Supergen ORE Hub Award FF2019-038
Passive Control of Wave Induced Platform Motions for Semi-submersible FOWTs

Project Summary

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1. Introduction

The offshore wind industry has experienced significant growth in recent years and continues to expand both in the UK and worldwide. Nearly all of the offshore wind turbines installed to date are located in relatively shallow water mounted on fixed bottom support structures. Given the limited availability of suitable shallow water sites with high wind resources and also to reduce the environmental and visual impact of wind turbines it is necessary to extend wind turbine systems to deeper water. However, fixed bottom support structures are not feasible in deeper water so it is necessary to explore floating offshore wind turbine (FOWT) systems. With the recent opening of the world's first full scale floating wind farm (Hywind Scotland) off the north-east coast of Scotland it is envisaged that 8 - 16GW of floating offshore wind capacity will be installed in UK waters by 2050 [1, 2].

There are a number of offshore wind turbine floating platform concepts in various stages of development. Of the three basic concepts (semi-submersible, tension leg platform (TLP) and spar), semi-submersible has recently received significant attention for its relatively shallow draft that improves site flexibility and installation cost effectiveness. However, FOWTs using semi-submersible support substructures may suffer unacceptably large heave, pitch and roll motions due to the resonant response of the structure and the action of extreme waves, which may increase the system downtime, adversely affect the turbine performance and cause damage to the system components including moorings and anchors. To prevent the potential large vertical motion, anti-heave plates, with their favourable hydrodynamic properties providing significantly enhanced system mass (added mass) and viscous damping without increasing support structure size, have been proposed for FOWTs with semi-submersible and spar substructures. On the other hand, owing to the relatively low installation and maintenance costs, passive motion control devices such as tuned mass dampers (TMDs) and tuned liquid column dampers (TLCDs) have found wide use in traditional civil engineering structures and proposed applications in wind turbines to suppress tower and blade vibrations through either blade or tower mounted dampers, but their potential use for limiting the horizontal and rotational motions of the FOWT support structures has not been adequately explored.

Within the context of FOWTs, although limited experimental and numerical investigations have been conducted to demonstrate the effectiveness of TLDs in reducing tower/blade vibrations and platform motions for the tension leg and spar types of support structures, no study of their use in isolation or in combination with anti-heave plates to suppress the motion of semi-submersible support platforms has been done. In a recent review of floating wind technology, the development of lighter and smaller support platforms for FOWTs has been identified as the key cost driver and is most critical for its commercial competitiveness. Of the three basic floating concepts, the semi-submersible platforms have the greatest potential for reducing platform size with improved installation procedures, hence the cost reduction. However, this needs to be achieved without compromising the stability of the structure to ensure that tower-top accelerations are minimised and the support platforms can withstand and survive the impact of extreme waves.

2. Project aims and objectives

The proposed work therefore addresses the broad themes of 'Fluid-Structure-Seabed Interaction' and 'Survivability, Reliability and Design' by evaluating the potential and effectiveness of applying TLD devices combined with anti-heave plates to suppress both translational and rotational motions of semi-submersible FOWT support structures. This will be achieved through a numerical and complementary experimental study of the dynamic response of FOWTs with/without TLDs under both operational and survival conditions.

The aim of the project will be achieved via the following specific objectives/tasks:

(1) Utilise a newly developed and efficient free surface CFD code based on hybrid nonlinear potential and Navier-Stokes solvers for this particular flow problem under both model and full scales; analyse the numerical results to identify the fundamental hydrodynamic loading on FOWTs with TLDs and anti-heave plates in place and scaling effects; set up and perform a small number of runs for FOWT platform motions based on focused wave groups to examine their hydrodynamic characteristics under extreme (random) wave conditions for improved design of TLDs and anti-heave plates.

(2) Conduct a set of carefully configured experiments informed by the numerical simulations on a FOWT model with TLDs and anti-heave plates under various wave conditions for validating the numerical model and aiding the analysis of the underlying flow physics.

