The Dynamic Response of Floating Offshore Wind Turbine
Platform in Wave-current Condition

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Abstract

In this paper, the fluid-structure interaction (FSI) of floating offshore wind turbine
(FOWT) platforms under complex ocean conditions is investigated using OpenFOAM
and in-house developed models. Two types of FOWT platform, i.e., a semi-submersible
platform and a barge platform, are studied for their dynamic responses to either wave
or current. Results reveal that a semi-submersible platform exhibits larger cross-flow
(CF) motion and lock-in phenomenon, while a barge platform experiences smaller
motion with no significant lock-in within the velocity range examined. The combined
wave-current conditions are further studied for the semi-submersible platform, with
different angles between wave and current, the current speeds and wave parameters.
Unlike other investigations focusing on colinear wave-current interaction, in which the
waves usually mitigate vortex-induced-motion (VIM), here, we find that waves might
lead to an enhanced VIM with a large angle between current and wave. The evaluation
on the interaction effect factor (IEF) shows that the largest wave height in the lock-in
region doesn’t lead to the most dangerous scenario, herein, the largest platform motion.
Instead, a smaller wave height with large wave period can induce even larger motion.

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I. INTRODUCTION

The increasing demand for renewable energy has led to the growth of wind energy, with floating offshore wind turbines (FOWTs) being a promising solution for generating energy in deep water where traditional turbines are unable to operate. FOWTs also benefit from greater and more consistent wind resources in deeper water and eliminate the visual impact associated with near-shore turbines. Several FOWT designs, such as OC4 DeepCwind, Hywind, TetraSpar, among others, have been developed extensively. For FOWTs, their applications are expected to expand to more diverse locations, which may present more complex sea states, resulting in more significant challenges in ensuring adequate stability, power output and reliability under diverse operating conditions, for the design of FOWT, and this has been investigated extensively both numerically and experimentally in our previous studies and other researchers.

In addition to wave-platform-interaction, the appearance of water current in some areas of sea may lead to additional platform motion, known as Vortex-induced Motion (VIM). This phenomenon usually occurs when a cylindrical structure or a bluff body is moored or elastically mounted in the presence of current. The amplitude of the response can be particularly high when the frequency of vortex shedding becomes synchronized with the structure vibration frequency. Such synchronization is known as lock-in, and it occurs over a wide range of flow velocity.

The VIM of cylinders and monocolumn platforms has been extensively studied experimentally. It was found that the platform follows a classic 8-shaped orbital trajectory for some cases. This low-frequency response, especially in cross-flow (CF) direction, may result in potential damage to FOWT’s mooring system and cause fatigue problem. The in-line (IL) motion is relatively small compared to that in CF direction.

Compared to wave, current-platform-interaction gets less attention during the design process of FOWT platform. This is partially because the water current caused by wind has a characteristic speed of 0.05 to 0.5 m/s, which is less than the minimal threshold required for VIM to occur. The speed of tidal current is usually larger than surface current, whose maximum value can be as large as 4.5 m/s as observed in some channel areas, with a water depth ranging from 40-110 m, but this velocity is much smaller in deep, open ocean. However, in certain locations, such as the Gulf Stream, the current velocity at the free surface can exceed 2 m/s, which is sufficiently large to induce VIM for a floating platform having cylinders, such as SPAR. The semi-submersible (SS) platform, on the other hand, has a smaller aspect ratio (draft/characteristic length), which has been investigated by Gonçalves et al. Their experimental findings confirmed that VIM occurs even at a relatively low current speed for two SS platforms with different geometric dimensions. Other research regarding VIM of different
platforms can also be found recently\textsuperscript{27,28}. Due to the inherent disadvantage of potential-
flow theory method, in which fluid is assumed irrotational and non-viscous, numerical
analysis involving offshore structure-fluid interaction has been conducted using finite
element method\textsuperscript{29} (FEM) or computational fluid dynamics (CFD) method. The later
considers viscosity of fluid directly by solving Navier-stokes equation with turbulence
models\textsuperscript{30-34}. In their studies, the formation and shedding of the vortices due to VIM is
clearly observed.

A combined colinear wave-current interaction with four square columns platform is
further studied experimentally\textsuperscript{35,36}. The findings indicated that the adding of wave
sometimes tends to have little impact on VIM, while mitigating VIM entirely in other
cases. This is further observed in the studies of Maximiano et al.\textsuperscript{37} and Li et al.\textsuperscript{38}. A
detailed examination on the fluid flow vorticity field indicated that the reduced
amplitude of VIM is caused by the wave interaction with current and platform, changing
the vortex shedding pattern, and thus the vortex shedding frequency.

While VIM mitigation by waves is observed in past studies, most of existing
investigations are focused on the flow condition where wave and current are aligned.
In reality, it is very likely the angle between the wave and current can vary in different
sea states. For instance, in the project of LIFE50+ for a 10MW wind turbine, the wave
and current inter-angle ranges from 82.5 to 150 degrees at three deployment sites with
a water depth over 50m\textsuperscript{39}. It is therefore critical to understand the wave-current-
structure-interaction under various angles and flow conditions.

In this paper, the dynamic response of the floating platform in complex sea conditions
is numerically studied using a high-fidelity CFD tool\textsuperscript{40}. We aim at illustrating the
underlying mechanisms that are related to the wave-current interaction with FOWT
platforms using this tool. The rest of the paper is organized as follows. The numerical
method including the governing equations of the fluid dynamics, the structural
dynamics, and the mooring system, will firstly be presented in section II, together with
a description of the physical problem to be studied and the parameters for both OC4
DeepCwind platform by National Renewable Energy Laboratory (NREL) and the BW
IDEOL platform with Électricité de France. Section III displays the numerical results,
where the wave-only, current-only conditions are firstly examined for two FOWT
platforms as comparisons. Then the combined wave-current condition studies for the
OC4 platform at various wave-current angles and wave parameters are conducted, and
the conclusions are drawn in the last section.

II. PROBLEM STATEMENT

The wave-current interaction of FOWT platform is simulated using an integrated
toolbox based on OpenFOAM code. Particularly, the solver is a multiphase flow solver
interFoam in OpenFOAM. To apply mooring lines as restraints, an in-house code is integrated into interFoam. Additionally, a wave generation boundary condition and active wave absorbing scheme are implemented in the simulation.

