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Experimental investigation into the influences of pontoon and column configuration on vortex-induced motions of deep-draft semi-submersibles

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ABSTRACT

Deep-draft design of semi-submersibles improves vertical motions but leads to critical vortex-induced motions (VIM) attributable to fluctuating loads on columns. As characteristic components, both columns and pontoons produce complex wake interference and thus have significant influences on the VIM of semi-submersibles. This paper presents an experimental study on VIM of deep-draft semi-submersibles (DDS) to examine the effects of pontoons and column configuration. There were four test models including four-pontoon DDS, two-pontoon DDS, four-square-column structure and four-rhombic-column structure with no pontoons. A number of current headings and reduced velocities were considered. The main results reveal that the two-pontoon DDS can generate larger lift forces in comparison with the four-pontoon DDS; consequently, the transverse motion amplitudes at high reduced velocities are larger. However, the four-square-column structure with no pontoons shows the most significant transverse and yaw responses owing to the largest excitation forces induced by the well-established wake. On the other hand, similar trend and values in the transverse response are observed for the four-square-column structure at the 45° current heading and for the four-rhombic-column structure at the 0° current heading. The incidence angle related to columns has more significant effect on the VIM of DDS than that related to the platform.

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1. Introduction

A bluff body immerged in a fluid (either air or water) is susceptible to the oscillating hydrodynamic force that arises from alternating eddies or vortices shedding downstream from one side of the structure to the other, thereby causing flow-induced vibration. The vibration is known as vortex-induced motion (VIM) on large-volume offshore floating units, and is characterized mainly by horizontal motions at the free surface. A phenomenon referred to as lock-in can occur when the natural frequency of the structural response coincides with the vortex-shedding frequency. VIM remains one of the challenges in the design of offshore floating platforms, as it may pose a threat to safe and reliable operations and severely affect the fatigue life of risers and mooring systems (Cheng et al., 2011; Huang et al., 2003; Sagrilo et al., 2009).

Evaluation of VIM has been largely carried out for spar and mono-column platforms since offshore platforms were placed in the Gulf of Mexico, USA, where strong loop currents triggered significant motions stemming from vortex shedding. van Dijk et al. (2003a, 2003b) conducted model tests on the VIM of a truss spar in order to verify the effects of the hull geometry and mooring system. Typically, strakes are applied over the length of the spar hull to mitigate the VIM response. Model tests are an effective method of confirming and optimizing the strake configuration, as pointed out by Finn et al. (2003). In turn, more works have been performed to investigate strake developments, mainly by Irani and Finn (2005), Roddier et al. (2009), and Wang et al. (2009, 2010). These works demonstrated that strakes can be a good solution for VIM suppression but need to be correctly designed. The procedure of reliable model tests is regularly based on Froude scaling, resulting in Reynolds numbers at the model scale condition being much smaller than their field-scale counterparts. Mercier and Ward (2003), and Roddier et al. (2009) discussed the influence of the Reynolds number and indicated that tests performed at low Reynolds numbers showed higher amplitude levels than those at high Reynolds numbers, which implies conservative values in the early design stage. Therefore, the Reynolds number is an important consideration in the model test design for minimizing

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Nomenclature

A_p	submerged projected area
A_x	motion amplitude in the in-line direction
A_y	motion amplitude in the transverse direction
A_{yaw}	yaw motion amplitude
C	structural damping coefficient
C_D	drag force coefficient
$\bar{C}_D$	mean drag force coefficient
C_L	lift force coefficient
C_{Lrms}	root mean square value of the lift force coefficient
D	characteristic length of the structure normal to the current
f_0	natural frequency of the motion in the transverse direction in calm water
f_{0y}	natural frequency of yaw motion in calm water
F_x	hydrodynamic force acting on the platform in the in-line direction (or drag force)
F_y	hydrodynamic force acting on the platform in the transverse direction (or lift force)
f_y	response frequency of the motion in the transverse direction
f_{yaw}	response frequency of yaw motion
H	immersed column height above the pontoon
K_x	linear spring constant in the in-line direction
K_y	linear spring constant in the transverse direction
L	column width
Lp	pontoon width
m	platform mass
P	pontoon height
Rc	column radius
Re	Reynolds number
Rp	pontoon radius
S	centre-to-centre column spacing
St	Strouhal number
T_0	natural period of the motion in the transverse direction in calm water
T_{0y}	natural period of yaw motion in calm water
U	current velocity
U_r	reduced velocity
Δ	platform displacement
α	current heading
ρ	fluid density

boundary layer distortion. A number of other factors are relevant for the VIM of spar and mono-column platforms, such as the aspect ratio (the ratio between the immersed length and diameter) or draft conditions, line-induced damping, and surface waves. A brief overview of these relevant aspects of the VIM phenomenon can be found in Gonçalves et al. (2012a). The main results published in the literature presented studies of cylindrical platforms.

With the increasing dimensions of new semi-submersibles used at increasing water depth, the VIM of semi-submersibles has emerged as an important issue in offshore engineering. However, in contrast to spar platforms, where a significant body of literature has been devoted to the subject, VIM studies on semi-submersible platforms are more recent. Field observations of hull VIM occurring on DDS were described in Rijken and Leverette (2009) and Ma et al. (2013), serving to confirm the presence of VIM on semi-submersibles. In previous research on VIM of multi-column platforms, the main focus was on transverse motions, as reported by Rijken et al. (2004) and Rijken and Leverette (2008). Nevertheless, it is recognized that yaw motions may also affect the design of tendons and risers. Waals et al. (2007) presented the significant yaw response of semi-submersible platforms for the first time, which has shown to be important for semi-submersibles but was not thoroughly discussed in VIM studies of spar and mono-column platforms. The work by Waals et al. (2007) also showed the influences of the mass ratio (the ratio of the platform mass to the displacement) and draft conditions. Magee et al. (2011) pointed out lower amplitudes for lower draft conditions. Gonçalves et al. (2011, 2012b) performed a series of tests to examine the effects of different headings and hull appendages on the VIM of a semi-submersible platform with four square columns. The main findings of the work were that the largest transverse amplitudes obtained were around 40% of the column width for 30° and 45° current headings, and the largest yaw motions were verified for the 0° current heading. There are a number of other aspects that have an impact on the VIM of semi-submersibles. According to Rijken and Leverette (2008), equivalent linear damping of up to 10% did not significantly affect response amplitudes, but VIM onset was delayed. Subsequently, Martin and Rijken (2012) increased the horizontal damping level up to 17%, and their results showed a decrease of the VIM response under certain conditions. Irani et al. (2015) conducted model tests to investigate some effects on VIM response of a semi-submersible. The full-scale mooring and riser damping characteristics were systematically evaluated and included in the model test setup for the first time. The results indicated that realistic magnitudes of damping from the moorings and risers can reduce the VIM response to 30% or less, which is likely to be one explanation as to why the model test results have been consistently larger than the VIM response measured in the field. VIM model tests of semi-submersibles were also performed in the presence of both regular waves and sea states aligned to the current, such as in works by Hong et al. (2008), Stansberg (2008), and Gonçalves et al. (2013). Additionally, a comprehensive evaluation of the experimental investigations on the VIM phenomenon can be found in Fujarra et al. (2012), trying to gather a general understanding mainly about the fundamental aspects and point out a more prospective way of research.

Looking into these studies, the VIM of semi-submersible platforms is a more complex phenomenon than that of cylindrical structures owing to the wake interaction of vortices shed from multiple columns. As a consequence of vortex shedding from each column, the wake interference is different for each current heading. Gonçalves et al. (2015a) carried out VIM tests on two small-scale DDS models, one with four square rounded columns and the other one with circular columns. Different VIM responses were observed due to the column design and the different current incidence angles. The flow interference between four cylinders in a square configuration is helpful for understanding the behaviour of semi-submersible platforms for different current headings. The effects of interference between both circular-section cylinders and square-section cylinders in different array configurations were discussed by Liu et al. (2015a, 2015b). The main results showed that the downstream cylinders experienced higher fluctuating forces under the influence of unsteady wake vortices while the upstream ones were subjected to larger mean drag forces. When the spacing ratio values (the ratio between centre-to-centre spacing S and cylinder width L) fell into the typical range of semi-submersibles ($3.45 < S/L < 5.17$), the wake was well established in each cylinder and the spacing ratio had no significant effect.

Semi-submersible platforms commonly consist of multiple columns and pontoons, and their geometry implies more complex

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