3. Summary of work conducted

3.1 Numerical model development and validation

To model the flow problem of liquid sloshing inside a TLCD, the multiphase flow solver "interFoam" in the open-source CFD framework OpenFOAM has been adopted in this work [4, 6]. The flow inside the TLCD system consisting of water and air, as well as their interfaces, is assumed to be incompressible, transient and viscous, and is governed by the continuity and unsteady Reynolds-averaged Navier-Stokes (RANS) equations. The free surface between the water and air is captured by the widely adopted Volume of Fluid (VOF) method and the pressure velocity coupling is achieved through the PIMPLE algorithm (a combination of PISO: Pressure Implicit with Splitting of Operators and SIMPLE: Semi-Implicit Method for pressure-linked Equations).

To check the accuracy of the numerical model for internal liquid sloshing problems, three sets of test cases involving a simplified U-shaped TLCD and three-column star-like tuned liquid multi-column damper (TLMCD) are modelled, which include an internal liquid (water) free-decay test to calibrate the natural angular frequency of the system, the liquid sloshing inside a TLCD under prescribed roll motion and an internal liquid free-decay test for the TLMCD. Figure 1 shows the comparison between the current predictions and other numerical and experimental results for the test case of water sloshing in a U-shaped TLCD under prescribed harmonic rotational motions with a range of excitation frequencies – showing excellent agreements and in turn giving confidence of the current model for predicting liquid sloshing dynamics of TLCDs.

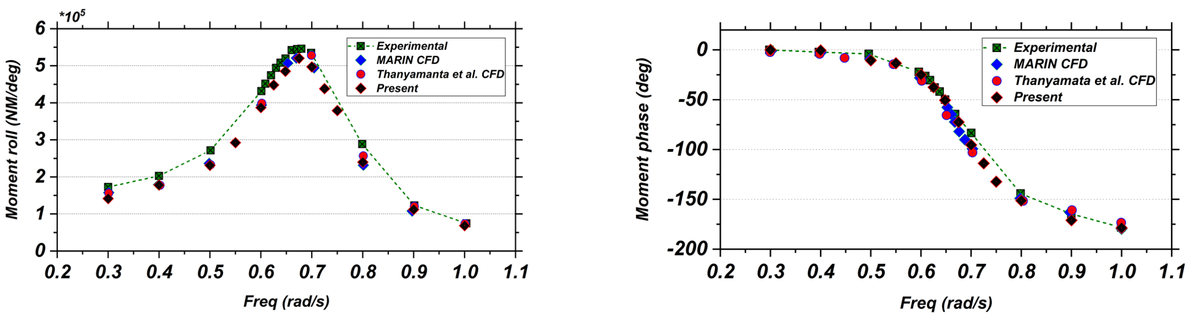

Figure 1 Comparisons of the roll moment amplitude and phase for a U-shaped TLCD

In addition, a fully non-linear potential flow theory based solver has also been developed in the framework of OpenFOAM for modelling liquid sloshing in a tank. The model can be used to analyse sloshing dynamics of TLCDs but with much reduced computational time [3, 5].

3.2 Sloshing dynamics of tuned liquid multi-column damper (TLMCD)

To illustrate how a TLMCD system can be incorporated into a FOWT support structure, the NREL OC4 semi-submersible platform is used as an example. As shown in Figure 2, a star-like TLMCD is designed based on the configuration of its substructure, i.e., the sizes of its offset columns and the crossing braces, and the total mass of the semi-submersible platform. As with other TLCD systems, the natural angular frequency of the TLMCD system i.e., $\omega = 0.233\ \mathrm{rad/s}$ has been tuned (based on Eq. (6)) to be the same as or very close to that of the OC4 semi-submersible platform pitch natural frequency. Note that to achieve this objective for the TLMCD system, the radius of the crossing braces of the semi-submersible support structure has been slightly increased. The lengths of the horizontal and vertical water columns are 56.1 m and 6 m, and the radius of the horizontal and vertical cross-sections are 1.6 m and 4.0 m, respectively.

