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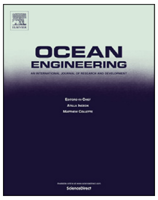

Numerical studies on vortex-induced motions of a multi-column deep-draft oil and gas exploration platform

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ABSTRACT

This paper presents numerical studies on vortex-induced motions (VIM) of a multi-column floating oil and gas exploration platform. Numerical computations are performed using an improved delayed detached eddy simulation (IDDES) together with a moving grid approach. The transverse (sway) and yaw motion responses, motion trajectories, motion frequencies and power spectral density of motions are computed and analyzed systematically. After extensive comparisons with experiments, it is confirmed that the present numerical solutions using IDDES agree well with the experimental results and are better than those via delayed detached eddy simulation (DDES). The differences of transverse motion responses between computational results and experiments are less than 10% in the lock-in region. The numerical simulations reveal that the transverse VIM responses occur in a range of reduced velocities from 7.0 to 14.0 at $H/D = 1.44$ (H and D are the column height and width, respectively). The largest nominal transverse amplitude, around 35% of the column width, occurs for 22.5° current incidence. It is found that the VIM responses mainly perform along the platform diagonals for 15°, 22.5° and 45° current incidences. The transverse and yaw motion frequencies for 15°, 22.5° and 45° current incidences are higher than those for 0° current incidence. The energy levels of the yaw motion responses for 15°, 22.5° and 45° current incidences are about 10% of that for 0° current incidence. Moreover, parametric studies have been performed to examine the effect of submerged column height on VIM. It demonstrates that VIM in transverse direction grows significantly when submerged column height H/D is greater than 1.0. To be more specific, compared to the case with $H/D = 1.44$, VIM in transverse direction at $H/D = 3.0$ increase by around 120%.

1. Introduction

Tension Leg Platform (TLP), Semi-submersible (SEMI), and Spar are the three major floater concepts adopted for oil/gas exploration and offshore floating wind turbine foundation in the past few decades. In order to improve the vertical motion performance such as heave and pitch for a SEMI or TLP, hull draft has been increased significantly over the past few years (Lee et al., 2014a). However, increased column draft can result in large-amplitude VIM, due to coherent vortex shedding behind the columns with either square or circular cross-section (Bearman, 1984; Williamson and Govardhan, 2004). Recently, oil and gas industry has recognized the importance of VIM on the development of deep-draft multi-column floating platforms, such as deep-draft SEMI or TLP. Large-amplitude VIM can not only impact the fatigue life of mooring and riser systems, but also cause destructive collision between a floater and supporting vessels (Huang et al., 2003; Vandiver et al., 2006; Dahl et al., 2007; Ma et al., 2013). The earlier studies on VIM are merely focused on Spar (Finnigan and Roddier, 2007; Irani et al., 2008; Stappenbelt, 2010; Pinto et al., 2007), whose VIM responses in loop current are very much intensive. The previous studies revealed that Spar VIM amplitude can reach the same order of magnitude as its diameter such that helical strakes must be adopted to mitigate VIM.

On the other hand, VIM of a multi-column floating platform such as SEMI or TLP, is more complex than that of either Classic Spar or Truss Spar owing to the complicated wake interactions among the multiple columns. A number of model tests have been carried out in either towing tank or water tunnel to study VIM. Through experiments in a water tunnel, Lam et al. (2003) investigated the flow pattern and velocity field of cross-flow around four cylinders in a square configuration. Several distinct flow patterns, which might lead to strong VIM, were observed for current incidence angles ranging from 0° to 45° with a spacing ratio of 4.0. Waals et al. (2007) investigated the effect of mass ratio on the VIM

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responses of two four-column floating platforms but with different pontoon configurations. They found that lower mass ratio resulted in larger transverse motion responses and the yaw responses were more considerable for 0° current incidence. Magee et al. (2011) performed VIM model test of a TLP in two different loading conditions and confirmed that the yaw responses were more significant for 0° current incidence than those for 45° current incidence. They also found that the aspect ratio of the column affected VIM responses mainly for 45° current incidence rather than 0° current incidence. Gonçalves et al. (2012) conducted model tests in a towing tank to investigate the VIM responses of a deep-draft SEMI and the effects of appendages. Previous experimental studies showed that VIM of a multi-column platform is characterized by 3 degree-of-freedom motions in horizontal plane, namely the in-line, transverse (sway) and yaw motions. Most of the model test results for multi-column platforms suggest that the largest transverse motion occurs in a range of reduced velocities between 6.0 and 10.0, also called the lock-in region (Waals et al., 2007; Magee et al., 2011; Gonçalves et al., 2012; Tan et al., 2014; Rijken and Leverette, 2008).

Compared to experimental studies, Computational Fluid Dynamics (CFD) can offer more flow details as CFD technologies have gained advances in solving complex flows in the past few decades. The numerical simulations can offer instantaneous and comprehensive information of the velocity field, the vorticity field and the pressure field, which are difficult to be measured in experiments. The typical CFD methods including Reynolds-averaged Navier-Stokes (RANS), detached-eddy simulation (DES), and large-eddy simulation (LES) have been developed to simulate VIM responses (Xu et al., 2012; Wu et al., 2014; Antony et al., 2015; Vinayan et al., 2015).

