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A new passive control technique for the suppression of vortex-induced motion in deep-draft semisubmersibles

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ABSTRACT

The control of vortex-induced motion (VIM) of deep-draft semisubmersibles has recently emerged as a serious concern in offshore semisubmersible platforms subjected to high ocean currents. With the increased draft of semisubmersibles, the coherent wake vortex fields behind the multi-column platforms become quite significant, which increase the impact of the coupled fluid-structure dynamics on the platform motion. In particular, the effective mitigation of the synchronization of wake vortices in a deep-draft semisubmersible is important for the reliable station-keeping and to extend the fatigue life of risers and mooring systems. The present study aims at the development of a passive control technique for the vortex synchronization of deep-draft semisubmersibles (DDS) via continuous cross-sectional twisting of the rounded square column along the spanwise direction. The computations are performed using a hybrid URAN-LES turbulence model based on the finite volume method. A validation study of the numerical results is performed with the available experimental data for the stationary and vibrating configurations of deep-draft semisubmersible. To begin, we first examine the VIM performance of a single column of the semisubmersible with a twisted angle of 45 °. We next examine the design of twisted column to understand its effect on the vorticity dynamics and the VIM response characteristics. In comparison to the untwisted square-column configuration, the twisted column produces the reduction in the transverse (sway) VIM amplitude up to 90% at the peak lock-in condition. The streamwise (surge) amplitude for the twisted-column semisubmersible is also found to be reduced by approximately 1/3 of the amplitude of the square-column counterpart. The twisted surface on the column results in a continuous spanwise (column-wise) variation of the shear-layer separation points. The three-dimensional (3D) variation of separation lines and the pressure distribution along the twisted and the square columns are analyzed to understand the underlying mechanism of the VIM suppression. We find that the modification of vortex shedding due to the variation in the separation line along the twisted column significantly influences the mean and fluctuating hydrodynamic forces. We extend the twisted column concept to the deep-draft semisubmersibles and demonstrate its effectiveness to produce a remarkable degree of VIM suppression. We explore the effects of the orientation of twisted columns and the incidence angle of the oncoming flow and present the 3D wake vortex structures and the motion histories of the DDS configuration.

1. Introduction

With the development of oil and gas in deep-water offshore areas, the safe and reliable operation of the drilling facilities of a floating platform is becoming increasingly important in offshore/ocean engineering. In the last two decades, with the need for deep-draft semisubmersibles (DDS), the challenges of vortex induced motion (VIM) has become a serious concern. It is mainly because the VIM effects can influence the structural stability, and fatigue of riser and mooring line that can lead to a larger operational downtime of the offshore platform. Under strong current conditions, deep-draft semisubmersibles are more susceptible to strong VIM effects due to the strong wake vortex interactions and the reinforcement of vortices among its multi-column configuration. Owing to highly nonlinear fluid-structure interaction, the VIM response characteristics of offshore platforms are strongly dependent on the platform dimension, the geometric arrangement, the draft condition, the oncoming current velocity, the lines-induced damping and the water depth. Effective and robust suppression of VIM response amplitudes and the manipulation of vortex wake generation of floating platforms pose serious challenges to engineers.

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Several recent studies on VIM of deep-draft semisubmersibles have mainly focused on experimental measurements [1–10]. The main emphasis of experimental campaigns was to measure the in-line (surge) and the transverse (sway) motion of the platform configurations. The model tests were generally performed in 1:50 to 1:100 scale at moderate Reynolds number range. The lock-in condition with the largest sway amplitude was revealed in these model tests at the reduced velocity around 5–8 for a DDS at a 45°-towed angle. For example, Waals et al. [1] showed the relationship between the mass ratio (the ratio of the platform mass to the displacement) and the draft condition. They also highlighted the significant yaw response of semi-submersible platforms, which was not evident in the VIM studies of the spar and mono-column platforms. Goncalves et al. [7–10] conducted a series of tests to examine the effects of current and waves on different headings and hull appendages for the VIM of a semisubmersible configuration with four square columns. In their findings, the platform with the largest transverse amplitudes, which was around 40% of the column width, occurred at 30°and 45° current headings. For the largest yaw motions of the semisubmersible, it was found at 0° current heading. They also found the periodic motion of platform by VIM undersea state tests, but the amplitude of the semi-submersible platform was lower than that of the current-only tests. The current has a dominant effect on VIM phenomena, whereas, the current-wave interactions were found to have mitigated the VIM of the platform. Liu et al. [11] carried out a series of VIM model tests to investigate the effect of interference between both circular cylinders and square cylinders in different array configurations. They concluded that the downstream cylinders experienced higher fluctuating forces due to the impingement of wake vortices, whereas the larger mean drag forces occur at the upstream columns. The vortex wake development between the columns with various spacing ratios was also explored. Liu et al. [12] further studied the influence of pontoon and column configurations on the VIM response of DDS. They found that the platform with a pontoon may disrupt the vortex shedding along the column resulting in a substantial reduction in the VIM amplitude.

