ABSTRACT

Vortex-Induced Motions (VIM) is a key issue for deep draft column stabilized floaters (DDCSF). An example of DDCSF is the concept design called Paired-Column semi-submersible (PC-Semi) with a pair of columns instead of single column at four corners of the platforms. The complex multi-column design involves several extra design parameters such as paired-column gaps and column cross-section areas than conventional semi-submersibles. These parameters can be tuned to mitigate dynamic response to waves and currents. However, it is expensive to perform parametric study of geometric variations by means of experiments.

In the present work, CFD method is utilized to investigate the VIM characteristics for different geometrical variations of the PC-Semi. An in-house CFD code naoe-FOAM-SJTU, which is developed on top of the open source framework OpenFOAM, is used for all numerical simulations. Delayed detached-eddy simulation (DDES) is used for turbulence modeling with massively separated flow. A geometry model scaled at 1:54 from MARIN is select as the baseline model for parametric study. VIM simulations of the baseline model is firstly carried out and compared with experiments to validate the current CFD code. After that, VIM characteristics of paired-column gaps geometrical variations are numerically investigated. Motions of the platform and hydrodynamic forces on columns are compared and analyzed. The ability of CFD method in optimizing geometric design parameters on mitigating VIM response for deep-draft semi-submersibles is demonstrated.

INTRODUCTION

As the increasing of global energy demand, the oil and gas industry has moved to deepwater and ultra-deepwater (more than 1,500 meters water depth) areas. Deepwater has been relatively more expensive and more technically challenging for operators to explore and drill oil and gas resources. There is an urgent demand for dry tree offshore platforms which can operate in deep and ultra-deep water, and provides larger deck space and payloads than mono-column hull platform such as Spar. Deep-draft semi-submersible (DDS) is an attractive alternative as it meets the aforementioned requirements and has better heave performance than conventional semi-submersible. However, there comes another serious issue with the deep draft column stabilized floaters (DDCSF). As pointed out by Waals et al. [1], DDS has a more pronounced vortex-induced motions (VIM) response than conventional semi-submersibles. Several efforts have been made to mitigate DDS VIM responses. Xu [2] proposed a next generation semi-submersible design with blisters attached to columns which effectively break the vortex shedding coherence along the column length and hence suppress VIM. Model tests was performed at FORCE Technology’s towing tank and the results show that VIM response is reduced by more than 50%. Xu et al. [3] called the new design HVS (Heave and VIM Suppressed) semi-submersible and performed model test and CFD validation on the VIM response of the HVS semi-submersible. They simulated different blister and pontoon size and an additional case of conventional hull with strakes on columns.

On the other hand, Zou et al. [4] introduced an eight-column design semi-submersible called paired-column semi-submersible.
submersible (PC-Semi) concept to public. The columns have larger slenderness ratio than DDS. It hypothesized to have more pronounced VIM response than DDS. However, the unprecedented design will more likely to receive unique VIM response characteristics.

BACKGROUND OF MODEL TEST
To better understanding the VIM characteristics of PC-Semi, the RPSEA has funded a project of model test for PC-Semi. Two sets of different scale model test are performed by Zou et al. [5,6]. The test model with small scale (1:160) was towed in the Berkeley Towing Tank. The larger one (1:54) was performed at MARIN. In this paper, the MARIN model was selected for CFD simulation. The main particulars of the PC-Semi are listed in Table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Notation (unit)</th>
<th>Prototype</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall width</td>
<td>B (m)</td>
<td>113.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Draft</td>
<td>T (m)</td>
<td>53.3</td>
<td>0.987</td>
</tr>
<tr>
<td>Immersed column height</td>
<td>H (m)</td>
<td>44.6</td>
<td>0.826</td>
</tr>
<tr>
<td>Outer column size</td>
<td>LOC × WOC (m)</td>
<td>13.4 × 14</td>
<td>0.248 × 0.259</td>
</tr>
<tr>
<td>Outer column characteristic length</td>
<td>D (m)</td>
<td>19.4</td>
<td>0.36</td>
</tr>
<tr>
<td>Inner column size</td>
<td>LIC × WIC (m)</td>
<td>10.4 × 14</td>
<td>0.192 × 0.259</td>
</tr>
<tr>
<td>Inner column characteristic length</td>
<td>d (m)</td>
<td>17.4</td>
<td>0.32</td>
</tr>
<tr>
<td>Center-to-center distance of outer column</td>
<td>SOC (m)</td>
<td>96.0</td>
<td>1.78</td>
</tr>
<tr>
<td>Center-to-center distance of inner column</td>
<td>SIC (m)</td>
<td>50.3</td>
<td>0.93</td>
</tr>
<tr>
<td>Pontoon height</td>
<td>P (m)</td>
<td>8.7</td>
<td>0.16</td>
</tr>
<tr>
<td>Pontoon width</td>
<td>Lp (m)</td>
<td>12.5</td>
<td>0.23</td>
</tr>
</tbody>
</table>

