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Interaction of vortex shedding processes on flow over a deep-draft semi-submersible

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ABSTRACT

A numerical study on the flow over a deep-draft semi-submersible (DDS) for both stationary and vortex-induced motions (VIM) was carried out using the computational fluid dynamics (CFD), with the aim to investigate the overall hydrodynamics of the structure. In order to study the fluid physics associated with VIM, a comprehensive numerical simulation was conducted to examine the characteristics of vortex formations, shedding processes and especially their interactions due to the multiple cylindrical columns. In addition to the vortex shedding characteristics, the drag and lift forces on each member of the overall structure were calculated. It is revealed that under 45 degree incidence, the transverse forces induced by the portside and starboard side columns are the dominant excitation forces responsible to VIM while the horizontal member - pontoons restraining VIM. In addition, the hysteresis phenomenon observed between the force and motion domains - the peak lift force occurs slightly earlier than the peak transverse motion is mainly due to the vortices shed from the upstream column move back to impinge on one of the side columns after impinging on the other side column and the symmetrical strong vortices which shed from the side columns.

1. Introduction

Vortex-Induced Motions (VIM) have been receiving continuous attention in the field of offshore exploration and exploitation as an increasing number of deep-draft floating structures have been operating in different regions around world. Deep-draft floating structures are well known for their favourable vertical motions behaviour compared with other types of floating offshore structures. However, the increases in the structure's draft can also lead to more severe VIM, which may lead to potential damage particularly causing fatigue to the mooring and riser systems.

VIM have often been observed since the Genesis Spar platform was commissioned in 1997 (Fujarra et al., 2012; Kokkinis et al., 2004). Rijken and Leverette (2009) reported VIM phenomenon on a semi-submersible in field measurements. Ma et al. (2013) also observed the presence of VIM from recent field measurements. In this aspect, a number of studies on the VIM behaviours have been carried out, including both experimental and numerical studies. On the experimental investigation side, as pointed out by Fujarra et al. (2012) in their comprehensive review, VIM are now much better understood. However, it is still lack of understanding about the VIM mechanism on multiple cylindrical structures such as the semi-submersible and the tension leg platform (TLP). The vortex shedding processes and subsequent VIM are much more complex than those of single cylindrical structures due to the multi-columns, pontoons and their interactions with the vortex shedding processes.

Waals et al. (2007) conducted several VIM tests on both DDS and TLP to examine the influences of mass ratio and draft effects. A series of model tests on a DDS were carried out by Hong et al. (2008), and the results showed that under a strong current, the DDS will have more significant VIM responses compared with the wave-current coupling condition. Rijken and Leverette (2008) experimentally studied the VIM responses of a DDS, and observed that wave and external damping can affect the VIM responses. Through their tests, it was noted that the relatively low sea states do not particularly influence the VIM responses under the so-called "lock-in" region. Moreover, the additional damping delayed the onset of VIM to a higher reduced velocity. Rijken et al. (2011) analysed the influences of SCR systems and appurtenances on VIM for a DDS. Their work showed that the appurtenances on the vertical faces of the columns and above the pontoon can alter the VIM responses. Gonçalves et al. (2012) subsequently investigated the effects of the current angle and appendages on a conventional semi-submersible. The presence of VIM on a conventional semi-submersible has been confirmed in their works. Following on from their initial outcomes, Gonçalves et al. (2013) further studied other relevant factors such as the draft conditions, the external damping and wave effects on VIM developing by performing a series of towing tank tests. Additionally, Gonçalves et al. (2015) performed

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Nomenclature

A_x/L	Non-dimensional characteristics amplitude of in-line motion
A_y/L	Non-dimensional characteristics amplitude of transverse motion
B_L	Platform width
B_T	Platform draft
C_a	Added mass coefficient
C_D	Drag force coefficient
C_L	Lift force coefficient
D	Column projected length
f	Vortex shedding frequency
f_0	Natural frequency in still water
Fr	Froude number
F_D	Hydrodynamic drag force acting on the structure
F_L, F_y	Hydrodynamic lift force acting on the structure
GCI	Grid convergence index
H	Immersed column height above the pontoon
L	Column width
m	Platform mass
m_a	Added mass
P	Pontoon height
Re	Reynolds number
rms	Root mean square
S	Distance between centre columns
St	Strouhal number
T_0	Natural periods in still water
Δt	Numerical simulation time step
U, U_c	Current speed
Ur	Reduced velocity
ρ	Fresh water density
Δ	Displacement
λ	Scale ratio
$\vec{\omega}_x$	Streamwise vorticity
$\vec{\omega}_y$	Transverse vorticity
$\vec{\omega}_z$	Spanwise vorticity
X	In-line motion
Y	Transverse motion
y^+	Y plus value

experimental tests focusing on the effects of different column designs on the VIM responses. The results showed that the circle section shaped column design has the most severe transverse motions at 0 degree flow incidence and that the square section shaped column design has the most significant transverse motion at 45 degree flow incidence. Recently, Antony et al. (2016) studied the effects of damping on VIM and investigated the force distribution on each member of the structure in detail by an experimental routine. The work done by each member was presented in their investigations. The investigations showed that for 45 degree flow incidence, when the maximum transverse VIM response occurs, three upstream columns excited VIM. The horizontal member - pontoons, however, were noted to limit the VIM responses.

