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Experimental and numerical study on vortex-induced motions of a deep-draft semi-submersible

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ABSTRACT

An experimental study on vortex-induced motions (VIM) of a deep-draft semi-submersible (DDS) was carried out in a towing tank, with the aim to investigate the VIM effects on the overall hydrodynamics of the structure. In order to study the fluid physics associated with VIM of the DDS, a comprehensive numerical simulation was conducted to examine the characteristics of vortex shedding processes and their interactions due to multiple cylindrical columns. The experimental measurements were obtained for horizontal plane motions including transverse, in-line and yaw motions as well as drag and lift forces on the structure. Spectral analysis was further carried out based on the recorded force time history. These data were subsequently used to validate the numerical model. Detailed numerical results on the vortex flow characteristics revealed that during the "lock-in", the vortex shedding processes of the upstream columns enhance the vortex shedding processes of the downstream columns leading to the rapid increase of the magnitude of VIM. In addition to the experimental measurements, for the two uniform flow incidences (0° and 45°) investigated, comprehensive numerical data of the parametric study on the VIM characteristics at a wide range of current strength will also serve as quality benchmarks for future study and provide guidance for practical design.

1. Introduction

Along with the continuing developments in the field of offshore technology, an increasing number of deep-draft floating structures have been fabricated and installed in different deep-water regions around the world such as the Gulf of Mexico (GoM). Deep-draft floating structures have favourable behaviour in vertical plane motions and therefore are easy to accommodate steel risers. Most of the deep-draft floating structures consist of four vertical cylindrical columns with connecting deck and lower pontoon type members. When a current flows past the columns, a complex issue named VIM can generate strong cyclic dynamic effects on the floaters, especially when the vortex shedding frequency is approaching the natural frequency of the structure leading to the so-called "lock-in" phenomenon. VIM is a cyclic rigid body motion induced by vortex shedding on a large floating structure. It is a common practice to increase the draft of the columns in order to achieve the desired hydrodynamic characteristics in vertical plane motions. However, the increase in columns' draft can also lead to more severe VIM. In this context, both experimental and numerical methods are used to investigate the mechanism of VIM and the effects on overall hydrodynamics of the DDS.

In deep-water developments, a favourable motion response of the floater is critical to the safe operations of top-tensioned facilities, as well as the fatigue life of the mooring system and the risers. In the GoM, due to the strong loop currents, VIM have been often observed since the Genesis Spar platform commissioned in 1997 [1,2]. Finn et al. [3] and van Dijk et al. [4] investigated VIM effects on different designs of Spar platform. To reduce the potential problems, spiral strakes attached to the hull were examined as an acceptable design approach in order to minimize the VIM phenomenon. Several experiments on Spar VIM were carried out to mitigate VIM, such as Irani and Finn [5], Halkyard et al. [6], Wang et al. [7] and Wang et al. [8]. In the last decade, computational fluid dynamics (CFD) provided a reasonable alternative way to predict VIM on Spar platforms. Halkyard et al. [9], Oakley and Constantinides [10] combined the results from experimental and numerical studies in order to compare the VIM effects on Spar from experimental measurements and CFD predictions. Thiagarajan et al. [11] further investigated a bare cylinder and a cylinder with strakes to

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Nomenclature

A	Projected area
A_x/L	Non-dimensional characteristics amplitude of in-line motion
A_y/L	Non-dimensional characteristics amplitude of transverse motion
$A_{1/3}/L$	Non-dimensional significant values of the transverse peaks
B_L	Platform width
B_T	Platform draft
C	Structural damping
C_D	Drag force coefficient
C_L	Lift force coefficient
D	Column projected width
f_s	Vortex shedding frequency
f_0	Natural frequency in clam water
Fr	Froude number
F_D, F_x	Hydrodynamic drag force acting on the structure
F_L, F_y	Hydrodynamic lift force acting on the structure
g	Acceleration of gravity
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
P	Pontoon height
Re	Reynolds number
rms	Root mean square
S	Distance between centre columns
St	Strouhal number
T_0	Natural periods in calm water
Δt	Numerical simulation time step
U, U_c	Current speed
u_*	Friction velocity at the nearest wall
Ur	Reduced velocity
ρ	Fresh water density
Δ	Displacement
Δy_1	First layer thickness
λ	Scale ratio
θ	Attack angle; flow incidence
ν	Kinematic viscosity of the fresh water
ω	Vorticity magnitude
x, X	In-line motion
y, Y	Transverse motion
y^+	Y plus value

study the VIM phenomenon. A guideline of numerical simulation of the VIM on the Spar platform was proposed by Lefevre et al. [12].

