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Wave-Current Interaction with Floating Offshore Wind Turbines

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1 Introduction

Wave properties such as wave height (H), wavelength (λ) and water particle velocities change as the wave field interacts with currents of different profiles, speeds and direction, see e.g. Swan et al. (2001). It is observed that the effect of currents cannot be recreated by linear superposition of the wave properties with current properties (Kumar & Hayatdavoodi (2023)). Presence of currents in a wave field changes the loads on structures, see e.g. Venugopal et al. (2009). It is imperative to understand the way in which the loads on and responses of offshore structures change due to wave-current interaction. In this study, wave-current interaction with a barge platform housing the 5-MW NREL Wind Turbine tower is investigated. Current profiles vary between uniform, shear and custom currents. The wave-current-structure interaction is studied by developing a numerical model using a computational fluid dynamics approach. Results of wave-current-structure interaction in the numerical domain are first compared with available experiments and computational data. The numerical model is then used to study the total force, drift force and responses of the Floating Offshore Wind Turbine (FOWT) structure due to the combined wave-current field, and the effect of currents is investigated by comparison with the wave-only case.

2 Theory and Numerical Solution

The two-dimensional numerical domain is set up using the Cartesian coordinate system, where waves propagate along the positive x-axis, z-axis points upward and the still-water level (SWL) marks the origin. Effect of turbulence is assumed negligible and a laminar flow model is adopted in this study. Pressure and velocity are considered differentiable in space and time and the flow is governed by the mass and momentum conservation equations,

$$\overrightarrow{\nabla}.\overrightarrow{V} = 0, \tag{1}$$

$$\frac{\partial \overrightarrow{V}}{\partial t} + \nabla \overrightarrow{V}.\overrightarrow{V} = -\frac{1}{\rho}\nabla p + \nu \overrightarrow{\nabla}^2 \overrightarrow{V} - \overrightarrow{g}, \tag{2}$$

where ∇, $\overrightarrow{\nabla}$ and $\overrightarrow{\nabla}^2$ represent the gradient function, divergence & Laplacian vectors, respectively. t is time, $\overrightarrow{g}$ represents the body force vector due to gravity, ρ is the density of the fluid, $\overrightarrow{V} = u_x \overrightarrow{i} + u_z \overrightarrow{k}$ is the velocity vector, where $\overrightarrow{i}$ and $\overrightarrow{k}$ are the unit normal vectors in $x-$ and $z-$ directions, respectively, p is the pressure and ν is the kinematic viscosity. The pressure and velocity fields are obtained by simultaneously solving Eqs. (1) and (2), while the Volume of Fluid (VoF) method is used to track the free surface. PIMPLE algorithm solves the pressure-velocity coupling problem iteratively. Finite volume approach is used to discretize the domain in the open source computational fluid dynamics package, OpenFOAM.

A nonlinear, deep-water wave is generated by defining the pressure and water particle velocities following the Stream Function wave theory. The numerical domain comprises of three regions, (i) the wave-current generation zone, where the horizontal water particle velocity due to the wave, $u_{x(w)}$, is linearly superposed with the current velocity, u_c, to obtain the horizontal

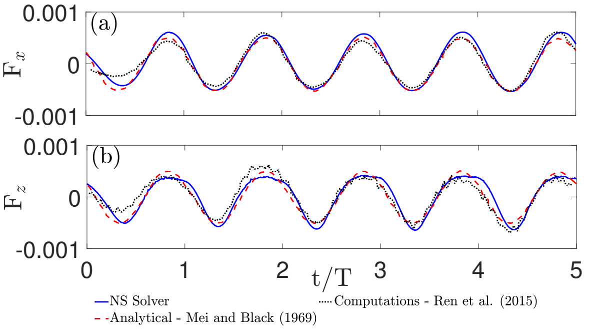

Figure 1: Time series of (a) horizontal and (b) vertical forces acting on a fixed barge. $H = 0.05$, $T = 3.4$, $h = 1.2$ m.

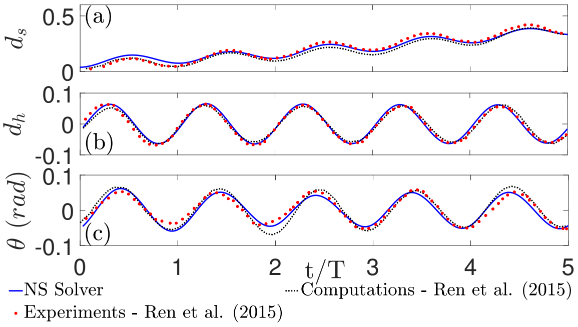

Figure 2: Time series of (a) surge, (b) heave and (c) pitch response of a freely floating barge. $H = 0.1$, $T = 5.9$, $h = 0.4$ m.

particle velocity of the wave-current system, $u_{x(wc)}$, (ii) the computational zone, where the fluid flow is governed by Eqs. (1) and (2) and (iii) the wave-current absorption zone, where the pressure and velocity fields are allowed to gradually dissipate and the waves & currents are absorbed. No-slip boundary condition is imposed on the flat and stationary tank floor.