In the last decade, the continued technological advances offer ever-increasing computational power, in which CFD methods are rapidly gaining popularity for VIM predictions. Lefevre et al. (2013) proposed the guidelines for undertaking the Spar VIM simulations. Tan et al. (2013) performed a series of CFD simulations for VIM on a multi-columns floater. Lee et al. (2014) studied the differences between the prototype and model VIM responses by numerical predictions. Antony et al. (2015) numerically and experimentally investigated the VIM responses of a deep-draft column stabilized floater. Their work shows that the damping effects of the riser and mooring systems are very important in CFD simulations. Vinayan et al. (2015) increased the confidence for CFD simulations on the VIM predictions of a deep-draft column stabilized floater through a series of numerical simulations on a PC-semi with different drafts and arrangements. Liu et al. (2015) numerically investigated the effects of pontoon on hydrodynamic forces for a stationary DDS model and revealed that the DDS with the different numbers of pontoons affects both drag and lift forces on the stationary structures. Koop et al. (2016) carried out a series of CFD studies to illustrate the results of the scale and damping effects for VIM on a semi-submersible. Their work showed that the scale effects at 45 degree incidence are less than that at 0 degree incidence. Under 45 degree incidence, the VIM response at prototype Reynolds number is found to be similar compared with that at model scale Reynolds number. Similar observation was also reported by Lee et al. (2014).

2. Numerical simulation

2.1. Computational overview

A comprehensive numerical study was conducted in this section, with the aim to examine the vortex shedding characteristics and the associated fluid dynamics. The numerical schemes are introduced and followed by a sensitivity assessment in order to perform a computationally efficient numerical analysis.

The detached eddy simulation (DES) method was used in this study. For the DES model, the improved delayed detached eddy simulation (IDDES) model (Shur et al., 2008) with the Spalart-Almaras (SA) (Spalart et al., 1997) was used. All the simulations were carried out by using a Star-CCM+ 9 package.

The principle dimensions of the deep-draft semi-submersible analysed in this section are given in Table 1 and shown in Fig. 1. Two models with different scale ratios are simulated in the present study, with resulting flow conditions ranging from Reynolds number 3×10^5 to 1.1×10^6. Model I is used for the stationary structure simulations where the model scale ratio is 1:128. Model II is for the VIM simulations where the model scale ratio is 1:64. For all simulations, the computational domain $9B_L \times 6B_L \times 3B_T$ is used (where B_L is the overall hull width of the semi-submersible and B_T is the draft of the semi-submersible) based on the convergence study. The computational domain were $6B_L \times 4.5B_L \times 2.8B_T$ and $5B_L \times 4B_L \times 2.2B_T$ in the studies by Lee et al. (2014). Tan et al. (2013) performed their analysis using a $27B_L \times 18B_L \times 6.5B_T$ domain and Liu et al. (2015) used a $11B_L \times 6B_L \times 3B_T$ domain. Koop et al. (2016) chose a $10B_L \times 6B_T$ cylindrical domain. Compared with aforementioned computational domain sizes, a $9B_L \times 6B_L \times 3B_T$ domain (see Fig. 2) was considered to be large enough to eliminate the far field effects from the boundaries and the three-dimensional effects from a spanwise cross flow direction.

The polyhedral mesh (CD-adapco, 2014) was used in the present study. The overall elements mesh is shown at a middle-depth horizontal layer in Fig. 3. In the present study, a near wall refinement method named "Prism Layer Mesher" is adopted. The y^+ values are

Table 1
Main characteristics of the DDS unit (The model I is the stationary model which presents scale ratio as 1:128, and the model II is the VIM model which presents scale ratio as 1:64).

	Prototype (m)	Model I (m)	Model II (m)
Distance between centre columns (*S*)	72.5	0.567	1.133
Column width (*L*)	19.5	0.152	0.305
Immersed column height above the pontoon (*H*)	37.0	0.289	0.578
Pontoon height (*P*)	10.0	0.078	0.156