The presence of the VIM phenomenon on more complex multiple cylindrical structures, such as tension-leg platform (TLP) and DDS, is confirmed from field measurements made by Rijken and Leverette [13]. Waals et al. [14] studied the draft effects on VIM. When the draft changed from a typical conventional semi-submersible to a DDS, significant increases of VIM were observed.

Table 2
Main characteristics of the DDS unit.

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

Hong et al. [15] also reported that deep-draft floaters experience strong VIM. Gonçalves et al. [16] found that even the conventional semi-submersible with appendages can also suffer from VIM. For most of the multiple cylindrical structures, VIM were predicted by undertaking the aforementioned experiments. CFD is still rarely applied for the study on VIM of multiple cylindrical structures at present time due to its computational intensity. Among very limited recent studies reported in the literature, Tan et al. [17] numerically predicted VIM on a multi-column floater. Lee et al. [18] investigated the VIM responses on both model and prototype DDSs by using CFD tools. Tan et al. [19] conducted that model tests are necessary in order to validate the numerical model by using experimental results obtained from a towing tank.

As pointed out by Fujarra et al. [2] in their comprehensive review, after one decade of experimental investigations, VIM on single or multiple cylindrical structures are now much better understood. Details about the deep-draft structures, which were studied during the last decade, are summarised in Table 1 and compared with the outcomes from the present study to emphasize and confirm the results. Fig. 1 shows the definition of the dimensions for the configurations.

2. Model test

2.1. Model set-up

The experimental set-up is characterized by a DDS model supported above the waterline by four low friction air bearings and a set of equivalent horizontal mooring springs in the Zhejiang Ocean University towing tank with dimension of 130 × 6 × 3 m (length × width × depth). The DDS model and experimental set-up in the towing tank are shown in Figs. 2 and 3.

It is important for keeping the similarity between prototype and model. Thus, the Froude scaling approach recommended by van Dijk et al. [23] was used. It is essential to note that the Reynolds number ($Re = UD/\nu$, where U is the current velocity, D is the projected width of the column and ν is the kinematic viscosity of the fresh water) for the prototype DDS is in the order of 10^7 while the Reynolds number at model scale is significantly lower. Since the DDS model is a relatively bluff body, the flow is expected to separate at the corners of the columns. The vortex shedding phenomenon is mostly independent of the Reynolds number from the transcritical region to the subcritical region. The scale effects for square section shaped structure are less than that for circle section shaped structures [2]. The main characteristics of the DDS model are shown in Table 2 with the dimensions defined in Fig. 1.

Table 1
Summary of the studies on VIM of deep-draft structures ("*" is the numerical result).

	λ	*Mass ratio*	H/L	S/L	H/P	Re	Ur	A_y/L at 45°
Waals et al. [14]	1:70	0.83	1.75	4.14	2.33	6×10^3∼7×10^4	4.0∼40.0	0.32
Rijken and Leverette [20]	1:50	–	2.18	3.75	4.83	∼10^5	1.0∼15.0	0.48
Rijken et al. [21]	1:48	–	1.71	4.04	3.04	3×10^4 ∼ 3×10^5	5.0∼9.0	0.64 [16]
Tahar and Finn [22]	1:56	0.77	1.74	3.20	4.00	∼5×10^5	2.0∼15.0	0.33
Lee et al. [18]	1:67	–	1.78	3.50	3.62	2×10^4 ∼ 9×10^4	4.0∼20.0	0.4*
Present study	1:64	0.91	1.90	3.72	3.70	2×10^4 ∼ 1×10^5	3.4∼20.2	0.742/0.751*