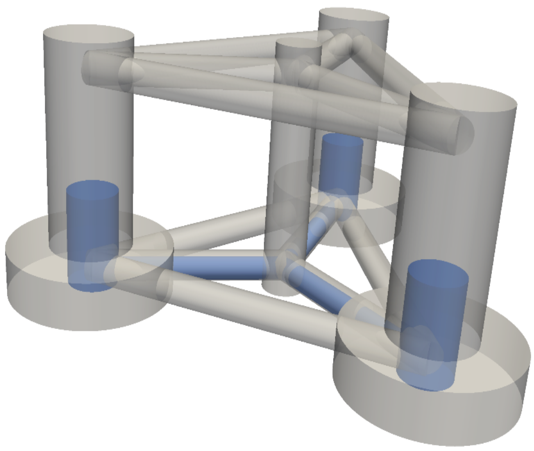

Figure 2 Design of a TLMCD for a semi-submersible FOWT platform

To reveal sloshing dynamics and damping mechanisms of the novel TLMCD as a passive control device for semi-submersible FOWTs, a series of tests of the TLMCD under various external excitations have been conducted using the developed numerical model [6].

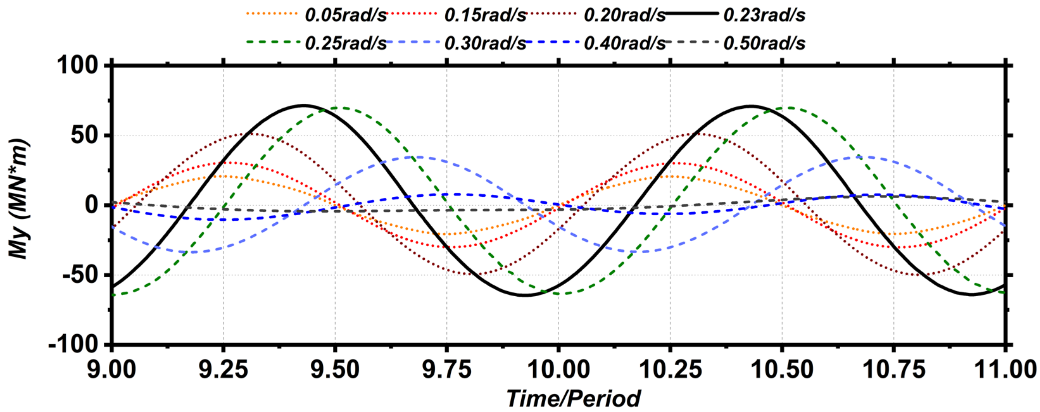

Figure 3 Pitch moment predictions of the three-column star-like TLMCD under pitch excitation

Figure 3 shows the time history of the sloshing induced pitch moment of the TLMCD under pitch only excitation between the sampled oscillation periods (from 9T to 11T) for eight selected excitation frequencies ranging from 0.05 rad/s to 0.5 rad/s. It can be observed that when the external excitation frequency is close to the natural frequency of the TLMCD system (resonant frequency), i.e., ω=0.23 rad/s, the amplitude of the pitch moment reaches a maximum value of nearly 76 MNm. In terms of the phase lag, its value increases from 0 degree at the low excitation frequency to 180 degrees at the high excitation frequency. Close to the resonant frequency, the phase lag is sensitive to the frequency of external excitation, e.g., under the resonant excitation (ω=0.23 rad/s), the phase lag $\varphi = (9.17-9.00)\times 2\pi = 1.068$ rad = 61.2 degrees while it is about 90 degrees when ω=0.25 rad/s. Consider when the TLMCD system is incorporated into a semi-submersible FOWT platform, under wave excitations at or close to the resonance frequency, the phase lag between the hydrodynamic force and dynamic motion of the FOWT is about 90 degrees, and if the phase lag between the dynamic motion of FOWT (the prescribed motion of TLMCD in the current case) and the restoring moment induced by the internal sloshing is also around 90 degrees, then the phase lag between the internal restoring moment and wave hydrodynamic moment will be close to 180 degrees. In other words, the sloshing induced moment from a TLMCD will cancel out part of the wave induced moment on the structure and hence a reduced rotational motion. However, from the simulation results, it can be shown that at the resonant frequency, the phase lag between the sloshing induced moment and the external excitation is below 90 degrees and to achieve optimal damping from a TLMCD, a small shift from the resonant frequency may to be applied to the natural frequency of the device.