As noted in the table, the sizes of outer column (OC) and inner column (IC) are different. The non-dimensioned reduced velocity, which is an important characteristic parameter that dominant VIM response, was defined by the OC’s characteristic length

\[ U_r = \frac{UT_u}{D} \]  

In VIM model test, the model was constraint in the horizontal plane and only dominant motions (e.g., surge, sway and yaw) are allowed. This is achieved by utilizing a frictionless air bearing device. The mass and mooring stiffness from the model test are provided in Table 2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>490.2</td>
<td>kg</td>
</tr>
<tr>
<td>Radius of gyration</td>
<td>0.77593</td>
<td>m</td>
</tr>
<tr>
<td>Transverse stiffness</td>
<td>173.98</td>
<td>N/m</td>
</tr>
<tr>
<td>Yaw stiffness</td>
<td>5.23</td>
<td>Nm/deg</td>
</tr>
<tr>
<td>Transverse natural period</td>
<td>15.45</td>
<td>s</td>
</tr>
<tr>
<td>Yaw natural period</td>
<td>9.32</td>
<td>s</td>
</tr>
</tbody>
</table>

GAP VARIATION DEFINITION
Figure 1 shows the plane view of baseline model that was used in MARIN’s experiments. The gap of baseline model in prototype is 20.4m.

Figure 1: Plane view of the baseline model

Besides baseline model, another two PC-Semi variations with different gaps were constructed to investigate the column gap influence on VIM response. These variations keep the IC invariant and change the position of OC and the length of pontoon connected to IC and OC. Figure 2 shows the three different gap variations. Here, the three configurations are assumed to have the same mass properties.

Figure 2: Gap definition for hull configurations

COMPUTATIONAL OVERVIEW
The in-house CFD solver naoe-FOAM-SJTU [7] developed on top of the open source framework OpenFOAM...
was utilized for all simulations. It was derived from *interDyMFoam* (a standard solver from OpenFOAM) with an in-house 6DoF solver based on Euler angles and a wave generation and absorption module for various types of regular and irregular waves common in marine and ocean engineering. Furthermore, the dynamic overset capability was implemented into the solver in coupled with Suggar [8]. It was recently upgraded to use Suggar++ [9], which is an improved version of Suggar.

VIM involves strong unsteady effects such as flow separations and vortex shedding which should be treated carefully. It is well-known that the statistical turbulence modeling methods such as the Reynolds Averaged Navier-Stokes (RANS) employ statistical averaging procedure to model the mean flow quantities. The turbulent fluctuations are eliminated during averaging so that it is not appropriate to use these kinds of methods for VIM simulations. The large-eddy simulation (LES) could capture the unsteady characteristics of the turbulent scales very well. It is, however, too costly for wall-bounded high Reynolds number flow to resolve eddies in the thinner boundary layers. Detached-eddy simulation (DES) shows the potential of predicting massively separated flow with good accuracy and low cost. It employs RANS near wall and switches to LES subgrid-scale-like behavior after flow separation. In the current study, delayed DES (DDES) based on the two-equation shear stress transport (SST) [10] model was used for turbulence modeling.

The 6DoF rigid body motion solver in naoe-FOAM-SJTU is flexible to perform predicted and/or prescribed motions. It can be tuned to constrain arbitrary degrees of freedom. To be consistent with air bearing device settings in model test, only surge, sway and yaw motions are allowed in simulations. In coupled with the rigid body motion solver, a dynamic mesh strategy based on overset grid was employed. The current overset grid consists of two mesh-blocks, the hull mesh-block which translates and rotates along with the model in horizontal plane, and the background mesh-block which is fixed. The two mesh-blocks do not share any points, edges or faces. Flow information are exchanged by interpolation using domain connectivity information (DCI) generated by Suggar++.

The computational domain is set as $7B \times 4B \times 3.5T$ (length $\times$ width $\times$ depth) for all simulations as shown in Figure 3. Here, $B$ is the overall width and $T$ is the draft of the hull. In previous studies of DDS VIM, the computational domain size are slightly different. Kim et al. [11] used a domain of $14B \times 12B \times 4.5T$. Tan et al. [12] adopted $27B \times 18B \times 6T$ as the domain size. Meanwhile, smaller domain size are also acceptable. For example, Lee et al. [13] numerically studied VIM response of a DDS using computational domains of $6B \times 4.5B \times 2.8T$ and $5B \times 4B \times 2.2T$. Liang and Tao [14] utilized a $9B \times 6B \times 3T$ domain in their studies of vortex shedding process of flow around a DDS. It is reasonable that the current domain size is large enough to eliminate effect from boundaries at two lateral sides, downstream and bottom.