All parameters are nondimensionalized using density of water (ρ), acceleration due to gravity (g) and the water depth (h), which constitute the dimensionally independent set. Therefore,

$$\begin{gathered}\overline{H} = H/h,\ \overline{T} = T/\sqrt{h/g},\ \overline{F}_x = F_x/\rho g h^3,\ \overline{F}_z = F_z/\rho g h^3, \\ \overline{d}_h = d_h/h,\ \overline{d}_s = d_s/h\ ,\ \overline{k} = k/\rho g h^2 \text{ and } \overline{u}_f = u_f/\sqrt{gh},\end{gathered} \tag{3}$$

where T is the wave period, F_x is the horizontal force on the structure, F_z is the vertical force on the structure, d_h and d_s are the heave and surge motions of the structure, respectively, measured by the displacement of the structure's centre of gravity from its initial position, k is stiffness and u_f is the current velocity at the free surface. Equation (3) shows a bar over the variables, however, this has been omitted from hereon for simplicity.

3 Results & Discussion

Comparison with available experimental and theoretical data is given first, followed by a discussion of the wave, current and structure parameters considered in this study. Then, results of the wave-current-structure interaction are presented and discussed.

3.1 Comparison with Experiments and Computations

Experimental and computational results of the wave-structure interaction study conducted by Ren et al. (2015) are used for comparison. Interaction of a wave with $h = 1.2$ m, $H = 0.05$ and $T = 3.4$, and a fixed barge (aspect ratio = 2) is studied initially.Time series of horizontal and vertical forces acting on the barge are presented in Fig. 1. It is seen that results of the numerical domain agree well with the analytical results and computations. Next, interaction of a wave, $h = 0.4$ m, $H = 0.1$ and $T = 5.9$, and a freely floating barge (aspect ratio = 1.5) is investigated (in the absence of ambient current). Time series of surge, heave and pitch, θ, responses of the barge are presented in Fig. 2. It is observed that the numerical domain is able to recreate the response of the structure.

3.2 Parameters of the Case Study

A deep-water wave with $H = 0.036$ and $T = 3$, propagating over a fixed water depth of h=0.15 m, is considered in this study. Current profiles that (i) remain constant along the water column,

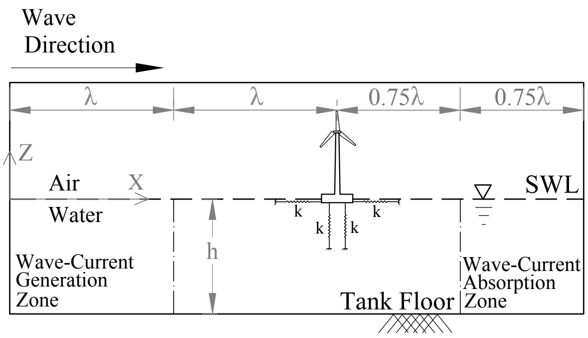

Figure 3: Schematic of the numerical wave-current domain with the FOWT barge structure. Figure not to scale.

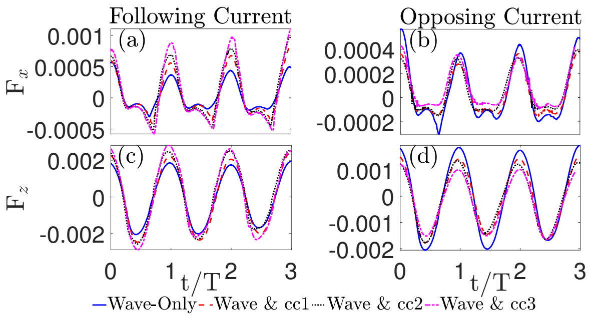

Figure 4: Time series of (a, b) horizontal and (c, d) vertical forces on the structure due to combined waves and (a, c) following and (b, d) opposing custom currents of increasing speeds. $H = 0.036$, $T = 3$, Custom Currents.

Table 1: Current conditions considered in the study.

Current Profile	Current ID	u_f
Uniform	uc1	±0.07
Shear	sc1	±0.07
	cc1	±0.04
Custom	cc2	±0.055
	cc3	±0.07

i.e. uniform currents, (ii) change linearly along the water column, i.e. shear currents, and (iii) maintain a constant value to mid-water depth and then change linearly, i.e. custom currents, are selected here. Current conditions are presented in Table 1. The FOWT structure, see Jonkman (2007), is incorporated into the wave-current tank and is held in place with two horizontal and two vertical linear springs (k=0.0027) acting as mooring lines. Schematic of the numerical domain is presented in Fig. 3.

3.3 Results of Wave-Current-FOWT Structure Interaction

Wave-current induced horizontal and vertical forces on the structure are assessed first. Time series of forces acting on the structure for custom currents of increasing speeds are shown in Fig. 4. Forces on the structure increase in case of following current (currents moving along wave propagation direction) and decrease in case of opposing current (currents moving against wave propagation direction). Larger current speeds have a stronger influence on the magnitude of force. Time series of forces acting on the structure as it interacts with the wave and currents of different profiles is shown in Fig. 5. Current direction has a similar effect on the force as observed previously in Fig. 4. Current profiles, however, have a weaker effect on the forces. Uniform current induces a slightly stronger change in forces on the structure.

