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Effects of wave-current coupled interaction on dynamic responses of a spar-type floating wind turbine under wind-wave misalignment

Zirui Xin[a], Xin Li[a], Yan Li[b]

a. State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

b. Department of Mathematics, University of Bergen, N-5020 Bergen, Norway

Emails: zr.xin@sjtu.edu.cn, lixin@sjtu.edu.cn, yan.li@uib.no

1 Introduction

Surface waves and current coexist and interact with each other in open oceans and coastal waters. They drive hydrodynamic loads on offshore structures, and thus pose a severe risk to the safety and reliability of offshore structures like floating wind turbines (FWTs) (Chen & Basu 2018). An extensive body of literature has investigated the loads on FWTs excited by waves and currents, whereas the wave-current coupled effects have been rarely addressed. The presence of current can greatly alter the properties of waves, including the modifications of the linear dispersion relation and the wave shape (Li & Ellingsen 2019), and thereby resulting in considerable differences in the estimate of the hydrodynamic loads on offshore structures compared with the decoupled model (Chen & Basu 2018, Xin et al. 2023). In our work, the ultimate strength and fatigue performance of a 15 MW spar-type FWT are examined in realistic sea states, with a special focus on the roles of wave and current coupled interaction.

2 Methodology

Here we assume that the presence of current can affect the characteristics of waves but not *vice versa*. The second-order accurate theory for narrowband waves atop a vertically sheared current is used to describe the wave-current coupled incident flow fields in the absence of a structure (Dalrymple & Cox 1976, Xin et al. 2023), which is incorporated in the hydrodynamic module of the open source solver OpenFAST. In this study, the differences in the wave incident loads between the wave-current coupled and decoupled models are considered, resulting in the differences in wave diffraction, radiation, hydrostatic, and drag loads being exerted on the wet surface of the spar.

3 Numerical setup

Here the IEA 15MW FWT installed on the WindCrete spar platform is used, for which the specifications of the FWT model can be found in Mahfouz et al. (2021). Turbulent winds, random waves and a spatially uniform current are generated. The effects of current are sepcifically considered on the linear dispersion relation of waves by numerically implementing the Direct Integral Method proposed by Li & Ellingsen (2019). The normal (NSS) and severe operation sea states (SSS) are chosen according to the IEC 61400-3-2 Standard, as shown in Table 1, where the characteristics of the sea states follow the measured data from the Norwegian sea (Li & Moan 2015, Bruserud et al. 2018).

Table 1: Parameters for design load cases. U_{hub} stands for the 1-h mean wind speed at hub height, and θ_a θ_w and θ_c stand for the directions of wind, wave and current, respectively. $|U_c|$ denotes the amplitude of current velocity.

No.	U_{hub}[m/s]	θ_a [deg]	H_s[m]	T_p[s]	θ_w [deg]	$\lvert U_c\rvert$[m/s]	θ_c [deg]
NSS1	5	0	1.5	10.5	0:30:180	0.13	F [1]/O [2]
NSS2	9	0	2.5	10.5	0:30:180	0.15	F /O
NSS3	13	0	2.5	9.5	0:30:180	0.15	F /O
NSS4	17	0	3.5	10.5	0:30:180	0.17	F /O
NSS5	21	0	4.5	10.5	0:30:180	0.19	F /O
NSS6	25	0	6.5	11.5	0:30:180	0.245	F /O
SSS	25	0	10.78	13.32	0:30:180	0.98	F /O

[1] F: a current in the same direction of wave propagation, i.e, a following current;
[2] O: a current in the opposite direction of wave propagation, i.e, an opposing current;

4 Results and discussion

In this section, we present the results and analysis based on the comparisons of the numerical simulations between the wave-current coupled and decoupled models using the design load cases shown in Table 1.