![Figure 3: Computational domain and boundaries](image1)

Figure 3: Computational domain and boundaries

Velocity inlet and pressure outlet are set as boundary conditions. Specifically, the velocity is set as $(U_t, 0, 0)$ ($U_t$ the current velocity) at inlet and zero gradient at outlet. As for pressure, a zero gradient boundary condition and zero value is set for inlet and outlet, respectively. Other boundaries of the domain including top, bottom and two lateral sides are set as symmetry. Note that free surface effects are neglected due to low Froude number condition. Furthermore, for the hull surface, a no-slip boundary condition is prescribed which assigns the velocity to $U_{wall}$ and the pressure to zero normal gradient.

Figure 4 shows the slice at $z/H=-0.5$ of overset mesh for small gap case. Red and blue grid represents background and hull mesh-block, respectively. The near hull and wake regions are refined in the hull mesh-block in order to capture the boundary layers and wake structures induced by flow separations. Four different levels of refinement zones are utilized to archive higher accuracy in critical regions. In the vicinity of columns and pontoons, 10 prism cell layers are applied to hull boundary to capture the boundary layer development. For all cases, the non-dimensioned wall distance of the first layer satisfies $y^+<1$, which makes sure the first layer cells are located in the viscous sublayer. The total cell number is 2.89 million.

![Figure 4: Slice at $z/H=-0.5$ of an example mesh](image2)

Figure 4: Slice at $z/H=-0.5$ of an example mesh

Grid and time step convergence study has been performed for large gap case at reduced velocity $U_r=5$. Three grids (G1,
G2 and G3) and three time steps (T1, T2 and T3) are selected for convergence study. The results are listed in Table 3. Two vital statistic parameters to describe VIM characteristics are compared here. The nominal sway response $A_y/D$ and zero crossing period $T_z$ are calculated from 14 response cycles after excluding initial response stage. The relative changes between G2 and G3 for both $A_y/D$ and $T_z$ are under 5%. Similarity, the relative changes between time step cases T2 and T3 are below 3%. The mesh G2 and time step T2 are chosen for the following VIM simulations. Simulation time for all cases are 300s, corresponding to approximately 20 VIM cycles.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cell No. (million)</th>
<th>Time step ($\Delta t \cdot U/D$)</th>
<th>$A_y/D$</th>
<th>$T_z$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>1.04</td>
<td>0.0064</td>
<td>0.295</td>
<td>13.76</td>
</tr>
<tr>
<td>G2</td>
<td>2.89</td>
<td>0.0064</td>
<td>0.324</td>
<td>15.00</td>
</tr>
<tr>
<td>G3</td>
<td>6.25</td>
<td>0.0064</td>
<td>0.331</td>
<td>15.68</td>
</tr>
<tr>
<td>T1</td>
<td>2.89</td>
<td>0.0128</td>
<td>0.349</td>
<td>14.98</td>
</tr>
<tr>
<td>T2</td>
<td>2.89</td>
<td>0.0064</td>
<td>0.324</td>
<td>15.00</td>
</tr>
<tr>
<td>T3</td>
<td>2.89</td>
<td>0.0032</td>
<td>0.317</td>
<td>14.75</td>
</tr>
</tbody>
</table>

The PIMPLE (merged PISO-SIMPLE) algorithm is used to solve the coupled pressure and velocity. PIMPLE treats every single time step as steady-state and performs SIMPLE correctors outside the PISO loop. It can run robustly at larger time step where Courant number is larger than one. All simulations are performed on a high-performance computing cluster equipped with Intel Xeon E5-2680v2 CPUs and interconnected with Infiniband FDR switches. Using 2 nodes or 40 CPU cores, the execution time is 36 hours for each case.

RESULTS AND DISCUSSIONS

VIM response especially transverse motion is non-stationary and not uniform amplitude. It is more appropriate to use statistical parameters to describe VIM. The non-dimensional nominal transverse motion $A_y/D = \sqrt{\text{RMS}(y/D)}$ is used in this paper. The first 100 seconds of the VIM simulation (approximately 6 VIM cycles) are considered as the flow developing stage and are excluded from the statistics.

