), numerical simulations (Lopez-Pavon and Souto-Iglesias, 2015; Tao and Thiagarajan, 2003a, 2003b; Tao et al., 2004, 2007; Tao and Cai, 2004; Garrido-Mendoza et al., 2015; Yang et al., 2014), and empirical formulas (Tao et al., 2007; Tao and Cai, 2004; Philip et al., 2013).

Water tank tests have been carried out intensively to study the hydrodynamic coefficients of circular single heave plate (Lopez-Pavon and Souto-Iglesias, 2015; Tao and Dray, 2008), and square single heave plate (Prislin, Blevins, Halkyard, 1998, Li et al., 2013; An and Faltinsen, 2013; Prislin, Blevins, Halkyard, 1998; Wadhwa and Thiagarajan, 2009). Hydrodynamic coefficients of circular and square single heave plates were compared between each other in the study by Lopez-Pavon and Souto-Iglesias (2015). They pointed out that both C_a and C_d of the square heave plate are smaller than those of the circular heave plate. They also confirmed that there is a relatively weak dependence of oscillating frequencies, and a large dependence with Keulegan-Carpenter (KC) number, as well documented in references (Li et al., 2013; An and Faltinsen,

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2013). Wadhwa et al. (Wadhwa and Thiagarajan, 2009; Wadhwa et al., 2010) investigated the hydrodynamic coefficients of a heave plate near the free surface. As the submergence of the heave plate decreases, the free surface is expected to be disturbed. It was observed that both C_a and C_d continuously increase as the distance to the free surface increases. Li et al. (2013) studied the influence of plates spacing on the hydrodynamic coefficients. It was found that the hydrodynamic coefficients decrease as spacing decreases.

A number of numerical studies on the hydrodynamic characteristics of heave plate have been conducted. Tao and Cai (2004) investigated influences of heave plate diameter and KC number on hydrodynamic coefficients by finite difference method. Predicted damping ratio agreed well with the measured ones in both low and high KC regimes. Tao and Thiagarajan, 2003a, 2003b presented three vortex shedding modes for oscillating heave plate and proposed a quantitative method of identifying the vortex shedding flow regimes. Lopez-Pavon and Souto-Iglesias (2015) performed a numerical analysis of the hydrodynamic performance of heave plate by a finite volume method with Shear Stress Transport (SST) turbulent model. The accuracy of the computations was found reasonable for a plain plate, while some errors were found for a reinforced plate. Holmes et al. (2001) examined the hydrodynamic coefficients of a square heave plate by a finite element method with LES turbulent model. It was observed that the predicted force by Morison's equation with determined hydrodynamic coefficients matched well with the measured force, even in random wave conditions. Tao et al. (2007) investigated spacing effects on the hydrodynamics of double circular heave plates, and provided a recommendation for the arrangement of adjacent heave plate. However, in these studies, hydrodynamic coefficients of the double heave plates were not validated by water tank tests, and mechanism of hydrodynamic force on multiple heave plates has not been clarified yet.

Formulas are beneficial for optimizing the design of offshore structures with heave plates. The added mass of a pure circular heave plate along its axis approximately equals to the mass of a sphere of water enclosing the heave plate (Sarpkaya, 2010). Tao and Cai (2004) proposed a formula for added mass of a circular heave plate attached by a column. A formula for double circular heave plates by considering the effect of spacing ratio is firstly proposed by Tao et al. (2007), and the predicted added mass coefficient matches well with that obtained from the numerical simulation at low KC number. Philip (Philip et al., 2013) put forward a simplified formula for added mass of a vertical cylinder with multiple heave plates. However, the formula is only suitable for non-interacting plates, which indicates the effect of heave plate spacing is not considered. All the proposed formulas are limited to circular heave plates, and influence of KC number is not taken into account. In contrast to the formulas of C_a, the formula of C_d is seldom studied. Tao and Thiagarajan (2003a) identified the coefficients in the formulas of C_d proposed by Graham (1980) for each defined vortex shedding flow regime, but it might be inappropriate to propose the piecewise formula of C_d since there are no clear watersheds to distinguish the vortex shedding regimes. Therefore, a formula of C_d covering those wide ranges of vortex shedding regime is preferred. Formulas of both C_a and C_d are also expected to cover various cross-sections of heave plates, such as circular, octagonal and square heave plate, and geometric parameters, such as aspect ratio, diameter ratio, and spacing ratio.