In Fig. 4 and Fig. 5, horizontal force is influenced more by the wave-current interaction. Hence, the drift force on the structure is obtained next by decomposing the horizontal force signal using Fourier transform, discarding frequencies higher than $2/T$ and reconstructing the signal using inverse Fourier transform, see Pinkster (1980). Change of drift force is then defined as $F_d' = ((F_{d(wc)} - F_{d(w)})/F_{d(w)}) \times 100$, where $F_{d(wc)}$ is the mean height of the drift force signal in the presence of current and $F_{d(w)}$ is the mean height of the drift force signal in the absence of current. Therefore, F_d' represents the change of mean height of drift force on the structure due to the current. Figure 6 shows the change of drift force with custom currents of increasing speeds and currents of varying profiles with $u_f = \pm 0.07$. Following currents increase F_d' while opposing currents reduce it. Current speed has a stronger influence on F_d' in case of following currents, when compared to opposing current conditions. Uniform currents have a stronger influence on F_d', followed by custom and shear currents.

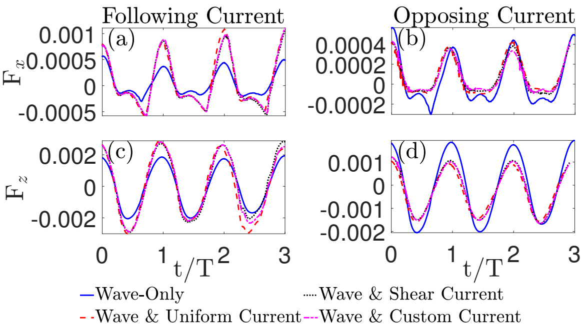

Figure 5: Time series of (a, b) horizontal and (c, d) vertical forces on the structure due to combined waves and (a, c) following and (b, d) opposing currents of different profiles. $H = 0.036$, $T = 3$, $u_f = \pm 0.07$.

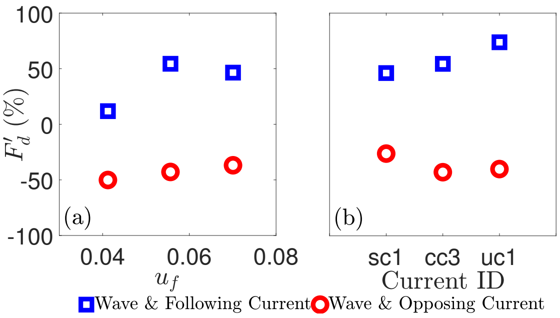

Figure 6: Change of mean height of drift force on the structure due to combined waves and different current (a) speeds and (b) profiles. $H = 0.036$, $T = 3$.

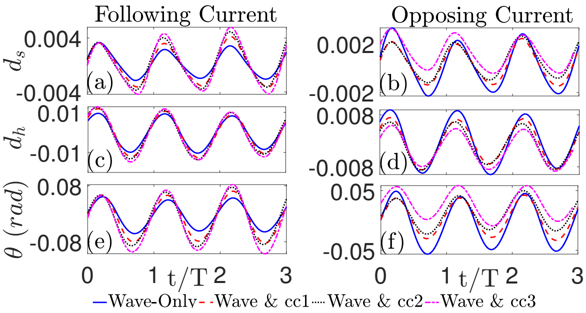

Figure 7: Time series of (a, b) surge, (c, d) heave and (e, f) pitch response of the structure due to combined waves and (a, c, e) following and (b, d, f) opposing custom currents of increasing speeds. $H = 0.036$, $T = 3$, Custom Currents.

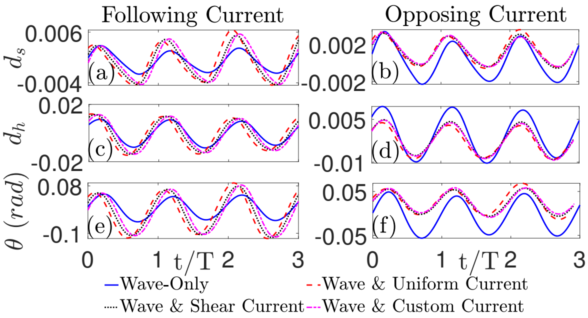

Figure 8: Time series of (a, b) surge, (c, d) heave and (e, f) pitch response of the structure due to combined waves and (a, c, e) following and (b, d, f) opposing currents of different profiles. $H = 0.036$, $T = 3$, $u_f = \pm 0.07$.

Figure 7 shows the time series of surge, heave and pitch responses of the structure due to the wave and custom currents of increasing speeds. Following currents increase all three motion responses and opposing currents reduce them. Larger current speeds have a stronger influence on the motion, and the effect of current speed appears to be nonlinear. Effect of current profiles on the motion of the structure is presented in Fig. 8. Changing current profiles weakly influence the motion with uniform current resulting in slightly larger amplitudes of motion.

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