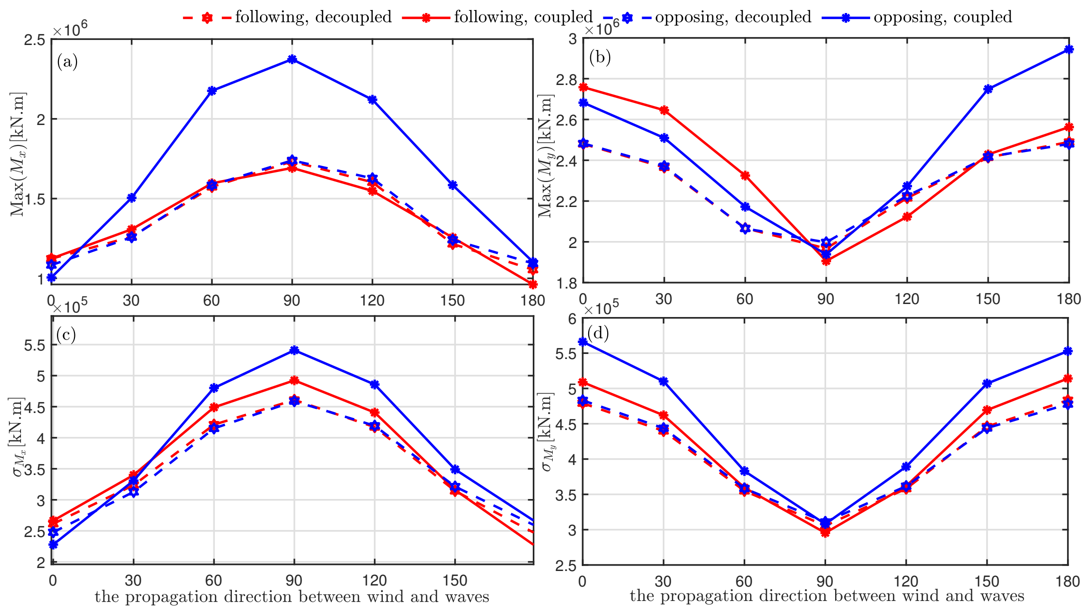

Figure 1: The maximum (panel a b) and standard deviation (panel c d) of hydrodynamic moments on the spar in the load case of SSS.

The maximum and standard deviation of hydrodynamic moments in the x and y direction on the spar with respect to the still water level are shown in Fig. 1, where the load case named SSS in Table 1 was used. Differences in the maximum moment between the wave-current coupled and decoupled models are the most obvious in Fig. 1(a), i.e., as large as by $\sim 36\%$, in the case where the waves propagate perpendicularly to the wind direction. Besides, the presence of both following and opposing currents increase the σ_{M_x} and σ_{M_y}, where the most significant influences are observed when the waves propagate in an angle of 90° and 0° to the wind direction, respectively.

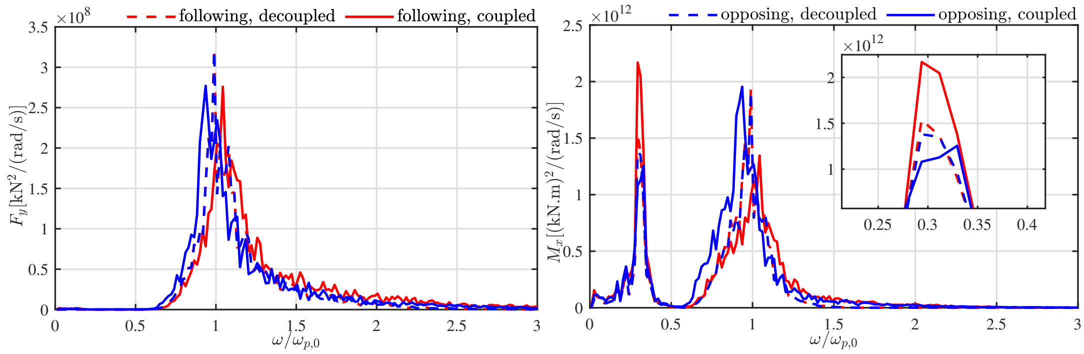

Figure 2: Power spectral densities of hydrodynamic loads when the waves propagate in the perpendicular direction to the wind using the environmental parameters in the load case of SSS in Table 1. $\omega_{p,0}$ denotes for the peak wave frequency in the absence of current.