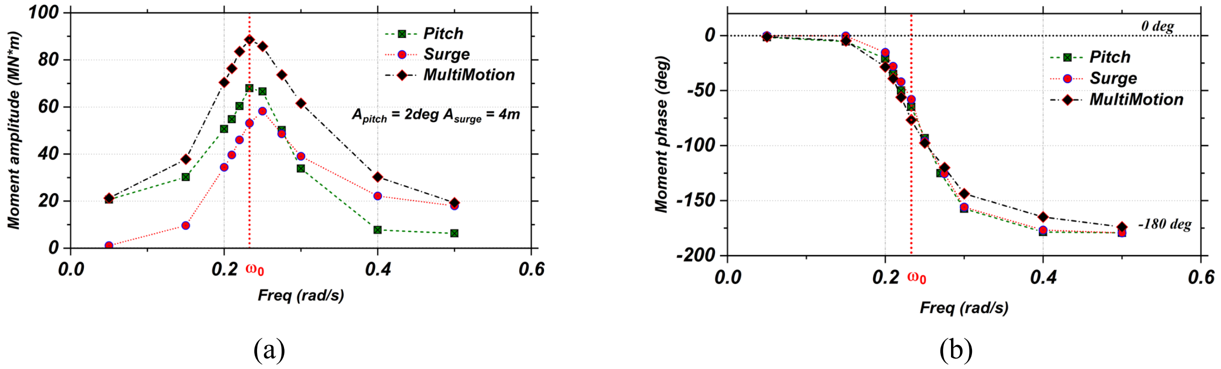

Figure 4 Pitch moment statistics; (a) Amplitude (b) Phase lag

Figure 4 (a) and (b) summarise the results of the pitch moment amplitude and phase lag for the three-column star-like TLMCD under the pitch, surge and combined pitch and surge excitations. From these results, two observations can be made. Firstly, the amplitude of the pitch moment induced by the combined surge and pitch motion is quite close to the linear superposition of the moment under the prescribed pitch only and surge only motion at either low frequency or high frequency excitation that strong nonlinearities do not occur, although the location of the maximum moment for the surge only case is slightly shifted to the right from the resonance frequency. Secondly, the phase lag in the sloshing induced pitch moment is not significantly affected by the motion types and in the region close to the resonance frequency, a phase lag of around 90 degrees can be achieved. As discussed in the previous sections, this has critical implications for a TLMCD to be effective in reducing the wave induced rotational motions of FOWTs.

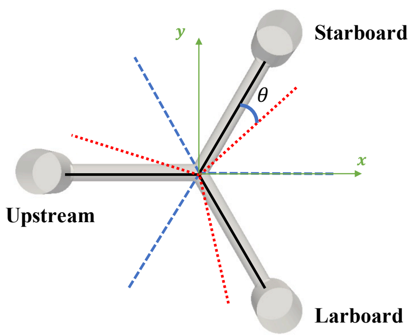

Figure 5 The change of TLMCD yaw angles

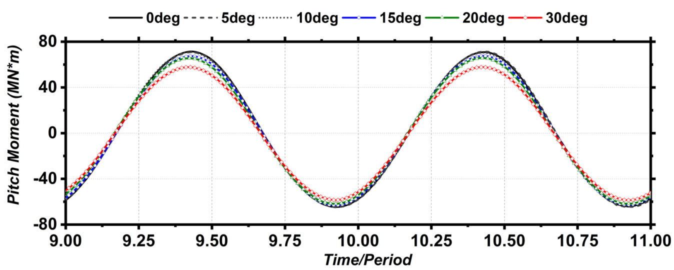

Figure 6 Sloshing induced pitch moment of the TLMCD under pitch and roll excitation and different yaw angles