Although the results of model tests can be used to estimate the VIM of full-scale DDS based on Froude scaling, their distinct difference between them is still a concern for many researchers. The differences are predominantly associated with the Reynolds number (Re) of model tests (moderate Re) and prototype (high Re) [2,6,13] and the damping caused by the risers and mooring system [14]. The current profile in a deepwater field, which is not a condition of uniform current, is also another influencing factor on the VIM response amplitude. Rijken and Leverette [15] and Ma et al. [16] performed field observations of VIM amplitude of DDS in the Gulf of Mexico. They found that the VIM response amplitudes of DDS in model tests were consistently larger than those measured in the field observations. Irani et al. [14] evaluated the full-scale mooring and riser damping characteristics and included them in the model tests. By incorporating the mooring system and risers, the VIM transverse amplitude of DDS was reduced by 30%.

There are a handful of numerical studies on the VIM analysis of DDS in literature. The reasons might stem from the difficulty of dealing with the effect of the free surface on VIM responses together with turbulence modeling and the massive requirements of computational resources. Most of the numerical studies of VIM have neglected the free surface effect to reduce the computational costs [17–20]. Chen and Chen [19] employed a Finite-Analytic Navier-Stocks (FANS) code to simulate the VIM with an overset approach. A wide range of reduced velocity was considered in their simulations, and the difference between the VIM simulations in the model scale and the full scale was highlighted. They also tested various round corner geometries and concluded that even small variations in the column geometry of DDS might generate different response amplitudes. Narendran et al. [21] used a stabilized finite element formulation with an explicit dynamic subgrid-scale model to simulate the VIM reduction of a semisubmersible due to prescribed jet flow on columns. They observed approximately 30% reduction of the fluid forces and the amplitudes of semisubmersible with the prescribed jet flow compared to that without the jet flow. The near-wake jet flow modifies the interaction of alternating vortices in the wake region and produces the near-wake stabilization effect, similar to splitter plates.

Table 1
The definition of dimensionless parameters.

Dimensionless parameters	Symbol	Non-dimensionalization
Mass ratio	m^*	$\frac{m}{\rho D_C^2}$
Reynolds number	Re	$\frac{U_\infty D_C}{\nu}$
Reduced natural frequency	F_n	$\frac{f_n D_C}{U_\infty}$
Reduced velocity	U^*	$1/F_n$
Strouhal number	St	$\frac{f_s D_C}{U_\infty}$
Time	T	$\frac{tU_\infty}{D_C}$
Cylinder or semisubmersible displacement	X_D, Y_D	$\frac{X}{D_C}, \frac{Y}{D_C}$
Drag and lift coefficients	C_d, C_l	$\frac{f_D}{0.5\rho U_\infty^2 D_C L}, \frac{f_L}{0.5\rho U_\infty^2 D^C L}$
Pressure and wall shear stress	P, τ^*	$p/\rho U_\infty{}^2$, $\tau_w/ \rho U_\infty{}^2$

For the suppression of VIV, many experimental or numerical works have been carried out for circular cylinders [5,22–29] via active and passive control techniques. For the active control method, external energy is needed to alter the vortex wake system and the boundary layer separation, e.g., suction [30,31], oscillating foil [32], synthetic jets [33] and distributed forcing [34]. The passive control for the suppression, such as helical strakes [35], passive jet [36], surface roughness [37], and splitter plate [38,39], is prevalent in these studies, which aims to modify the external shape of bluff body, to alter the separation points and to disturb the coherent vortex shedding process. For a detailed review of these suppressive methods, one can refer to Rashidi et al. [40]. Recently, Jung and Yoon [41] investigated flow over a twisted circular cylinder at a subcritical Reynolds number (Re = 3000). They found that the twisted circular cylinder can achieve a reduction in the mean drag approximately 13 and 5% compared with the results for smooth and wavy cylinders, respectively. The twisted circular cylinder causes the elongation of the shear layer and the weakening of vortical strength in the near wake, thereby the reduction of mean drag and oscillating lift force. However, the studies of VIV suppression of square cylinder are rare in the literature due to its complexity associated with sharp corners. The incidence flow angle also plays a crucial role in affecting the vortex-induced vibration of square cylinders. It can become much more complicated when we consider the VIM suppression of full-scale floating multi-columns platforms at high Reynolds number. The role of twisting on a square cylinder has not been examined in the literature. More recently, Zou et al. [42] tested a dry tree paired-column design of DDS for the VIM suppression. Antony et al. [43] experimentally and numerically tested the effect of the rounded corner of square columns at various radii on the VIM of deep-draft semisubmersibles. Different radii of square columns significantly influenced the VIM responses of deep-draft semisubmersibles as well as VIM reduction. To the best of our knowledge, the VIM of DDS with the twisted column has not been studied in the past.

In this study, we present the suppression of VIM in deep-draft multi-column floating platform via a passive control technique based on twisted square columns. The idea is to introduce continuous twisted cross-sectional surfaces along the spanwise direction of the columns. A software package, OpenFOAM is employed to simulate the nonlinear dynamic processes of vortex shedding and the turbulent wake interactions with the freely vibrating DDS configuration. The motions of the vibrating configuration are restrained by springs and free to vibrate in the surge, sway and yaw directions. The present numerical methodology is systematically assessed with the available results from