A. Numerical method

For a fluid problem, the Reynolds number $Re = \frac{UL}{\nu}$ is one non-dimensional parameter to differentiate between laminar and turbulent flows, where $U$ is the fluid velocity, $L$ is the characteristic length of the structure and $\nu$ is the kinematic viscosity. In this study, $Re$ ranges from 8000 to 40000 for current-only cases, thus turbulence model is needed. The vortex shedding and the flow field surrounding structure are essential components in understanding VIM. As such, it’s crucial to capture a precise structure of the vortex, a task which is normally not optimally accomplished by utilizing the standard Reynolds-Averaged Navier-Stokes (RANS) model due to its highly numerical dissipation. In this study, Large Eddy Simulation (LES) wall-adapted local eddy-viscosity (WALE) model is used. In LES, the largest, most energy-containing turbulent structures (large eddies) are explicitly resolved on the computational grid, while the smaller, more isotropic structures (small eddies or sub-grid scales) are modeled. The unsteady, incompressible Navier-Stokes equations are solved in LES model:

\[
\frac{\partial \bar{u}_i}{\partial t} = 0 \tag{1}
\]

\[
\frac{\partial \bar{u}_i}{\partial t} \left( \bar{u}_i - u_i \right) \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_j} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial x_j}{\partial x_i} \frac{\partial \bar{u}_i}{\partial x_j} - g, \tag{2}
\]

where $u_i$ is the velocity component in the $i$-direction, $\bar{u}_i$ is the filtered velocity, $u_g$ is the speed of the motion of the mesh grid. $\rho$ is the density, $p$ denotes dynamic pressure. $g$ is gravity acceleration and $t$ is the time. $\nu$ is the kinematic viscosity of the fluid and $\tau_i$ is the subgrid-scale stress as following:

\[
\tau_i = \bar{u}_i u_i - \bar{u}_i \bar{u}_i \tag{3}
\]

In order to capture the fluid motion at the air-water free surface, the Volume of Fluid (VOF) method is applied to solve the two-phase flow problem. The volume fraction ($\alpha$) is governed by the following transport equation:

\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot \left( \alpha \mathbf{u} \right) + \nabla \cdot \left( \alpha \right) \mathbf{u} = 0 \tag{4}
\]

To better capture an accurate interface, it is crucial to maintain a sharp interface and ensure that the $\alpha$ remains conservative and bounded between 0 and 1. To achieve this, OpenFOAM utilizes an artificial compression term $P(\alpha \left( 1 - \alpha \right))$, where $u_i$ is a velocity field used to compress the interface and only functions near the free surface. For a water-air problem, fluid density and viscosity can be written as a mixture of water and air:

\[
\rho = \alpha \rho_w + \left( 1 - \alpha \right) \rho_a \tag{5}
\]
\[ \mu = \alpha \mu_w + (1-\alpha) \mu_a \]  

where \( \rho_w \) and \( \rho_a \) denote the density of water and air, \( \mu_w \) and \( \mu_a \) denote their dynamic viscosity.

To generate numerical waves, the fluid velocity at the inlet boundary is prescribed using Stokes second-order wave theory:

\[
\begin{align*}
    u &= \frac{\pi H}{T} \frac{\cosh k(z + d)}{\sinh kd} \cos \beta + \frac{3\pi H}{4T} \frac{2k(z + d)}{\sinh^2 kd} \cos 2\beta \\
    w &= \frac{\pi H}{T} \frac{\sinh k(z + d)}{\sinh kd} \sin \beta + \frac{3\pi H}{4T} \frac{2k(z + d)}{\sinh^2 kd} \sin 2\beta
\end{align*}
\]

where \( H \) and \( T \) denote the wave height and wave period, \( k \) and \( d \) denote wave number and water depth, \( \beta \) is the phase.

In this paper, to impose an non-reflection boundary conditions on the computational outlet boundary, an active wave absorbing scheme is utilized, with which the waves are directly absorbed along the boundary without relaxation zones. This can significantly reduce the computational domain size required by the relaxation zones. The primary concept is to produce waves with a phase opposite to that of the incident waves, but with the same characteristics at the outlet boundary. The corrected velocity at the outlet boundary is described by

\[ \Delta u = -\Delta \eta \frac{\pi H}{T} \frac{\cosh k(z + d)}{\sinh kd} \]

where \( \Delta \eta \) is the difference of the surface elevation \( \eta \) due to reflected waves. In this paper, two different models of moorings are utilized for two separate platforms. For the modeling of the spring-type mooring, it is simulated as a linear force proportional to the displacement:

\[ f = k_s x \]

where \( k_s \) is the stiffness of the spring and \( x \) is the position of the center of rotation.

To model the catenary mooring lines constraining the platform, a quasi-static mooring line analysis model is utilized, in which a mooring line is treated as multiple segments with identical length. For each segment, equations of static equilibrium are established in both horizontal and vertical directions, which can be illustrated in Figure 1. The equilibrium equations are:

\[ T_{\text{ext}} = T_e, \quad T_{\text{int}} = T_e + w_i dl \]
\[ \begin{align*}
  ds \cos(\phi_{i+1}) & = x_{i+1} + x_i = \bar{x} \\
  ds \sin(\phi_{i+1}) & = z_{i+1} + z_i = \bar{z} \\
  ds & = dt \left(1 + \frac{T_{ci}}{EA}\right) 
\end{align*} \] (12)

where \( ds \) is the stretch length of the segment, \( E \) and \( A \) denote Young’s modulus and cross-sectional area for the segment, respectively.

Although the mooring lines are not directly simulated using CFD, the hydrodynamic forces are estimated by using Morison’s equation. The fluid information is derived from the field information from the CFD background mesh at the corresponding positions.

The dynamic response of the platform is governed by the following motion equations:

\[ \begin{align*}
  m \ddot{x} + c \dot{x} + kx &= F_x \\
  m \ddot{y} + cy + ky &= F_y 
\end{align*} \] (13)

\[ \begin{align*}
  m \ddot{x} + c \dot{x} + kx &= F_x \\
  m \ddot{y} + cy + ky &= F_y 
\end{align*} \] (14)

where \( m, c \) and \( k \) represent the platform mass, structural damping coefficient, and spring stiffness, respectively. \( F_x \) and \( F_y \) denote the IL and CF hydrodynamic force acting on the platform. The Newmark-beta method is adopted to solve Eq. (13) for the motion of the platform. To ensure simulation stable, an acceleration relaxation factor of 0.9 is adopted. Since we focus on the IL and CF motion of the platform, only \( x \) and \( y \) degrees of freedom are considered.