Figure 5 shows the comparison of current CFD and MARIN’s experimental results. Overall, the predicted nominal transverse response and zero crossing period shows good results with experiment. However, it’s worth noting that there is a large discrepancy between the repeat runs for experiments at $U_r = 5$. Similar results were observed by Zhao and Wan [15] in their CFD studies of PC-Semi VIM. Two distinguished VIM response regimes exist at $U_r = 5$.

Figure 6 shows the vortex structures non-dimensioned by OC diameter and current velocity at different time step of $U_r = 5$. Flow reattachment to the backward hull surface of the upstream columns after flow separation are observed in the right figure which represents fully developed flow field. The reattachment reduces the backward surface pressure and amplifies VIM response.
Figure 7 and Figure 8 shows the nominal transverse and yaw motions for three different column gaps variations. At $U_r=5$, as the column gap reduces, the transverse motion response decreases. This can be explained by Figure 9, which illustrated the velocity, vorticity and pressure contour on a horizontal plane at $z/H=0.5$. Velocities and vorticities are nondimensionalized by OC’s diameter and current velocity. Vortices shed from upstream column directly impinge on the downstream column, then collide and interact with the vortices shed from downstream columns. These vortices quickly break into small eddies in the wake region of downstream columns. In Figure 9(a), small gap shows strong interactions of velocity field between upstream OCs and ICs are found. On the contrary, high velocity gradient field are observed in Figure 9(b), result a high vorticity region and even flow reattachment on the backward on upstream columns, as shown in Figure 9(d). Moreover, (d) and (f) show obvious synchronization behaviors of vortex shedding and pressure change between the four upstream columns.

VIM motions are presented here using spectral analysis. It is well-known that the fast Fourier transform (FFT) assumes the signal is periodic in the window which it is applied. In reality, the signal of motions and forces in VIM is non-stationary which is not suitable to use FFT for analyzing. Wavelet analysis is often used to present the frequency response of a non-stationary signal. However, wavelet transform convolves a signal with a predefined mother wavelet, which makes the definition of the energy-frequency-time distribution difficult. The Hilbert–Huang transform (HHT) [16], on the other hand, does not require any convolution and is totally data-driven. The main part of HHT is empirical mode decomposition (EMD), which transform the original signal into a finite set of intrinsic mode functions (IMFs). After that,
Hilbert spectral analysis (HSA) is applied to these IMFs to identify the localized features. Details for the process of EMD and HSA can be found in Huang et al. [17].

Taking the VIM response of mid gap PC-Semi at \(U_r=7\) as an example. Figure 10 shows the IMFs decomposed from non-dimensional transverse motion by EMD. It clearly shows that the first IMF dominants the energy in the transverse motion. However, looking at the IMFs generated from non-dimensional inline motion in Figure 11, the energy level are concentrated on the first and second IMF. Similar results are observed by Gonçalves et al. [18] in their experimental study for a monocolumn production, storage, and offloading system (MPSO). Gonçalves attributed this to the stronger non-stationary signal behavior.

Figure 10: IMFs and residual (trend) decomposed from the non-dimensioned transverse motion \(y/D\) by EMD

Figure 11: IMFs and residual (trend) decomposed from the non-dimensioned inline motion \(x/D\) by EMD

Figure 12 plots the instantaneous phase of transverse motion and hydrodynamic forces on a pair of upstream columns. There is always a relative phase difference between motion and total force. Notably at \(U_r=5\) for large gap PC-Semi, the phase angles of hydrodynamic force on two upstream columns are perfectly matched with the transverse motion, indicating a strong synchronization in the system, which can also be proved in Figure 9(d) and (f). With the increasing of reduced velocity, the frequency of hydrodynamic force on column increases faster than motions and overall hydrodynamic force on the model. The out-of-sync column forces at high reduced velocities may also explain the increasing of yaw motions.

CONCLUSIONS

In this paper, VIM characteristics of three different geometry variations on PC-Semi’s paired-column gaps have been numerically investigated. The CFD simulations are performed by an in-house CFD solver naoe-FOAM-SJTU.

The transverse motion and zero-crossing period of the present CFD shows good agreement with experiments, which implies the current numerical approach is valid and efficient for VIM problems. Parametric studies of gap variation show large discrepancy of transverse motions at \(U_r=5\), but not so much at higher reduced velocities. Flow visualization and HHT analysis both show the strong synchronization in the system at \(U_r=5\) for large gap. As for small gap model, the column may be treated as one single large column which shifts the “lock-in” range to larger \(U_r\).

This study tries to understand the VIM phenomena from the perspective of transverse motions and forces on each column by using spectral analysis method. It reveals some
aspects of how the unique paired-column design affects the VIM response. However, a comprehensive analysis on the vortex shedding and wake interaction and its impacts on columns is still needed.

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