To assess the robustness of the three-column star-like TLMCD in providing restoring moments against the rotational motions of a semi-submersible FOWT under different incident wave directions, sloshing inside the TLMCD with different yaw angles under the pitch excitation has also been modelled. As shown in Figure 5 the angle between any two adjacent columns of the TLMCD is 120 degrees and if the TLMCD is turned by 60 degrees around the z-axis, the structure will be simply mirrored to the YoZ plane, resulting in identical sloshing dynamics. Therefore, to avoid duplication of test cases, the considered yaw angles of the device range from 0 deg to 30 deg. The prescribed amplitude of pitch motion is 2 degrees and the oscillation angular frequency is set at the resonance value of 0.233 rad/s. Focusing on the predicted pitch moments, which are plotted in Figure 6, while they are in phase with each other, their amplitudes will slightly drop with an increase in the yaw angles. For example, only a small drop of the pitch moment amplitude from the maximum value of 69.4 MNm at the 0 degree of yaw angle can be observed for the cases of 5, 10, 15 and 20 degrees. At 30 degrees, the amplitude of the pitch moment reaches its lowest value of 59.6 MNm, which is around 14% smaller than the result under 0 degree. This can be explained by the fact that as the yaw angle is 30 degrees, only two columns (the Upstream and Larboard columns as referred to in Figure 5) will be most effective for providing restoring moments through water sloshing up and down. The above results demonstrate that the three-column star-like TLMCD is more robust for FOWT applications as the sloshing-induced anti-rotational pitch moment is not significantly affected by the change of the yaw angle and could be a better option than U-shaped TLCDs for reducing the platform motion.

3.3 Analysis of the integrated FOWT and TLMCD system

Further to the sloshing only modelling, dynamics of the coupled floater and TLMCD system under regular waves are modelled. Figure 7 plots the surge and pitch motions of the semi-submersible platform with/without TLMCD under two different incident wave periods, i.e., T=12.1 & 18.0s. From these results, we can conclude that the existence of the star-like three-column TLMCD has a negligible influence on the translational motions such as the surge under different incident waves. It is noted that in the North Sea the widely adopted regular wave is at the wave period of T=12.1s. In addition, the TLMCD does not lead to the unexpected additional pitch motion response of the entire system compared to the original design.

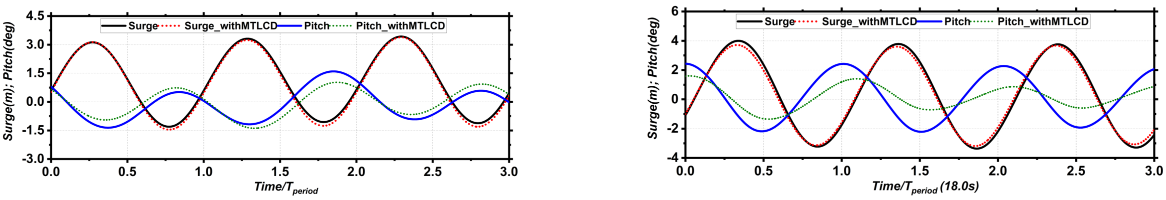

Figure 7 Surge and pitch motions for different semi-submersible configurations with different incident wave periods, top: T=12.1s; bottom: T=18.0s

However, the difference of the pitch motion between different semi-submersible platform configurations is notable when the floating structure experiences the regular wave with the wave period close to the pitch natural period, i.e., T=18.0s. At this wave frequency, the pitch motion decreases significantly with the introduction of TLMCD. Additionally, it is shown in Figure 7 that there is a phase lag in the pitch motion around 1/5T between different semi-submersible platform models, indicating that not only the internal sloshing force acts adversely with the external wave forces, but also the phase lag between those two forces is evident.

In particular, the performance of FOWT aerodynamic is different with both the offshore bottom-fixed wind turbine and the onshore wind turbine aerodynamics due to the existence of the floating structure. The large surge and pitch motion amplitudes of the FOWT can increase the fluctuations of either the thrust force or the power output. If the passive control TLMCD system can work efficiently with the FOWT in a wide range of wave periods, even under extreme sea states, it could contribute significantly to the design and manufacture of the FOWT industry, and relatively decrease the level of LCOE regarding the maintenance and fatigue damage evaluation.

3.4 Wave Tank Tests (Ningbo University, China)

To provide validation test cases and as part of the in-kind contributions (worth over £20k) to the project, in the original plan, a series of complementary laboratory experiments at the Marine and Naval Architecture Laboratory at Ningbo University was proposed to investigate the dynamic responses of a semi-submersible FOWT model with and without TLMCDs under a range of wave conditions. However, due to the restrictions imposed by COVID-19 in China, the laboratory was closed for the majority time in 2021 and 2022, meaning the experiments could not go ahead as planned. To mitigate the impact on the project, existing experiments and other numerical results have instead been used to validate the current numerical models for liquid sloshing problems.

4. Summary of outputs and dissemination

Through the support of the project, 2 journal and 2 conference papers have been published [3-6]. In [3], a new 3-dimensional finite volume method based fully nonlinear potential flow solver in the non-inertial coordinate system was developed and validated against a number of experimental and numerical results for liquid sloshing in tanks. The developed the code is computationally efficient and can be applied to investigate sloshing dynamics of tuned liquid dampers for FOWTs. The conference paper was further extended and updated into a journal paper which was published in International Journal of offshore and Polar Engineering [5]. In [4], OpenFOAM has been adopted and further developed to study the impact of a novel multi-column tuned liquid damper on dynamic response of a semi-submersible FOWT support structure. A fully coupled floating-sloshing modelling was conducted to simulate the semi-submersible FOWT with an integrated TLMCD under regular wave conditions. The study indicates that while the TLMCD system as a passive control device has little influence on the translational motions such as surge and heave, the pitch motions can be reduced significantly when the incident wave frequency is close to the natural pitch frequency of the platform. To better understand the mechanisms of the TLMCD for mitigating rotational motions of a semi-submersible floating offshore wind turbine (FOWT) and to evaluate its performance, in [6], flow inside the novel passive control device is numerically modelled using a high-fidelity CFD approach. Test cases of the device under various external excitations including single degree surge and pitch as well as combined surge/pitch have been simulated. Through analysing the results of the predicted sloshing induced moments on the TLMCD structure and their phases under a range of external excitation frequencies, it was found that although the maximum sloshing induced moments always occur at or very close to the resonance excitations, their phases may not be exactly opposite to those of the wave-induced moments on a FOWT platform - this has important implications to the optimal design of the TLMCD system for floating wind turbine applications.

Finally, summary presentations of the project were given at the Supergen ORE Annual Assembly in November 2019, January 2021and June 2022, as well as at other workshops and project meetings relating to floating offshore wind technologies.

5. New funding opportunities

During the project, further support from the EPSRC has been sought and granted through our successful application for the Access to HPC Call Autumn 2021, with a project titled 'Survivability and Passive Control Design of Offshore Floating Wind Substructures'. The project provided the required computational resources for the Supergen ORE Hub Flexible Fund project with the allocation of the 4,617,000 Corehs with 500GB /home and 8TB /work on the EPSRC Tier-2 Cirrus Service.

The outcome from the project will contribute to a planned new grant application to the EPSRC which will develop advanced modelling tools for the next generation of floating offshore wind turbines including the incorporation of the passive control strategies developed in the project for mitigating platform motions of FOWTs.

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