B. Model description

The two platforms studied are OC4 semi-submersible platform and a barge IDEOL platform as shown in Figure 2. The OC4 semi-submersible platform model is based on a 1:73 model test performed at the University of Tokyo by Gonçalves et al. The platform is made up of four columns, one central column with a smaller diameter and three offset columns with larger diameters. Columns are connected by crossbars in between. There are base columns attached below the side columns. In the experiment, the model was restrained by four perpendicular mooring lines. The main parameters, including the equivalent stiffness of the mooring system, are summarised in Table 1.
The natural frequencies of the platform in IL and CF directions are 9.4s and 9.6s, respectively, which were obtained via free decay tests.

The barge IDEOL platform is a 1:50 model, which was experimentally tested in the National Research Institute of Fisheries Engineering (NRIFE) wave tank in Japan, shown in Figure 2(b). The width of the barge semi-submersible platform is 0.82m, with a draught of 0.14m. The skirt with 0.055m width is attached at the bottom to reduce the dynamics motion response. Compared to the OC4 platform, this barge platform has a simpler geometry and is easier to construct, with a larger area of water plane and smaller draft. To constrain the platform, three catenary mooring lines are applied. The nominal diameter of these studless chains is 3mm with a total length of 8m. The geometric parameters of the platform can be found in Figure 2 and Table 1.

In ocean engineering, the geometry of a platform significantly influences its motion response, particularly in interaction with water currents. The above two platforms exhibit distinct geometries, primarily differentiated by their waterplane (WP) area. The IDEOL barge platform, akin to a hollowed-out box, has a substantially larger WP area compared to the SS platform. This expands WP area results in a shallower draft and a reduced aspect ratio (defined as draft/characteristic length). In a vortex-induced motion (VIM) study, a lower aspect ratio typically exhibits enhanced three-dimensional characteristics at the platform’s bottom edge, subsequently altering the motion amplitude.

<table>
<thead>
<tr>
<th>OC4 Platform</th>
<th>IDEOL Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central column diameter $D_1=0.09$m</td>
<td>Thickness of Skirt plate $d_s=0.004$m</td>
</tr>
<tr>
<td>Offset Column diameter $D_2=0.165$m</td>
<td>Skirt plate width $W_s=0.055$m</td>
</tr>
<tr>
<td>Base column diameter $D_3=0.33$m</td>
<td>Width $W_0=0.82$m</td>
</tr>
<tr>
<td>Height of base column $d_3=0.083$m</td>
<td>Height $H_0=0.19$m</td>
</tr>
<tr>
<td>Platform draft $d=0.27$m</td>
<td>Platform draft $d=0.14$m</td>
</tr>
<tr>
<td>Distance between offset columns $L=0.688$m</td>
<td></td>
</tr>
</tbody>
</table>

Inertia properties

<table>
<thead>
<tr>
<th>OC4 Platform</th>
<th>IDEOL Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the Platform $m=36.7$kg</td>
<td>Mass of the Platform $m=62.31$kg</td>
</tr>
<tr>
<td>Centre of mass $z_c=-0.134$m</td>
<td>Centre of mass $z_c=0.03$m</td>
</tr>
</tbody>
</table>

Mooring parameters

<table>
<thead>
<tr>
<th>OC4 Platform</th>
<th>IDEOL Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness in x direction $k_x=27.5$N/m</td>
<td>Type Studless</td>
</tr>
<tr>
<td>Stiffness in y direction $k_y=28.1$N/m</td>
<td>Weight in water 0.067kg/m</td>
</tr>
</tbody>
</table>

Table 1. Geometric parameters and the mooring parameters
C. CFD settings

The computational domain is shown in Figure 3 with top and side views. The boundary conditions are set as follows: the zero-gradient pressure condition is applied at the inlet and outlet boundaries with the air speed equal to zero, while the fluid velocity are given by a build-in boundary based on the wave theory, for the generation of inflow wave-current condition and wave absorbing. For those cases with oblique incident waves, the front boundary is imposed the same settings as the inlet boundary condition for wave generating. A non-slip wall boundary condition is applied to the bottom.

Figure 2. Sketch of the scale-down model for (a) OC4 Platform (b) IDEOL platform
The dynamic response of floating offshore wind turbine platform in wave-current condition

Figure 3. (a) Top view (b) Side view of the numerical wave tank for IDEOL platform

Figure 4. Computational mesh for the OC4 platform, the inner red zone is structured mesh to capture boundary layers with high quality, outside which is the unstructured far-field mesh, where the mesh is only refined near the water-air surface.
To accurately model the motion of platform under both wave and current conditions, it is essential to ensure that the mesh resolution meets different mesh density requirements. For instance, to capture VIM, the separation of the boundary layer around the structure and the vortex street at the downstream should be accurately modelled. Therefore, CFD mesh is refined at the near wall field region as well as the wake region. To reduce the overall cell numbers of the computational domain, a hybrid mesh is used, which is made up of the near-field structured mesh (red one) and the far-field unstructured mesh as shown in Figure 4. Within the boundary layer, the thickness of the mesh is set that the $y^+$ around the platforms ranges from 1.0 to 4.0. The surface cell on the platform is 1/100 of the characteristic length $D$. At the near field of the structure, the average cell size is 1/50 $D$. At the far field region, to ensure the accuracy of numerical wave generation, the cells near air-water free surface are refined. In particular, at least 8 cells are used along $z$ direction per wave height, and at least 180 cells per wavelength.

The convergence test of the numerical simulation is conducted, and the results are shown in Table 2. Three mesh sets with different cell counts are used, with which the normalized IL and CF motion ($A_x/D$ and $A_y/D$) are compared, as well as the frequency of the cross-flow oscillation $f/f_n$. The disparity between the Medium and Fine cases is less significant than that between the intermediate and coarse cases. This suggests that the intermediate grid is sufficient fine for the current research. Similarly, for the sensitivity study with different time steps, the predicted motion hardly changes when $U\Delta t/D < 0.002$. Considering the cost of computational time, a time step of $U\Delta t/D = 0.002$ is chosen for the CFD modelling in this study.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Cell count</th>
<th>$U\Delta t/D$</th>
<th>$A_x/D$</th>
<th>$A_y/D$</th>
<th>$f/f_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>2,650k</td>
<td>0.002</td>
<td>0.050</td>
<td>0.424</td>
<td>0.990</td>
</tr>
<tr>
<td>Intermediate</td>
<td>3,510k</td>
<td>0.001</td>
<td>0.055</td>
<td>0.403</td>
<td>0.959</td>
</tr>
<tr>
<td>Fine</td>
<td>5,400k</td>
<td>0.002</td>
<td>0.059</td>
<td>0.410</td>
<td>0.958</td>
</tr>
</tbody>
</table>

Table 2. Sensitivity study for computational mesh and unsteady time step for OC4 platform with $V = 8.1$

PIMPLE (a combination of Pressure Implicit with Splitting of Operator (PISO) and Semi-Implicit Method for Pressure-Linked Equations (SIMPLE)) algorithm is utilized to solve the pressure-velocity coupling. A second-order Crank-Nicolson scheme is used for temporal discretization. Second-order upwind scheme is adopted for convective terms. Gradient terms are handled via a second-order cell-limited Gauss linear scheme. The total cell of the simulation is around 350 million for both platforms. The
computations are made in parallel with 5 nodes (180 cores) for each case on Cirrus HPC (http://www.cirrus.ac.uk). The average simulation time is $3T_n$ per day which may vary depending on the specific cases.