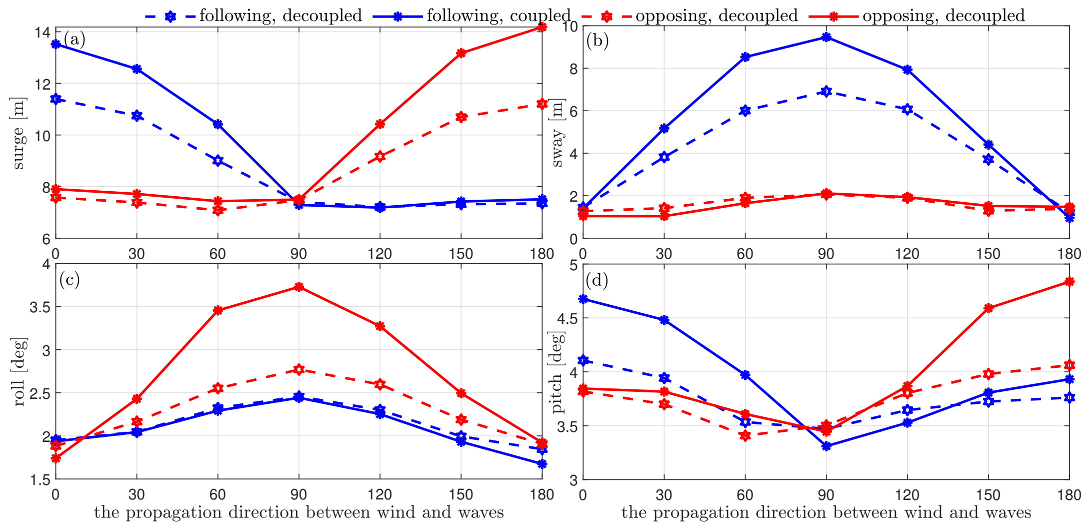

Figure 3: The maximum motions of the spar platform in the load case of SSS.

The power spectral densities (PSDs) of hydrodynamic loads on the spar are shown in Fig.2, where the waves propagate in the perpendicular direction to the wind using the environmental parameters in the load case of SSS. In the general wave frequency range, the wave-current coupled model leads to a frequency shift of the PSD, where the direction of current to wave determines the direction of frequency shift. In the low frequency range, due to the coupled interaction between waves and a following current the peak of the PSD of M_x increases by 41.07%, compared to the decoupled model.

Fig. 3 displays the maximum motions of the spar in the load case of SSS. The wave-current coupling amplifies the magnitudes of the maximum motions of the spar under a particular directional combination of wind, wave, and current. The surge (pitch) and sway (roll) motions exhibit different characteristics, because the former is the result of the combined behaviour of wind, wave and current and the latter is dominated by the loads induced by wave and current. The most notable influence of wave-current interaction on the surge and pitch (sway and roll) motions appears when the waves propagates in an angle of 0° (90°) to the wind direction. Especially, the coupled model of waves and an opposing current leads to a significant increase in the maximum of roll motion by 34.63% when the waves propagate in the perpendicular direction to the wind.

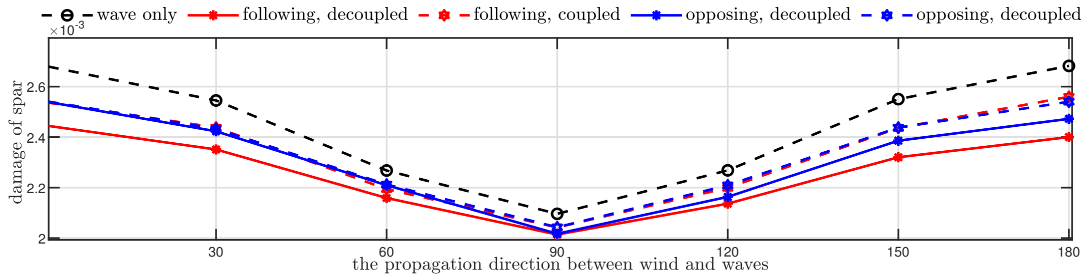

Figure 4: The long term fatigue damage of the spar platform in the load case of NSS.

Fig.4 shows that the 20-year long-term fatigue damage of the spar platform is overestimated slightly in the wave-current decoupled models, especially in the presence of a following current. Overall, the wave-current coupling shows insignificant influences on the fatigue damage of the spar in the load case of NSS in Table 1.

5 Conclusions

This study investigates the roles of wave and current coupled interaction in the hydrodynamic responses of a 15 MW spar-type FWT, like the loads on the spar, the motions of the six degrees of freedom, and fatigue damage to the spar. We report that a coupled model especially plays a considerable role in cases where the wave and current propagate perpendicularly to the wind direction, compared with a decoupled model. The wave-current decoupled model quantitatively differs in a minor manner from the coupled model in normal sea states, while significantly in extreme sea states, highlighting the importance of accurately accounting for the wave-current coupling in extreme sea states.

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