In this paper, section 2 describes governing equations and volume of fluid method, grid arrangement, boundary conditions, cases of simulations, and provides the validation of numerical results by a water tank test. Section 3 clarifies the mechanism of hydrodynamic forces on multiple heave plate, and investigates the effect of geometrical parameters, such as spacing ratio, diameter ratio, and aspect ratio. In Section 4, formulas of C_a and C_d for a single and double heave plates are proposed, and the accuracy of hydrodynamic coefficients predicted by proposed formulas is validated by published data in literature and present numerical simulations. The conclusions are summarized in Section 5.

2. Numerical model and validation

In this section, numerical model of a floater with multiple heave plates is introduced, which is a 1/100 down-scaled Froude model of a substation (Yoshimoto, 2016) employed in Fukushima FORWARD project. The floater contains three hulls, which are connected by one cylindrical column. The fully submerged middle and lower hull have the function of heave plate in reducing heave motion. The overview of the floater and its dimensions are shown in Fig. 1. The center line of the upper hull is located at still water level (SWL). All the hulls are octagonal cross-sectional plate. The detailed dimension of the model is specified in Table 1.

The governing equation and VOF method is given in section 2.1. The computational domain and grid arrangement are described in section 2.2. Section 2.3 presents the numerical schemes and boundary conditions. Cases conducted in this study are shown in section 2.4. The definition of the hydrodynamic coefficients is provided in section 2.5. The description of water tank test and validation of numerical results are given in section 2.6 and 2.7, respectively.

2.1. Governing equation

Large-eddy simulation (LES) is adopted and the Boussinesq hypothesis is employed, and the standard Smagorinsky-Lilly model is used to calculate the subgrid-scale (SGS) stresses. The governing equations in Cartesian coordinates are expressed in the form of tensor as Eq. (1) and Eq. (2).

$$\frac{\partial \tilde{u}_i}{\partial x_i}=0 \tag{1}$$

$$\rho\frac{\partial \tilde{u}_i}{\partial t}+\rho\frac{\partial \tilde{u}_i\tilde{u}_j}{\partial x_j}=-\frac{\partial \tilde{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial \tilde{u}_j}{\partial x_i}\right)\right]-\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where, $\tilde{u}_i$ and $\tilde{p}$ are filtered mean velocity and filtered pressure, respectively. μ is dynamic viscosity, ρ is the density of fluid. $\tau_{ij}=\rho(\widetilde{u_i u_j}-\tilde{u}_i\tilde{u}_j)$ is SGS (subgrid-scale) stress resulting from the filtering operations, and is modeled by Eq. (3) as follows:

$$\tau_{ij}=-2\mu_t\tilde{S}_{ij}+\frac{1}{3}\tau_{ii}\delta_{ij} \tag{3}$$

In which, μ_t is subgrid-scale turbulent viscosity, and $\tilde{S}_{ij}$ is the rate-of –strain tensor for the resolved scale defined by Eq. (4):

$$\tilde{S}_{ij}=\frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j}+\frac{\partial \tilde{u}_j}{\partial x_i}\right) \tag{4}$$

Smagorinsky-Lilly model is used to calculate the subgrid-scale turbulent viscosity, μ_t defined as Eq. (5)

$$\mu_t=\rho L_S^2\left|\tilde{S}\right|=\rho L_S^2\sqrt{2\tilde{S}_{ij}\tilde{S}_{ij}} \tag{5}$$

where, L_S is the mixing length for subgrid-scales, defined as Eq. (6)

$$L_S=\min\left(\kappa\delta, C_s V^{1/3}\right) \tag{6}$$

In which, κ is the von Karman constant, 0.42, C_s is Smagorinsky constant is set as 0.032 following the suggestion in the reference (Oka and Ishihara, 2009), δ is the distance to the closest wall and V is the volume of a computational cell.

The volume of fluid (VOF) model is used in this study to model air and water. Volume fraction of water will be solved to capture the interface between air and water. Continuity equation for the volume fraction of water, α_w , reads: