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Comparison of wave load effects on a TLP wind turbine by using computational fluid dynamics and potential flow theory approaches

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ABSTRACT

Tension Leg Platform (TLP) is one of the concepts which shows promising results during initial studies to carry floating wind turbines. One of the concerns regarding tension leg platform wind turbines (TLPWTs) is the high natural frequencies of the structure that may be excited by nonlinear waves loads. Since Computational Fluid Dynamics (CFD) models are capable of capturing nonlinear wave loads, they can lead to better insight about this concern. In the current study, a CFD model based on immersed boundary method, in combination with a two-body structural model of TLPWT is developed to study wave induced responses of TLPWT in deep water. The results are compared with the results of a potential flow theory-finite element software, SIMO-RIFLEX (SR). First, the CFD based model is described and the potential flow theory based model is briefly introduced. Then, a grid sensitivity study is performed and free decay tests are simulated to determine the natural frequencies of different motion modes of the TLPWT. The responses of the TLPWT to regular waves are studied, and the effects of wave height are investigated. For the studied wave heights which vary from small to medium amplitude (wave height over wavelength less than 0.071), the results predicted by the CFD based model are generally in good agreement with the potential flow theory based model. The only considerable difference is the TLPWT mean surge motion which is predicted higher by the CFD model, possibly because of considering the nonlinear effects of the waves loads and applying these loads at the TLPWT instantaneous position in the CFD model. This difference does not considerably affect the important TLPWT design driving parameters such as tendons forces and tower base moment, since it only affects the mean dynamic position of TLPWT. In the current study, the incoming wave frequency is set such that third-harmonic wave frequency coincides with the first tower bending mode frequency. However, for the studied wave conditions a significant excitation of tower natural frequency is not observed. The high stiffness of tendons which results in linear pitch motion of TLPWT hull (less than 0.02 degrees) and tower (less than 0.25 degrees) can explain the limited excitement of the tower first bending mode. The good agreement between CFD and potential flow theory based results for small and medium amplitude waves gives confidence to the proposed CFD based model to be further used for hydrodynamic analysis of floating wind turbines in extreme ocean conditions.

1. Introduction

Wind energy is one of the best options to produce renewable energy. Although land-based wind turbines are well developed, the offshore wind industry is still in development. Currently only 2% of the electricity, produced from wind resources, comes from offshore [1]. The main problem regarding harvesting energy from offshore wind turbines is the total cost of energy, which can be reduced if lighter support structures can be designed to carry offshore wind turbines. Lighter support structure design requires more reliable and precise analysis of the environmental loads.

TLP is one of the support structures which remains stable mainly through the mooring system which includes a number of pre-tensioned stiff tendons. The TLP concept was introduced in 1970s [2] for the oil and gas industry and has been built and used successfully afterwards, however there have always been concerns about nonlinear wave loads on TLPs. These nonlinear wave loads might excite the natural frequencies of the TLPs. Different experimental tests such as the experiments performed by Mercier et al. [3] and Lonergan et al. [4] showed the importance of this high order wave loads on TLPs. Later Faltinsen et al. [5] developed a formula (known as FNV formula), based on potential flow theory, to calculate some components of nonlinear wave loads on slender vertical cylinders.

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Their calculations and derived formula showed the importance of the third-order wave loads when the wave amplitude is of the same order as the cylinder diameter. For TLP structures these third-order wave loads are important since they might coincide with one of the structure's natural frequencies and can lead to transient large amplitude response of the structure (known as ringing) [6].

Initial analysis of TLP platforms to carry wind turbines also shows promising results [7,8]. TLP platforms are very favourable to carry wind turbines because of very small pitch motion, leading to small nacelle motion. However, just as for TLPs designed for the oil and gas industry, TLPWT natural frequencies may be excited by the nonlinear wave loads. The linear hydrodynamic analysis of TLPWT has been studied extensively [9–11]. However, nonlinear models have only been used recently. Roald et al. [12] studied the effect of second-order wave loads on a TLP wind turbine and showed that including the sum-frequency second-order wave loads have considerable effects on the heave response of TLP wind turbine. Bae and Kim [13] studied the sum-frequency second-order wave loads on a TLP wind turbine. Their results for the considered 5 MW TLPWT showed that considering the sum-frequency wave loads may excite the TLPWT pitch natural frequency in the survival condition. Bachynski and Moan [14] studied the third-order loads on a TLPWT using the FNV formula. Their results indicated that, ringing has a considerable effect on the responses of TLPWTs which have natural pitch/bending periods around 3–4 s.

All of the mentioned nonlinear hydrodynamic load investigations are based on potential flow theory analysis which limits the hydrodynamic modeling to linear or weakly nonlinear models. Another approach is to use CFD methods which can model nonlinear wave loads very well. The CFD based models to simulate floating wind turbines are very recent. Beyer et al. [15] studied surge free decay test of a floating wind turbine by coupling a CFD model with FAST [16], a wind turbine design tool. They intended to obtain the damping coefficient of a floating wind turbine by using a CFD approach. Ren et al. [17] used a CFD based commercial software to simulate wind and wave loading on a TLPWT, however their model was only allowed to have surge motion, hence heave and pitch natural frequencies could not be excited. Benitz et al. [18] used OpenFOAM, an open source CFD based code, to study the wave loads on a semi-submersible wind turbine and compared the results with HydroDyn, a potential flow theory based code for hydrodynamic analysis [16]. A good agreement between two results was achieved, however in the simulations the effects of semi-submersible motions on the hydrodynamic loads were neglected. Finally, Liu and Hu [19] and Hu et al. [20] carried out CFD based analysis of different types of semi-submersible floating wind turbines with focus on hydrodynamic loads. They used CIP method [21] for the CFD simulations and compared their results with experimental data and achieved good agreement.

In order to better understand the nonlinear wave loads on TLPWTs, a CFD model in combination with multi-body approach for modeling a TLPWT is presented here and is used to study the interaction of this floating wind turbine with regular waves. Based on the presented model, the tower base bending moment due to the wave loading can also be investigated. All of the numerical results are compared with a potential flow theory-finite element software, SR. By using this CFD approach, the platform is completely free to float, linear assumption for the incoming wave is not required, and nearly all the nonlinear wave loads on the TLPWT can be captured without relying on any experimental coefficients. The current CFD model was initially proposed by Nematbakhsh et al. [22] and used to simulate a single rigid body TLP and a spar buoy floating wind turbine [23]. The numerical model was extended in Nematbakhsh et al. [24] to a two-body model and initial comparisons with potential flow theory approach results were performed for a modified TLPWT which has very stiff tendons and pitch motion was extremely small. The present research significantly extends the previous works [22–24] by improving the structural model of the TLPWT in which the tower and tendons damping effects are also considered, by presenting a more complete description of the two-body model of TLPWT, and by studying the responses of a TLPWT, designed by Bachynski et al. [11] for regular waves. In comparison of the results calculated by the CFD and potential flow theory approaches, in general good agreement between both models is obtained, although some limited differences in nonlinear components of the TLPWT responses are observed which will be discussed.

The rest of the paper is organized as follows. In Section 2, the CFD based model and potential flow theory based software, SR, are described. In Section 3, initially TLPWT free decay tests are performed and natural frequencies of the TLPWT are assessed. Then the responses of the TLPWT to incoming wave which has a chance of exciting the tower first bending mode are examined, and finally the effects of varying wave amplitudes on the TLPWT responses are studied. Conclusions are presented in Section 4.

2. Computational model

In this section the CFD based model which is the main focus of the current work is described in detail and a brief review of the potential flow theory based model is given.

2.1. CFD based model

The numerical model consists of a fluid–structure interaction part and a structural part. The fluid–structure part is developed based on solving Navier–Stokes equations. The structural part consists of the models used to simulate components of the floating wind turbine namely, the tendons, tower, rotor and the nacelle. These two parts are coupled and information is exchanged between these two parts at every time step. In the present work, NREL 5 MW wind turbine [25] is mounted on a TLP. The TLPWT is shown in Fig. 1 and the properties are described in Table 1.

2.1.1. Fluid–structure interaction model

This part consists of solving the Navier–Stokes equations to follow the fluids' motion (water and air), tracking the free surface by using the level set method, modeling the floating wind turbine hull which interacts with water by an immersed boundary method, and finally determining a forcing term which couples this part with the structural part. This part has been verified in the works by Nematbakhsh et al. [22,24,26] by performing different numerical tests including; studying vortex shedding behind a circular cylinder and comparing the results with experimental data, comparing wave induced surge, heave and pitch responses of a barge with experimental data, and comparing hydrodynamic loads on a surface piercing fixed cylinder with experimental data.

The Navier–Stokes equations which are supplemented by the continuity equation can be written as follows for incompressible flows;

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\nabla\cdot(\mathbf{u}\mathbf{u})\right)=-\nabla p+\rho\mathbf{g}+\nabla\cdot\mu(\nabla\mathbf{u}+\nabla\mathbf{u}^T)+\mathbf{F} \quad (1)$$

$$\nabla\cdot\mathbf{u}=0, \quad (2)$$

where ρ is density, $\mathbf{u}$ is velocity, $\mathbf{g}$ is the acceleration due to gravity, and μ is the dynamic viscosity. Eqs. 1 and 2 are the standard equations to model incompressible fluids. There is only a force term $\mathbf{F}$ added to the right hand side of Eq. 1. This term couples the fluid–structure part with the structural part and will be discussed at the end of Structural Model subsection.

The Navier–Stokes equations are solved in the whole domain including the water, the air and the solid by using second-order