For instance, Koop et al. (2016) used RANS with k-ω SST turbulence model to compute VIM of a SEMI, and studied the effects of Reynolds number on VIM responses. Lee et al. (2014b) and Chen and Chen (2016) developed a Finite-Analytic Navier-Stokes (FANS) code to simulate VIM of a SEMI in both model scale and full scale. They analyzed the pre-lock-in, lock-in and post-lock-in behaviors, and investigated the effect of the column corner radius on VIM. Kim et al. (2011) applied RANS and DES to simulate VIM of a TLP. They found that the computed transverse and yaw motion responses had some discrepancies with the experimental data at high reduced velocities. Tan et al. (2013) also applied DES to compute VIM of a TLP in two loading conditions and discussed the sensitivities of numerical results to the modeling assumptions, such as mesh size, time-step size and turbulence modeling. Kim et al. (2015) compared numerical simulations of VIM of a Paired-Column (PC) SEMI using both RANS and DDES. They found that DDES gave better predictions of the motion responses and average zero-crossing periods compared to RANS. Pontaza et al. (2015) used LES to study VIM of a SEMI in random waves, but only 8 VIM cycles were obtained. As expected, the computing cost using LES was much more than that by using RANS or DES.

Although RANS with $k{-}\varepsilon$ or $k-\omega$ models has been adopted in simulating flows over cylinders (Catalano et al., 2003; Ong et al., 2009; Rajani et al., 2012), small-scale turbulence eddies are filtered out because of the averaging process (Wilcox, 1998). The small-scale turbulence eddies may be important to accurately simulate the full wake dynamics in flows over cylinders (Khorrami et al., 2007). Rosetti et al. (2012) investigated the flow around a cylinder and found that traditional RANS model can not provide sufficient resolution for flows over a cylinder, especially at high Reynolds number, because of its intrinsic properties of isotropic eddy viscosities and homogeneous Reynolds stresses. In a recent work on simulating flows over a cylinder at a range of Reynolds number (Stinger et al., 2014), the results of lift fluctuations and drag coefficients showed that at high Reynolds number ($Re > 10^4$) using RANS model led to relatively larger differences compared with the experimental data.

In order to overcome the excessive cost of LES and the limitation of RANS for simulating the flows over a bluff body at high Reynolds number, DES, a hybrid RANS/LES approach (Spalart et al., 1997), has been successfully applied to simulate the flows over a cylinder (Travin et al., 1999) as well as the vortex induced vibrations (VIV) of a cylinder (Nguyen and Nguyen, 2016). The original DES model (Spalart et al., 1997) requires well-crafted grids to avoid inappropriate behavior known as grid-induced separation due to direct impact of grid spacing on transition from modeled to resolved turbulences in free and separated shear layers. Later, based on DES, DDES (Spalart et al., 2006), where the model shields against grid-induced separation, and improved DDES (IDDES) (Shur et al., 2008), which incorporates wall-modelling LES (WMLES), have been developed to simulate the flows over cylinder. More recently, DDES and IDDES were adopted to predict the unsteady flow past tandem cylinders (Garbaruk et al., 2010; Xiao et al., 2012; Xiao and Luo, 2015). These work confirmed that IDDES performed relatively better than DDES though both models were capable of simulating massive separation flows past tandem cylinders.

The main objective of the present study is to investigate the validity of the IDDES model based on Spalart-Allmaras (S-A) turbulence closure for the prediction of VIM of a multi-column floating platform. The numerical results using IDDES are extensively compared against those using DDES. The characteristics of the VIM are analyzed in a broad range of reduced velocities for four different (0°, 15°, 22.5° and 45°) current incidences. The motion trajectories, non-dimensional motion frequencies and power spectral density (PSD) of motions are analyzed. The flow patterns for different current incidence angles are examined by plotting the vorticity contours and streamline. Finally, the effects of the submerged column height on VIM are investigated through systematic parametric studies.

2. Numerical model

2.1. Governing equations

The governing Navier-Stokes equations solved for the incompressible flows can be written as

$$\nabla\cdot\overline{\mathbf{u}} = 0 \tag{1}$$

$$\frac{\partial\overline{\mathbf{u}}}{\partial t} + \overline{\mathbf{u}}\cdot\nabla\cdot\overline{\mathbf{u}} = -\frac{1}{\rho}\nabla\overline{p} + \upsilon\nabla^2\overline{\mathbf{u}} + \frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} \tag{2}$$

where ∇ is the Hamiltonian operator; $\mathbf{u}$ is the velocity vector; t is the time; p is the pressure; ρ is the density of water; υ is the kinematic viscosity of the water; The last term of Eq. (2) is the Reynolds stress tensor $\boldsymbol{\tau} = -\rho\left(\overline{\mathbf{u}'\mathbf{u}'}\right)$, where $\mathbf{u}'$ denotes the fluctuating velocity. The Reynolds stress tensor is an additional term that represents the effects of turbulence, but it must be modeled in order to close Eq. (2). It should be noted that these governing equations are written in a general form. It can be applied to both RANS and LES formulations, depending on the definition of the overbar, which denotes an ensemble average in RANS and an explicit filtering operation in LES.

2.2. IDDES approach

The IDDES model is chosen for simulations of flows over a multi-column floating platform as a turbulent flow modelling approach. The IDDES is a hybrid model which combines DDES and WMLES. The DDES length scale is implemented to eliminate the modeled-stress depletion in the original DES approach, while WMLES is applied to achieve more accurate prediction of the mean velocity in the boundary-layer. In this approach, the turbulent stress is written as

$$-\rho\left(\overline{\mathbf{u}'\mathbf{u}'}\right) = 2\mu_t\overline{\mathbf{S}} - \frac{2}{3}\rho k\mathbf{I} \tag{3}$$

where $\overline{\mathbf{S}}$ is the mean strain rate tensor; μ_t is the turbulent eddy viscosity; k is the turbulent kinetic energy; $\mathbf{I}$ is the Kronecker delta.

The turbulent eddy viscosity is obtained by solving a transport equation for a transport variable $\widetilde{\upsilon}$ in the S-A turbulence formulation