III. Results & Discussions

When waves and currents coexist, their respective motions become coupled. To decouple this effect, we start with a comparative study on a fluid-structure-interaction either induced by wave or current separately for both OC4 and IDEOL platforms. Because of their different geometric characteristics, it is expected to observe different dynamic motion response. For the validation purpose, the comparison between our CFD results with experimental testing has been done for waves interaction with IDEOL platform. Other validations for this CFD tool can be found from our previous publications on (a) wave-structure interaction for floating platforms$^8$, $^47$, (b) wave energy devices$^48$, and (c) the current-structure interaction for the OC4 platform with VIM studies$^49$, $^50$.

A. Response of the OC4 Platform with Current-only and Wave-only conditions

Either current or wave interaction with OC4 platform is firstly studied and the flow conditions are listed in Table 3. Figure 5 displays the amplitude of the motion response in the current-only scenario along with the experimental data, in which IL component ($A_{cx}$) and CF component ($A_{cy}$) are plotted against flow velocities. They are calculated by multiplying the root mean square (RMS) displacement by $\sqrt{2}$, and then normalized with the characteristic length, which is $D_s$ for OC4 platform and $W_B$ for IDEOL platform.

<table>
<thead>
<tr>
<th>Wave Parameters</th>
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</thead>
<tbody>
<tr>
<td>$H$ [m]</td>
</tr>
<tr>
<td>Scaled 1:73</td>
</tr>
<tr>
<td>0.02 0.04 0.07 0.09 0.116</td>
</tr>
<tr>
<td>$H$ [m] Full-scale</td>
</tr>
<tr>
<td>1.45 2.91 5.09 6.54 8.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$ [m/s]</td>
</tr>
<tr>
<td>Scaled 1:73</td>
</tr>
<tr>
<td>0.05 0.08 0.11 0.14 0.17 0.20 0.24</td>
</tr>
<tr>
<td>$U$ [m/s] Full-scale</td>
</tr>
<tr>
<td>0.43 0.68 0.94 1.20 1.45 1.70 2.05</td>
</tr>
<tr>
<td>$V_r$</td>
</tr>
<tr>
<td>2.30 3.7 4.6 8.1 9.9 11.6 14.3</td>
</tr>
</tbody>
</table>

Table 3. Wave and current parameters for OC4 Platform testing.
In VIM analysis, the freestream velocity is commonly normalized using the natural frequency of the system \((f_n)\). The reduced velocity is defined as \(V_r = U/f_nD\), where \(U\) and \(D\) are the flow velocity and characteristic length of the structure. It can be re-written as \(V_r = UT_n/D\), where \(T_n\) is the natural frequency of structure. From a physical perspective, the numerator can be considered as the distance that the constant fluid flows over the structure in one natural vibration period. Thus, \(V_r\) is an indicator for the ratio between this distance and the structural dimension. In this study, cases with different \(V_r\) are achieved by only varying the flow velocity, meanwhile Re number is also synchronized with \(V_r\) since they are both a representative of the flow velocity.

The plot indicates that the CFD predictions are in good agreement with the experiments. The IL motion is significantly smaller compared to that of CF motion with \(A_{v/d}\) being less than 0.1, indicating that the IL movement of platform is not dominant. The CF motion response shown in Figure 5(b), however, reveals a very typical current-structure-interaction VIM phenomenon. In particular, the lock-in region ranges from \(V_r\) = 5 to 10, in which the maximum \(A_{v/d}\) characterized by VIM reaches a value of 0.41 at \(V_r\) = 8.1. At real sea conditions, the full-scale current velocity in the lock-in region can vary from 1.0 to 1.45 m/s. Therefore, it is expected to observe significant platform motion within this velocity range.

![Figure 5. Variation of the motion response amplitude with \(V_r\) in (a) IL direction and (b) CF direction for OC4 platform with current-only condition](image)

The added mass coefficient in the CF direction \((C_a)\) also agrees well with the experiment as shown in Figure 6, which is defined as \(C_a = R \{ FFT[F_y(t)] / FFT[y(t)] \}/m\) where \(F_y(t)\), \(y\) are the hydrodynamic force and displacement in CF direction, respectively. \(R()\) represents the real part of the complex number and \(FFT\) represents Fast-Fourier Transform (FFT) operator. The large and positive values of \(C_a\) with \(V_r < 9.9\) denote the synchronization with the vortex shedding frequency. As the velocity increases, \(C_a\) decreases and becomes negative after \(V_r > 9.9\), indicating the end of resonance.
Figure 6. Variation of added mass coefficient with $V_r$ in CF direction for OC4 platform with current-only condition.

Figure 7. Time-series and FFT analysis of CF motion response for $V_r = 3.7, 8.1$ and $11.6$ for OC4 platform with current-only condition.

The resonance in lock-in region is also reflected by the time-series and the corresponding FFT analysis shown in Figure 7, where a dominant VIM motion can be observed at $V_r = 8.1$ in lock-in region. With a smaller $V_r = 3.7$, the periodic motion exists but has a lower frequency and smaller amplitude. At larger $V_r$ beyond lock-in region, the amplitude is small but with higher-order frequency components.

The vorticity field is plotted and examined in Figure 8 to reflect the typical vortex shedding associated with VIM phenomenon. It is seen that with the increase of $V_r$, the vorticity becomes stronger, and the flow field becomes more irregular. Within the lock-in region at $V_r=8.1$, (Figure 8(d)-(f)), the vortices generate alternately from both sides of column, and then shed from either side of the column at a frequency equal to the
Figure 8. Contours of spanwise vorticity $\omega_z$ at the section with $z=-0.1m$ at the time instants shown in Figure 7 at $V_r=3.7$ (a)-(c), $V_r=8.1$ (d)-(f), $V_r=11.6$ (g)-(i) for OC4 platform with current-only condition.
Figure 9. Variation of surge RAOs with wave periods of OC4 platform for wave-only condition

lock-in frequency $f_n$. An anti-clockwise vortex is observed when the platform reaches $y_{\text{min}}$ in Figure 7 (e), and another anti-clockwise vortex is observed while a clockwise vortex is shed when $y_{\text{max}}$ at (f), revealing a typical 2P mode for the wake in VIM. At $V_r = 3.7$, no obvious vortex shedding is observed, which associates with a smaller motion in CF direction.

In addition to the above current-only condition, the wave-only condition is also examined for OC4 to set up a baseline model for the subsequent wave-current investigations. Figure 9 shows the predicted surge RAO with various wave heights ($H$) and wave periods ($T$). It is seen that the RAO increases with $T$, as the platform’s structure natural period aligns more closely with it, increasing the motion response. The RAO relationship with $H$ is rather complex due to enhanced mooring forces with increasing $H$, as well as the higher nonlinearity with larger $H$. Therefore, the variation follows a nonlinear trend.

B. Response of the IDEOL Platform with Current-only and Wave-only conditions

The IDEOL platform is analysed starting with the current-only scenarios. The response amplitudes in IL and CF directions are shown in Figure 10, with the parameters summarised in Table 4. It is seen that, barge-type platform has an even smaller IL motion compared with OC4 platform. The motion in CF direction is also relatively smaller. For the largest reduced velocity of $V_r = 9.6$ ($U = 2.3$ m/s at full-scale), the maximum $A_c/D$ is less than 0.2. Only at this largest $V_r$, the periodic platform motion characterized by VIM becomes notable, as shown in the time-series plots in Figure 11.

Compared to OC4 platform, the VIM phenomena are less profound, which might be due to several reasons.
Firstly, the most pronounced Vortex Induced Motion (VIM) for the SS platform occurs around $V_r=8.1$. Comparatively, for the IDEOL platform to experience significant VIM, it requires a much higher reduced velocity of at least 10.0 or even higher, as can be seen in Figure 10. Thus, the VIM of IDEOL platform is not obvious. In addition, the aspect ratio of IDEOL platform is 0.17, which is much smaller than that of 1.64 for OC4 platform. This finding agrees with the research by Goncalves et al. that the response of CF motion of a cylinder weakens as its aspect ratio decreases. The VIM could be even negligible if the aspect ratio is less than 0.3\textsuperscript{18}.

Table 4. Wave and current parameters for IDEOL platform testing

<table>
<thead>
<tr>
<th>Wave parameters</th>
<th>Current parameters</th>
</tr>
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<tbody>
<tr>
<td>$T$ [s]</td>
<td>$U$ [m/s]</td>
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<td>Scaled 1:50</td>
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Figure 10. CF and IL motion amplitude versus reduced velocity for IDEOL platform with current-only condition

Figure 11. Time-series and FFT analysis of CF motion response for $V_r=6.1$, 8.0 and 9.6 for IDEOL platform with current-only condition
Then, the dynamic response of IDEOL platform for wave-only condition is studied for a series of wave periods (Table 4). In the experiment, the wave heights varied from 2.5m to 7.5m. In this validation, an intermediate wave height of $H=5$m is chosen. Figure 12 shows the predicted RAOs in comparison with the experiment (EXP) and numerical modelling (SIM) data. In the SIM studies, the potential-flow-based method is used, the hydrodynamic coefficient is obtained by Ansys Aqwa software and the dynamic response is calculated using DNV-GL’s Bladed software package to couple the hydrodynamic loads. The RAOs are normalized by the wave amplitude for heave and surge motions, while the pitch response is normalized by $kH/2$ Figure 12.

![Variation of RAOs with wave periods with $H=5$m for (a) surge (b) pitch (c)heave for IDEOL platform with wave-only condition](image)

**Figure 12.** Variation of RAOs with wave periods with $H=5$m for (a) surge (b) pitch (c)heave for IDEOL platform with wave-only condition
Wetted surface changes on the IDEOL platform at different sampling time (a) $t/T=3.5$ and (b) $t/T=4.0$ with $H=5\text{m}$ and $T=14.1\text{s}$

For the wave periods studied, an averaged RAO for the surge and heave are typically 0.84 and 1.0, respectively, from CFD and EXP. However, the pitch RAO reveals an initial increasing and then decreasing trend. The peak RAO occurs at $T=14.1\text{s}$. It is evident that better agreement between the present CFD predictions and the experimental data has been reached than the results obtained from the potential-flow-based tool (SIM). One explanation for the improved accuracy of CFD modelling over the potential theory method is that the later linearizes the wave-air free-surface equation at the time-averaged positions, therefore, the nonlinear effect of fluid-structure interaction, represented by the changing wetted surfaces, is not very well captured.

As shown in Figure 13, the green water can be observed clearly showing the changing wetted surface. Also, for the CFD modelling, tuning the viscous damping to fit the experiments is not required which is usually needed for a viscous-modified potential flow model.

C. Response with combined current-wave at different angles

In the above two sections for current-only and wave-only cases, it is observed that the VIM phenomena are more profound for a semi-submersible platform than a barge platform. Therefore, the following studies on a combined wave-current-structure interaction will be focused on OC4 semi-submersible platform.

It is well known that in a real sea state, current and wave do not always exist alone, and the extreme loading condition for a FOWT platform may occur with specific combinations of wave and current. In our previous study on a colinear wave-current condition, it was found that the current-induced CF motion can be mitigated with the addition of waves, depending on $V_r$ under investigation. This conclusion is consistent with others’ findings. Some other studies also found that if the wave and current were non-colinear, the mitigation became less obvious. To investigate this phenomena, this section is dedicated to examining the impact of the angle of the flow direction between current and wave ($\theta$) on the platform’s dynamic responses. Three angles varying from $\theta=0^\circ$ to $90^\circ$ are selected. Typical wave period and wave height are $T=2.0\text{s}$,
$H = 0.09 \text{m}$. The current speed varies from 0.05 to 0.20 m/s, leading to the reduced velocity $V_r$, ranging from 2.3 to 11.6, as shown in Table 5.

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<tr>
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</tr>
<tr>
<td>$V_r$</td>
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<td>3.7</td>
<td>4.6</td>
<td>8.1</td>
<td>9.9</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Table 5. Current parameters for wave-current interaction with OC4 platform on the effect of angles.

The responses of platform are shown in Figure 14 with different angles. Given a combined wave-current condition, the IL motion varies a little with reduced velocity, indicating that varying current speed does not affect IL motion significantly, as shown in Figure 14 (a). However, the IL motion is noticeably impacted by angles variation ($\theta$).

In fact, with $\theta = 0^\circ$, $A_c/D$ is the largest and close to $A_w$ in the wave-only cases, while $\theta = 90^\circ$, $A_c/D$ is the smallest and close to that in the current-only cases. Unlike the above
IL response, CF motion varies significantly with reduced velocity and the peak values can be clearly captured (Figure 14 (b)). As the angle $\theta$ increases, $A_y/D$ increases across all $V_r$. Therefore, for safety design purposes, it is recommended to pay more attention to those cases with $\theta = 90^\circ$. Beyond the lock-in region, with $\theta > 0^\circ$, $A_y/D$ are greater than those observed in the current-only cases, and close to $A_w$. However, within lock-in region, with increasing $\theta$ to $90^\circ$, $A_y/D$ is always larger than that of either wave-only or current-only. The large CF motion in this wave-current condition is induced by non-zero wave-current angle. As the velocity components along $y$-axis increase with the angle, CF response increases due to the enlarged inertia wave force acting on the platform. In addition, the flow field and VIM are altered with a combined wave-current interaction.

To examine the individual effect of current and wave on the motion response, the above CF motion ($A_y/D$) is decomposed:

$$a_c = |Y(f_c)| \quad \text{and} \quad a_w = |Y(f_w)|$$

where $|Y(f)|$ is the FFT of CF motion. $a_c$ and $a_w$ are the motion amplitudes induced by current and wave, $f_c$ and $f_w$ are the peak frequency corresponding to VIM and the wave. The decomposed $a_w$ and $a_c$ for $\theta = 45^\circ$ and $90^\circ$ are shown in Figure 15 (a) and (b). For both angles, $a_w$ almost remain unchanged with $V_r$. As a result, the contribution of wave to the total response is nearly constant with varying $V_r$.

![Figure 15. Variation of decomposed CF motion excited by current ($a_c$) and waves ($a_w$) ($H=0.09m \ \text{and} \ \text{T}=2.0s$) at angles of (a) $45^\circ$ and (b) $90^\circ$. $a_c$ is normalized by characteristic dimension $D$ and $a_w$ is normalized by wave amplitude multiplied by $\sin(\theta)$.](image)
Figure 16. Variation of dominant frequency with $V_r$ ($H=0.09m$ and $T=2.0s$)

However, the variation of $a_c$ with $V_r$ resembles the pattern of current-only cases, with the peak amplitude occurring at $V_r=8.1$ and decreasing beyond this $V_r$. This indicates that the VIM effect still exists even with waves. Hence, the response peaks in the wave-current cases depicted in Figure 14 are primarily due to the current's contribution within lock-in region. A comparison between Figure 15 (a) and (b) indicates that larger $\theta$ leads to an amplified VIM. It is also worthwhile to note that with a larger angle, the $a_c$ near the peak value at $V_r=8.1$ also increases, which means the VIM becomes significant for a wider range of reduced velocities with the addition of waves.

The effects of angle are also reflected in dominant frequencies, as analysed in Figure 16. For current-only cases, $f_\theta$ increases with $V_r$, locks onto $f_c$ in lock-in region, leading to a large motion response. For cases with $\theta=0^\circ$, $f_\theta$ is the same as that of current-only. However, for those with $0^\circ < \theta < 90^\circ$, outside lock-in region, $f_\theta$ is close to $f_w$ indicating the platform's motion is dominated by waves. Within lock-in region $f_\theta=f_c$, the resonance occurs. With an increasing $\theta$, the lock-in region becomes wider, revealing a more vulnerable platform due to large-scale motions under a wide range of current velocity. The time-series distribution of $y/D$ and their FFT analysis displayed in Figure 17 reinforce the above observations. In fact, two dominant frequencies appear in relation to $f_c$ and $f_w$. Outside lock-in region, the low-frequency components are not as prominent compared to the high-frequency components. Within lock-in region, the low-frequency component is substantially large and increases with angles. In addition to the above dominant frequencies, other spikes are also noted, which might be caused by the nonlinear coupling between the vibration of platform and fluid flow. The difference frequency $f_{\text{diff}} = f_w - f_c$ and sum frequency $f_{\text{sum}} = f_w + f_c$ exist, although with a relatively small magnitude, which is also noticeable in the cases with $90^\circ$ with heir magnitudes increasing with angle.
Figure 17. Time-series and FFT analysis of CF motion response in wave-current condition \((H=0.09m\text{ and }T=2.0s)\) of (a) \(V_r=4.6\) (b) \(V_r=8.1\) (c) \(V_r=11.6\). In the time-series, black line represents the response caused by the current only, while red line indicates the addition of waves to the current.
Figure 18 to Figure 19 present vorticity field under the combined waves and current conditions for $\theta=0^\circ$ and $\theta=90^\circ$ at $V_r=8.1$. Unlike the current-only cases in Figure 8, the fluid field with waves for $\theta=0^\circ$ in Figure 18 becomes chaotic and its precise pattern is hard to discern. It displays the characteristics of cylindrical structures interacting with both steady and oscillatory flow. The steady flow leads to a typical VIV vortex shedding, while the oscillatory flow leads to a different shedding pattern. The specific appearance of pattern highly relies on the Keulegan-Carpenter number ($KC$ number)\textsuperscript{53}, which describes the relative importance of the drag forces over inertia forces in an oscillatory flow. In a pure oscillatory flow scenario, VIM only occurs at a large $KC$, by the hydrodynamic lift force in CF direction

\[
KC = \frac{U_M}{f_w D}
\]

where $U_M$ is the maximum flow velocity in the IL direction. At time instants of (c) to (e), the vortices are shed from both sides of offset columns (the larger columns) and move downstream, having a symmetric pattern. The vortex shedding frequency of this process is 1/2 seconds, much smaller than lock-in frequency, but is identical to the wave frequency $f_w$, indicating that the symmetric vortex pair is dominated by oscillatory flow/waves. When oscillatory flow passed a cylinder at a small $KC$ number between 1.6-4.0, the vortex separation begins to occur in the form of a pair of symmetric attached vortices\textsuperscript{16}, as also observed for offset column with $KC=2.1$. Two vortex pairs generate in one cycle, one from the previous half period where flow passes in one direction. Another pair generate from the second half period when the oscillatory direction reverses. In the present case for wave-steady current, only one vortex pair generates within one cycle and is flushed downstream, showing a 2T mode (Figure 18(b)), where three vortices are seen to be shed from the lower offset column. This mode was also observed in Zhao’s study for steady and oscillatory current around a cylinder\textsuperscript{54}. The 2T mode is observed when the motion displacement reaches its maximum at the steady flow-dominated frequency. Away from this time periods, the double pair mode dominates (Figure 18 (a) and (d)). For the central smaller column, the vortex shedding is also dominated by waves but with a different pattern than the offset column. The $KC$ number for the central column is 3.8, and the vortex is seen shed alternatively from one side of the column with an asymmetric pattern. Typically, this pattern occurs for a pure oscillatory with a cylinder when $KC > 4.0$\textsuperscript{16}. However, in cases where a steady flow is present, this pattern is also observed at a smaller $KC$ number.
Figure 18. Contours of spanwise vorticity $\omega_z$ at the section with $z=-0.1\text{m}$ and $\theta=0^\circ$ in wave-current condition ($H=0.09\text{m}$ and $T=2.0\text{s}$) at different time instants at $V_r=8.1$ for (a) to (f), (g) is the corresponding time series, on top of which is the sketch of angle between wave and current.
Figure 19. Contours of spanwise vorticity $\omega_z$ at the section with $z=0.1m$ and $\theta=90^{\circ}$ in wave-current condition ($H=0.09m$ and $T=2.0s$) at different time instants from (a) to (f), at $V_r=8.1$, (g) is the corresponding time series, on top of which is the sketch of angle between wave and current.
It should be noted that the symmetric vortex pair doesn’t provide net force along CF direction, but it interferes with the vortex formed by the steady flow. Moreover, the flow in the -x direction caused by the waves mitigates the generation of a complete vortex due to a steady current, leading to a possible reduction in crossflow motion.

Compared to the cases with θ=0°, the vortex field for θ=90° in Figure 19 shows more asymmetric characteristics. Since the waves propagate along y-axis, the flow along x-axis is less affected. As a result, when a vortex forms, it is periodically stretched and carried by oscillatory flow in CF direction, causing it to split into smaller vortices. At (y/D)_{max} and (y/D)_{min} in Figure 19 (a) and (e), a large vortex is generated on one side of the offset column, but breaks down into small eddies. The vortex from the central small column presents a 2S mode with one clockwise and one counter-clockwise vortex detaching from the central column within one cycle. Moreover, the shed vortex not only moves downstream but also along CF direction, bringing it closer to the platform and increasing the chances of encountering between the clockwise and counter-clockwise vortices, thereby changing the motion frequency. This is clearly depicted from Figure 19 (b) to (c), where \( V_y \) is positive, while \( V_y \) is negative at Figure 19(f). It is clearly
indicated that when the wave and current are colinear, oscillatory flow mitigates the generation of a complete vortex due to current, thus the VIM is mitigated. The disturbed vortex field by the symmetric vortex from the oscillatory flow contributes to this trend.

The platform motion trajectory with different $\theta$ and $V_r$ is shown in Figure 20. For current-only cases, the platform experiences significant motion displacement within the lock-in region at $V_r=8.1$. The predominant motion is along $y$-axis and the movement along $x$-axis is limited. This pattern of movement is similar to that in the study on a four-square column semi-submersible platform, where a typical eight-shaped trajectory is not found.

D. Response for $\theta=90^\circ$ with different wave parameters

Previous studies on colinear wave-current-structure interaction indicated that the CF response was not only affected by the reduced velocity, but also influenced by the wave parameters, i.e., the wave height and wave period (Gonçalves et al. 35, 36). In addition, our findings from Section C for various $\theta$ values reveal that the largest CF motion occurs at $\theta=90^\circ$. In this section, the investigation is focused on the study of wave-current-platform interaction at $\theta=90^\circ$ for a series of wave heights and wave periods (Table 6). The reduced velocity is fixed at $V_r=8.1$, where the strongest VIM occurs.

The effect of wave parameters on the platform’s response is shown in Figure 21. It is seen, IL motion is relatively small compared with the large platform dimensions. The overall CF motion is larger than that observed in the current-only cases and increases with wave period $T$. The motion response is also influenced by wave height $H$. As $H$ increases, $A_y/D$ approaches that of wave-only cases. $A_y/D$ decreases monotonically with $H$ for $T=1.5s$. However, peaks are observed for $T=2.0s$ and $T=2.6s$, the peak $A_y/D$ is seen at $H=0.04m$ and $0.07m$, respectively. This concludes an important finding, e.g. waves with small wave height may also lead to large platform motion under wave-current condition.

<table>
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<tr>
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<td>5.1</td>
<td>3.0</td>
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Table 6. Parameters for wave-current-platform interaction with OC4 platform on the effect of wave conditions with $\theta=90^\circ$
Figure 21. Response amplitude in wave-current condition with different wave heights and periods along (a) IL direction (b) CF direction, with $\theta=90^\circ$. The grey line indicates the motion amplitude with current-only.

Figure 22. (a) Decomposed motion amplitude excited by current and waves (b) Dominant frequencies at $V_r=8.1$ with different wave parameters
The dynamic response of floating offshore wind turbine platform in wave-current condition

This can be further inferred by decomposing the motion amplitude shown in Figure 22(a). For cases with small $H < 0.06m$, the motion induced by current, indicated by $a_c$, varies between $0.4 < a_c/D < 0.5$, which is larger than that observed in current-only cases, indicating an enhanced VIM effect. However, for $H > 0.06m$, $a_c$ decreases significantly with increasing $H$, indicating a mitigated VIM effect by waves. Meanwhile, $a_w$ becomes dominant after $H > 0.11m$, and the motion is locked onto $f_w$ rather than $f_c$, as shown in Figure 22(b). The shift in the predominant influence from currents to waves can also be observed from the time-histories of $y/D$ and FFT plots in Figure 23. As $H$ increases, the low-frequency motion induced by current becomes less prominent. The FFT analysis indicates the appearance of difference frequency and sum frequency components, especially for $\theta = 90^\circ$. These frequencies are only excited when the contribution of current and wave to the system's energy is roughly equivalent. As $H$ increases, the energy at $f_c$ weakens, causing above two frequencies to become less significant.
Figure 24. Contours of spanwise vorticity $\omega_z$ at the section with $z=-0.1\text{m}$ with $T=2.6\text{s}$ and $H=0.04\text{m}$ in wave-current condition with $\theta=90^\circ$ at $V_r=8.1$, at different time instants from (a) to (f), (g) is the corresponding time series.
The differences in wave parameters are also reflected in the vorticity field shown in Figure 24 for $H=0.04\text{m}$. Compared with larger $H=0.09\text{m}$ in Figure 19, the vortex herein are less disturbed by waves, thus leading to a larger CF motion response. The vortex shedding appears a 2P mode, with 2 pairs of vortices shed in one cycle, such as the vortex $A_1$ and $B_1$ at instant b and $A_2$ and $B_2$ at instant c. As the wave period decreases, the vortex flow exhibits greater levels of turbulence and disorder, as seen from Figure 25(a) and (c). Additionally, the vortex motion is observed to occur in close proximity to the structure with smaller $T$.

According to Iwagaki, and Asano, velocity ratio can be an important parameter in the study of a combined wave-current environment. It is defined as:

$$\alpha' = \frac{U}{\sigma_U + U}$$

where $U$ and $\sigma_U$ are the current velocity and the particle velocity amplitude in wave. With this definition, $\alpha'$ quantifies whether a flow is viscous or inertial dominant, and thus $\alpha'=1$ and 0 represent a wave-only or a current-only scenario, respectively. Previous study by Gonçalves et al. for a semi-sub platform revealed that VIM is governed by both viscous and inertia forces. The threshold between the viscous and inertia zones can be quantified by:

$$KC = \frac{1 + C_a^2}{C_d^2} \pi (\alpha')^2$$

where $C_a$ and $C_d$ is the added mass and drag coefficient, which are 0.63 and 0.61 for OC4 Deepcwind platform respectively.

Figure 26 plots velocity ratio ($\alpha'$) as a function of $KC$ number with $\theta=90^\circ$. For the wave parameters examined, most cases are within a regime where VIM is obvious, thus associate with a large CF motion. For those falls into inertia force regime, the response is mainly wave-dominant.

It should be noted that, falling in the drag zone does not correspond to larger motion. For instance, the cases with a $V_f$ beyond the lock-in region has a very small velocity ratio, and should be located in the drag zone. However, the absence of resonance leads to a smaller VIM amplitude. The interaction effect factor ($IEF$) is normally used to which is defined as

$$IEF = \frac{\text{stddev}(y_w)}{\text{stddev}(y_w) + \text{stddev}(y_c)}$$

where $y_w$ is the CF motion in wave-current combined environment, $y_w$ and $y_c$ is the CF motion in wave and current independently; $\text{stddev}$ means the standard deviation function. $IEF$ can be viewed as the ratio between the amplitude of $y_w$ and $y_w+y_c$. For larger $H$ and smaller $T$, the IEF becomes lower than 0.75 as shown in Table 7, suggesting that the interaction of waves and current mitigated the sum of their original
Figure 25. Contours of spanwise vorticity $\omega_z$ at the section with $z=-0.1m$ with $T=1.5s$ and $H=0.04m$ in wave-current condition with $\theta=90^\circ$ at $V_r=8.1$, at different time instants from (a) to (f), (g) is the corresponding time series.
motion. For small $H$ and large $T$, the IEF is the largest and close to 1, which means the motion can be considered as the sum of the motion in waves and current alone. For some cases, the IEF exceeds 1 and reaches 1.35 when $H=0.07m$ and $T=2.6s$, indicating that the motion is enhanced by the wave-current interaction. Special attention should be paid to those cases when the extreme conditions for the platform are considered during the design process.

![Figure 26. $\alpha'-KC$ plot with $\theta=90^\circ$ denoting predominant region of either drag or inertia force in wave-current condition for OC4 platform. The point with colour denotes CF motion response. The black line denotes the threshold between drag range and inertia range.](image)

<table>
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Table 7. IEF with different wave parameters for $\theta=90^\circ$ and $V_r=8.1$

IV. Conclusion

This study explores the fluid-structure interaction of floating offshore wind turbines under various scenarios, including wave-only, current-only, and wave-current conditions in which the motion response is one of the main concerns. The CFD package OpenFOAM with further developed models is used for the simulation. To reduce the computational size for wave-current cases, a hybrid mesh and active wave absorbing scheme are utilized. Comparison study shows that a semi-submersible platform has a larger aspect ratio, exhibits a larger cross-flow (CF) motion and experiences the lock-in phenomenon for the reduced velocities considered. Conversely, a barge platform,
with a larger cross-surface area and low aspect ratio, shows a much smaller motion. Obvious vortex-induced motion (VIM) is not seen with selected $V_r$, indicating there is little chance for a floating barge platform undergoing a lock-in phenomenon.

The angle between the directions of wave and current significantly affect the platform’s CF motion, with a mitigated VIM and small CF motion being observed when the wave and current are colinear or having a small angle. Increasing the angle from 0° to 90° leads to a more significant VIM and larger CF motion, with the oscillation frequency being more synchronised with the system’s natural frequency. The motion displacement reaches its maximum at angle of 90°, where the motion induced by wave and current are in the same direction and coupled nonlinearly. A combination of largest wave height and the most significant VIM does not result in the largest CF motion. The motion can be even larger for smaller wave height, in some cases. The study of Keulegan-Carpenter number ($KC$ numbers) and velocity ratio shows that the motion is mitigated if the problem is inertia-force dominant and whereas motion will be enhanced if it is drag-force dominated.

The interaction effect factor ($IEF$), which represents the motion ratio in wave-current condition compared to the sum motion in wave and current conditions separately, is evaluated. For large wave height and small wave period, the ratio is lower than 0.75, suggesting that the interaction of wave and current mitigates the sum of their individual motion. However, the most extreme motion does not necessarily take place with the largest wave height. With a smaller wave height, the ratio may be larger than 1.0. Remarkably, the interaction of wave and current could sometimes amplify the IEF to values as high as 1.35. At design stage of floating offshore wind turbines platforms, these coupling effects have generally not been accounted for though it sometimes critical as we illustrated. Therefore, our findings offer valuable insights for engineers considering the installation of wind turbines in regions where currents and waves coexist, potentially leading to more efficient and safer designs.

Although with the above findings, one limitation of present study is the omission of wind loads and the resultant motion responses, critical elements in the interaction between FOWTs and current/waves. This is because the load generated by the upper turbine can alter the pitch and yaw motion, potentially influencing the vortex shedding around the structure. Although our current model does not include an aerodynamic simulation for wind turbines, future work is planned to expand the model's capabilities to address this aspect.

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Reference


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