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INVESTIGATIONS ON THE EFFECTS OF INTERNAL LIQUID SLOSHING OF SEMI-SUBMERSIBLE FLOATING OFFSHORE WIND TURBINES

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ABSTRACT

Originally developed for civil engineering applications, the tuned liquid column damper (TLCD) has been applied not only on tall buildings but also on floating offshore wind turbines (FOWTs) to minimize structural vibrations. This concept has also been adopted widely in navel architecture to reduce the roll motion. However, whether the damper will bring positive effects on mitigating the dynamic motions of FOWTs remains unknown.

To this end, the paper studies the star-like three columns tuned liquid multi-column damper (TLMCD) impacts on the dynamic motions of a semi-submersible FOWT. The modelling is achieved by using a high-fidelity computational fluid dynamic (CFD) solver based on OpenFOAM. After the verification of the numerical model for the TLMCD system, it is extended to the modelling of the internal sloshing of TLMCD under prescribed pitch motions. A fully coupled floating-sloshing modelling is then conducted to simulate a semi-submersible FOWT with an integrated TLMCD under regular wave conditions. The study indicates that the passive-control TLMCD system has nearly no influence on the translational motions such as surge and heave. However, the pitch motions can be reduced significantly when the incident wave frequency is close to the natural pitch frequency of the platform. Apart from the natural pitch frequency, the TLMCD has a minor effect at other incident wave frequencies.

Keywords: Multiple Tuned Liquid Damper (TLMCD), Computational Fluid Dynamics (CFD), Floating offshore wind turbine (FOWT), Semi-submersible, OpenFOAM

1. INTRODUCTION

The offshore wind industry has experienced significant growth in recent years and continues to expand both in the UK and worldwide. According to the Wind Europe reports in 2020 [1], 25GW offshore wind capacity has been installed in Europe across 11 countries. Meanwhile, over 5,000 wind turbines were deployed along 9 offshore wind farms that connected to the grid and covered nearly 1.5% of the annual European energy demand. Based on the pre-COVID-19 forecast [2], 450GW of offshore wind will be installed and 30% of Europe's annual electricity demand will be supplied by offshore wind resources in 2050. However, 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 to harvest abundant clean wind resources.

Despite the advantages of FOWTs due to their locations, i.e., higher average wind speed and less environmental impact when compared with onshore ones, the FOWTs are more likely to be exposed to complex and harsh environmental conditions induced by either high crest waves, windstorms or wave currents [3]. Those external excitations may increase the system downtime, adversely affect the turbine performance and cause damage to the system components including moorings and anchors. More importantly, the extreme wave loads will lead to potentially large translational and rotational motions of floating substructures. Accordingly, it is essential to investigate and attempt to mitigate the large motions with effective control methods to protect the offshore wind power life cycle.

Regarding the control system of FOWT, the majority of the studies focused on the active-control system to regulate the wind turbine aerodynamic performance, i.e., wind turbine pitch control and generator torque control [4]. Less attention has been paid to the control of the motion response of floating platforms. On the other hand, owing to the relatively low installation and maintenance costs, passive motion control devices of the platform motion such as tuned mass dampers (TMDs) [5] and tuned liquid column dampers (TLCDs) [6] have been adopted conventionally in traditional civil engineering structures to minimize vibrations. As one of the means of suppressing vibrations, a TLCD is a water tank partially filled with liquid and utilized in tall buildings to reduce the effects of seismic waves [7]. TLCD is designed to align with the natural frequency of a structure and its damping effects is achieved through the gravitational/sloshing restoring forces.

Similarly, the passive-control system is proposed for wind turbines to suppress tower and blade vibrations through either blade or tower-mounted dampers, but their potential use for limiting the dynamic motions of the FOWT support structures has not been adequately explored. Limited studies have shown that such low-cost control system can potentially adopted for the floating wind turbine system to reduce the dynamic motions. For

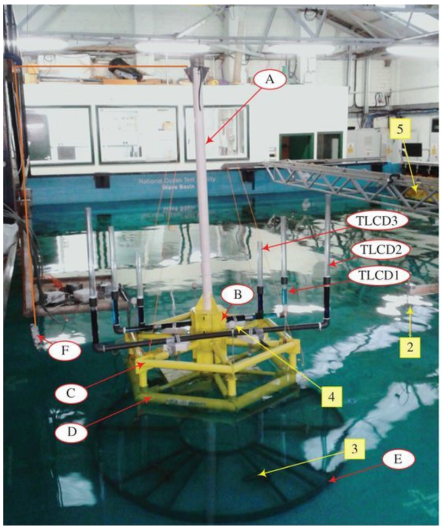

Figure 1 1:50 scaled TLP with multiple TLCDs in wave tank [8]

example, Ha et al. [9] tested out the applicability of the top-located TLCD on the spar-type FOWT by comparing the pitch motion response with/without a TLCD. The study indicated that the TLCD could aid the structure to reduce the pitch motions under certain excitation frequencies. The study also compared the pitch motions by using the single-layer TLCD and multi-layer TLCD and confirmed that the multi-layer TLCD is more promising to effectively minimize the rotational motion than the single-layer one. Jaksic et al. [8] studied the effect of the top-located multiple tuned liquid column dampers (TLMCD) on the dynamic response of the Tension Leg Platform (TLP) structure by using an experimental approach in a wave basin. The experimental study showed that the TLMCD can use the power of sloshing water to reduce surge motions of a floating TLP exposed to wind and waves.

Within the context of FOWTs, although limited experimental and numerical investigations have been conducted to demonstrate the effectiveness of TLCDs in reducing 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 most widely adopted FOWT semi-submersible support platforms has been done. Of the three basic floating concepts, the semi-submersible platforms have the greatest potential in reducing the 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 minimized and the support platforms can withstand and survive the worst impact during extreme waves. Moreover, most designed TLCDs applied on the FOWT are located on the top of the floating substructure which is similar to the one shown in Figure 1. Owing to the popularity of the semi-submersible platform with three side offset columns, it is worthwhile to investigate the possibility of designing an effective TLMCD which can be integrated into the exiting support structures, similar to the anti-roll tank applied on the ship to reduce the roll motions.

Aiming at understanding the fundamental physical mechanisms of internal liquid sloshing (passive control system) on motions of offshore floating support structures and hence their survivability under harsh ocean environments, an open source high-fidelity CFD software, i.e. OpenFOAM, is further developed and applied to model the complex wave-structure-internal liquid sloshing interaction problem. In this paper, as a preliminary investigation, a series of numerical tests are designed and conducted to reveal the damping mechanisms of the passive control system for improved survivability of FOWTs.

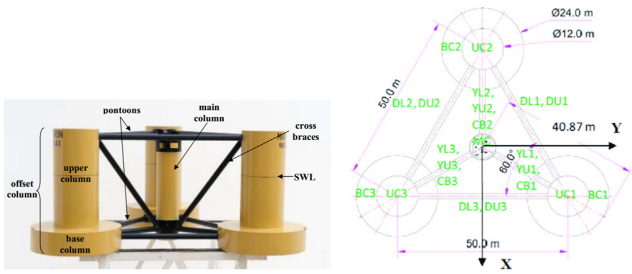

Figure 2 Definition of semi-submersible platform [4]

2. PROBLEM STATEMENT

As a benchmark for FOWTs, the DeepCwind semi-submersible platform (Figure 2) is adopted as the platform type for the present study. It is made up of three offset columns with large heave plate bases, one column at the centre to support the wind turbine and several connecting braces to reinforce the structure. Three mooring lines are attached to the floater with each mooring line's fairlead at each side column. The natural periods of semi-submersible for the mode of the surge, heave and pitch are 107s, 18s, and 27s respectively.

The supporting substructure type is further simplified to accommodate the passive control system, i.e., TLMCDs, as plotted in Figure 3, for a typical star-like three-column TLMCD. Since we have to make sure the natural frequency of the TLMCDs is identical to that of the floater, the analytical formulation of the natural frequency as provided in [10] can be written as,

$$\omega_0 = \sqrt{\frac{2 * g}{L_h * \frac{A_v}{A_h} + 2 * L_v}} \tag{1}$$

where ω_0 represents the natural frequency of the three-column TLMCD and g denotes the gravitational acceleration. As shown in Figure 3, A_v and A_h refer to the cross-sectional areas of the vertical and horizontal columns. L_h is twice the length from the bottom of the vertical column to the centre of the three star-like horizontal columns. L_h denotes the still water level in each vertical side column.

In the following study, a parametric study will be firstly conducted to investigate the impact of TLMCDs under prescribed motions without the introduction of incident waves which can be considered as a sloshing only modelling. The analysis includes the system natural period calibration, the influence of the external excitations on the hydrodynamic forces, the detailed flow phenomena near the sharp edges of the TLCDs. Next, the semi-submersible platform with an TLMCD will be modelled under several working conditions. The results will be analysed and a set of provisional guidance on the design of TLCDs for semi-submersible FOWTs will be provided.

3. METHODOLOGY

In order to conduct the complex floating-sloshing modelling with a high-fidelity approach, the incompressible unsteady Reynolds averaged Navier-Stokes (URANS) equations are solved for the viscous flow model while a volume of fluid (VOF) method is utilized for the two-phase flow in order to capture the free surface. The finite volume method is adopted to solve the N-S equations. A wave generation utility based on the multiphase solver “interFoam” in OpenFOAM is incorporated to generate and absorb waves. Detailed information is introduced in the following section.

3.1 Flow solver

The continuity equation for a transient, incompressible and viscous fluid is given as:

$$\nabla \cdot U = 0 \tag{2}$$

In addition, the Navier-Stokes equations are written as

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot \left(\rho \left(U - U_g\right) U\right) = -\nabla P_d - g \cdot x \nabla \rho + \nabla\left(\mu_{eff} \nabla \mathrm{U}\right) + (\nabla \mathrm{U}) \cdot \mu_{eff} + f_\sigma \tag{3}$$

in which $\mathbf{U}$ and $\mathbf{U_g}$ is the flow velocity of the flow field and the grid nodes in Cartesian coordinates; $\nabla = \partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$ is the differential operator; ρ refers to the mixed density of water and air; $\mathbf{g}$ denotes the gravity acceleration vector and $P_t = P - \rho \mathbf{g} \cdot \mathbf{x}$ is the dynamic pressure obtained by the total pressure P minus the hydrostatic pressure $\rho \mathbf{g} \cdot \mathbf{x}$. The formula $\mu_{eff} = \rho\,(v + v_t)$ is used to calculate the effective dynamic viscosity, in which v and v_t are the kinematic and eddy viscosity respectively; $\mathbf{f_\sigma}$ denotes the surface tension term included for the completeness of the equations and its effects can be ignored in the current simulations.

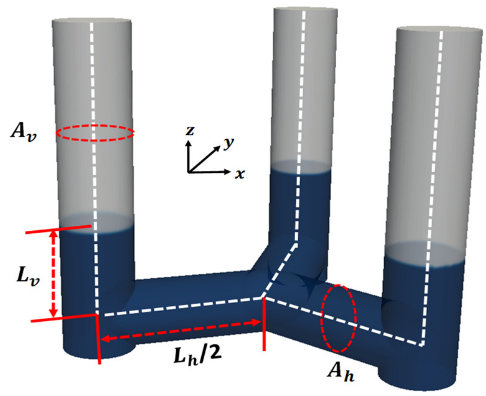

Figure 3 Sketch of a star like three column TLMCD design

In order to capture the water-air free surface, the Volume of Fluid (VOF) method [11] is adopted, using the following transport equations to govern the volume fraction variable α,

$$\frac{\partial \alpha}{\alpha t} + \nabla \cdot \left[\left(U - U_g\right)\alpha\right] + \nabla \cdot \left[U_r(1-\alpha)\alpha\right] = 0 \tag{4}$$

For a multiphase flow problem, the volume fraction of each liquid is used as the weighting factor to get the mixture properties, such as the density and the viscosity,

$$\rho = \alpha \rho_w + (1-\alpha)\rho_a \tag{5}$$

$$\mu = \alpha \mu_w + (1-\alpha)\mu_a \tag{6}$$

where ρ_w and ρ_a are the density of water and air. Furthermore, μ_w and μ_a refer to the viscosity coefficient of water and air respectively.

3.1 Wave generation and absorption

Toolbox “waves2Foam” [12] is used to generate and absorb free surface waves in a numerical wave tank. The relaxation zone technique is adopted to provide a better wave quality and to avoid the wave reflection in the absorbing zone, which are applied at the inlet and outlet boundaries of the numerical wave tank. The following equations specify the main function of the relaxation zones,

$$\alpha_R(\chi_R) = 1 - \frac{\exp(\chi_R{}^{3.5}) - 1}{\exp(1) - 1} \tag{7}$$

$$\phi_R = \omega_R \phi_R^{computed} + (1-\omega_R)\phi_R^{target} \tag{8}$$

where ϕ_R refers to either the velocity or the volume fraction α. The definition of χ_R is that the weighting function α_R is always 1 at the interface between the non-relaxed computational domain and the relaxation zone, and χ_R is a value between 0 and 1. The superscripts *computed* and *target* represent the values calculated in the computational domain and evaluated from the chosen wave model respectively. ω_R is a weighting function calculated based on different relaxation method.

Table 1 Configuration of the benchmark star-like three-column TLMCD

Parameter	L_h	A_v	A_h	L_v
Value	$10m$	$3.14m^2$	$3.14m^2$	$4.33m$

Table 2 Comparison of the natural frequency with different modelling approaches

Natural Frequency	Analytical	Yu et al. [13]	Present(medium)
ω_0 (rad/s)	1.028	1.053	1.087

4. VERIFICATION AND VALIDATION

4.1 Verification of TLMCD model

The verification of the star-like three-column TLMCD model is conducted first and the key parameters are provided in Table 1. The natural frequency of the system is compared with the analytical data and other CFD results for a benchmark three-column TLMCD configuration [13] via a transient decay test where the initial free surface elevation in different columns is 3, 5, 5 m, respectively. Under the effects of gravity and fluid viscosity, the water columns will exhibit oscillatory motions while their amplitudes reduce over the time.

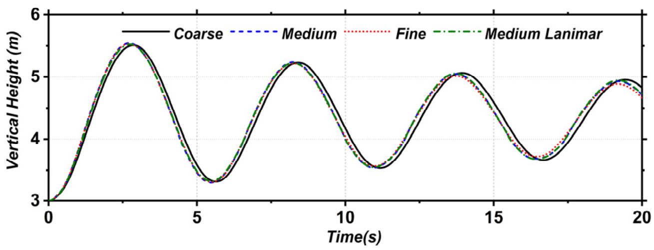

Figure 4 Transient decay test of benchmark three-column TLMCD under different mesh refinement methods

A mesh convergence test is carried out to find out the appropriate mesh sizes for the flow problem. The standard k-epsilon turbulence model is adopted in the present simulation. Three different meshes with different densities are used in the current study, i.e., Fine (83k cells); Medium (49k cells); Coarse (28k cells). The results in

Table *2* and Figure 4 show that with a sufficiently fine mesh, the predicted natural period is not sensitive to different mesh sizes and is in good agreement with the analytical results. It is noted that the green line is captured without using the turbulence model (laminar) under the medium mesh.

4.2 Validation of dynamic response of FOWT

The present high-fidelity CFD solver has been validated for a benchmark semi-submersible FOWT in the previous paper [14]. Specifically, the hydro-aero-mooring multiphase solver is carefully validated by predicting the dynamic responses of the floating substructure, the aerodynamic performance of the wind turbine and the tension loads of the mooring lines under regular wave and uniform wind conditions. The results are in a good agreement with the wave tank tests utilizing a 1/50 scaled model and widely used engineering tools based on a potential flow method and blade element method named NREL FAST.

5. SELECTED CASES AND NUMERICAL SETUP

To study the effects of the TLMCD on the semi-submersible floating platform especially its ability to minimize the pitch motions of the entire floating system, the passive-control TLMCD system is designed to ensure that the natural period is as close as that of the semi-submersible platform. Through comparing the configuration and dimensions of the semi-submersible platform and the TLMCD, L_h can be determined as a constant of 57.72m as can be referred in Figure 2. Since the original cross-sectional area of the bracers used to connect adjacent offset columns is not appropriate to for the TLMCD system, the radius of the crossing bracers has been increased from $R = 0.8m$ to $R = 2m$. Additionally, few crossing bracers together with the centre column are removed from the

Table 3 Selected case for TLMCD sloshing only

Selected cases	Pitch Amplitude(deg)	Frequency(rad/s)
TLMCD without nozzle	5	0.172;0.344;0.688
TLMCD with nozzle (1/9A)	5	0.172;0.344;0.688
TLMCD with nozzle (4/9A)	5	0.172;0.344;0.688

Table 4 Platform gross properties

Platform mass (without TLMCD)	1.414e7 kg
Platform mass (with TLMCD)	1.238e7 kg
Displacement	13,986.8 m^3
Platform draft	20 m
Centre of gravity below SWL	10.21m
Platform roll inertia	1.315×10^{10} kgm^2
Platform yaw inertia	1.315×10^{10} kgm^2
Platform roll inertia	1.906×10^{10} kgm^2

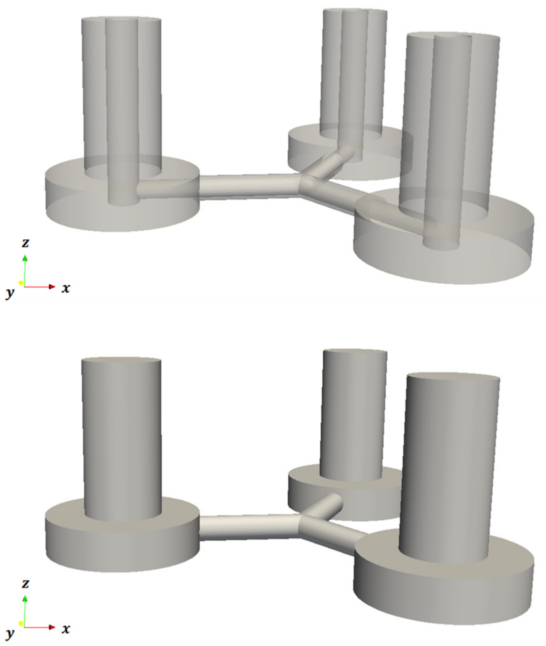

Figure 5 Sketch of the modified Semi-submersible platform; top: with TLMCD bottom: without TLMCD

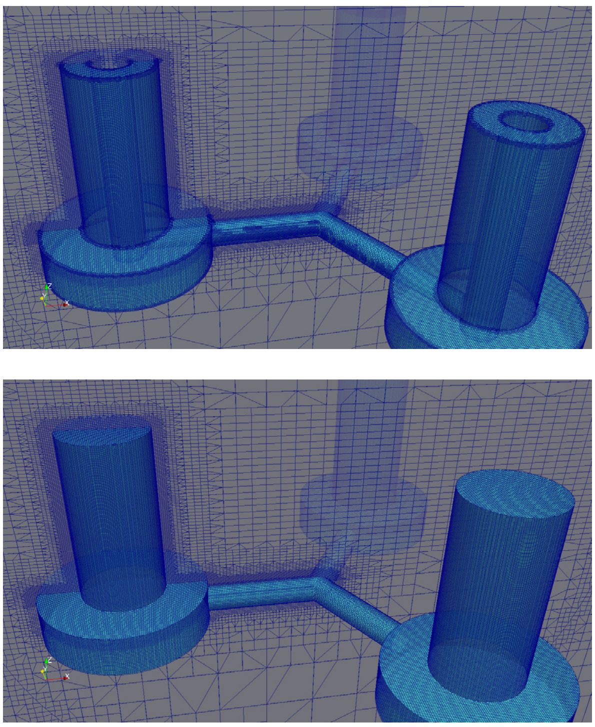

Figure 6 Computational domain of semi-submersible platform; top: with TLMCD bottom: without TLMCD

semi-sub model to better fit the inside sloshing system and to simplify the modelling process/subsequent analysis. Similar approaches has been conducted during the OC6 phase I project by removing all the bracers and centre columns to investigate the nonlinear forces conducted on the structure [15].

Figure 5 plots the sketch of the modified semi-submersible platform with/without the star-like three-column TLMCD system inside. As for the TLMCD system, the A_v and A_h are calculated based on Equation 1 and refer to 19.157 m^2 and 7.065 m^2, respectively.

Firstly, the three-column TLMCD only are modelled under prescribed pitch motions without the introduction of the semi-submersible floater and the incident waves. Similar to the design method on the anti-roll tank utilized on a ship, nozzles with different cross-sectional areas are added on the three horizontal columns TLMCD to investigate whether the range of working frequency can be changed or broadened. The cross-sectional area of the nozzle is set as 0.785 m2 and 3.14 m2, respectively, which is 1/9 and 4/9 of the original TLMCD horizontal cross-sectional area. Totally, nine cases are simulated as summarized in Table 3.

The prescribed pitch amplitude is fixed as 5 deg, while the excitation frequency refers to 0.172 ($0.5\omega_0$), 0.344 ($1\omega_0$), and 0.688 ($2\omega_0$) rad/s. These sets of cases can be regarded as sloshing only modelling. The aim of those cases is to understand the hydrodynamic loads conducted on the entire TLMCD system under different excitations, which can lay a solid foundation to understand what role the TLMCD will play when it is introduced in the semi-submersible platform.

Next, the semi-submersible platform together with the inner sloshing TLMCD system is modelled under regular waves which is selected based on some of the benchmark north sea states, i.e, A=3.79m, T=12.1 s & 18.0 s. This can be treated as coupled floating-sloshing modelling. Since the upper structures (tower and wind turbine) of the semi-submersible FOWT are not considered in the present simulation, the inflow wind is not introduced in the current model. The one without the inner passive control system is also modelled for the purpose of comparison. The gross properties are listed in Table 4. It is noted that the mass between the two models varies due to the existence of the sloshing water inside the model with TLMCD. Since the mass of sloshing water counts a small proportion of the mass of entire system, we assume the gross properties of the entire floating substructure is identical between two models. Additionally, three mooring lines are added to prevent the floater from drifting away, and the properties of the mooring line can be found in the following papers [14, 16].

Figure 6 shows the partial mesh on the semi-submersible platform in the computational domain. An OpenFOAM built-in tool (snappyHexMesh) has been used to generate the computational mesh. The total mesh numbers in the present CFD computations for all the cases refer to 4.35 million (with TLMCD) and 3.93 million (without TLMCD). Grid refinement is applied near the free surface and the floating substructure. The lengths of the inlet and outlet zones are equal to one and two wavelengths. The origin of the coordinate system is located at the centre of the semi-submersible platform and the incident wave flow direction is along the positive *x*-axis. The time step is

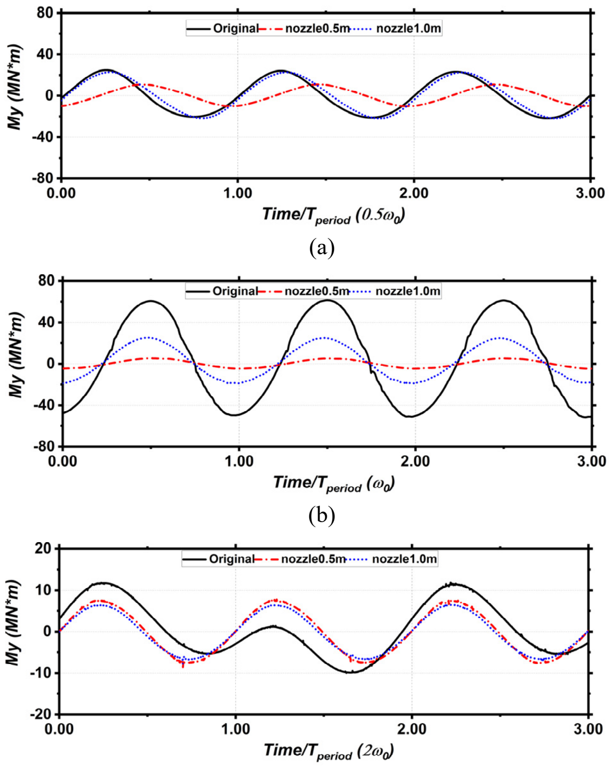

Figure 7 Pitch moment of different TLMCD configurations under pitch amplitude 5 deg and different excitation frequencies (a) 0.5 ω_0 (b) 1.0 ω_0 (c) 2.0 ω_0

set as small as 0.005s for the simulations. The total simulation time lasts for 200s.

6. RESULTS

6.1 Sloshing only modelling for the three-column TLMCD

Figure 7 shows the time history of the pitch moment of three types of TLMCDs under different excitation frequencies in three sampled periods. As can be seen, the difference in M_y is notable when the excitation frequency is identical with the natural frequency of the system as shown in Figure 7 (b). The TLMCD without the design of nozzles reaches the maximum pitch moment amplitude around 62MNm. This could be caused by the introduction of the nozzles which can affect the cross-sectional area of the bottom horizontal columns and lead to the change of the natural frequency. Referring to Figure 8, which plots the free surface contour at the upstream column and the streamline near the junction of the vertical and horizontal columns, high flow speed together with the flow vortices can be observed evidently. The introduction of nozzles can cause the vortices to be more complex and the flow speed is definitely influenced.

At the other excitation frequencies plotted in Figure 7 (a) & (c), when the frequency is lower than the TLMCD natural frequency, the variance between the original TLMCD design and the one with a width nozzle (1.0m) is negligible, and only small phase lag can be found. Nonetheless, the TLMCD with the smallest nozzle behaves differently with a phase lag of around 1/4T. As the excitation frequency increases from 0.5 ω_0 to 2 ω_0, the phase lag is not visible. Interestingly, a non-periodic state could be found under the original TLMCD model while the pitch moments of other geometries are more stable.

Based on the above results, we can conclude that when the excitation frequency of the prescribed rotational motion is aligned with the system natural frequency, the maximum pitch moment could be reached. As for the functionality of the nozzles, with proper design of such equipment, the phase lag of the pitch moment is different with the design without nozzles under the same level of pitch motion amplitude.

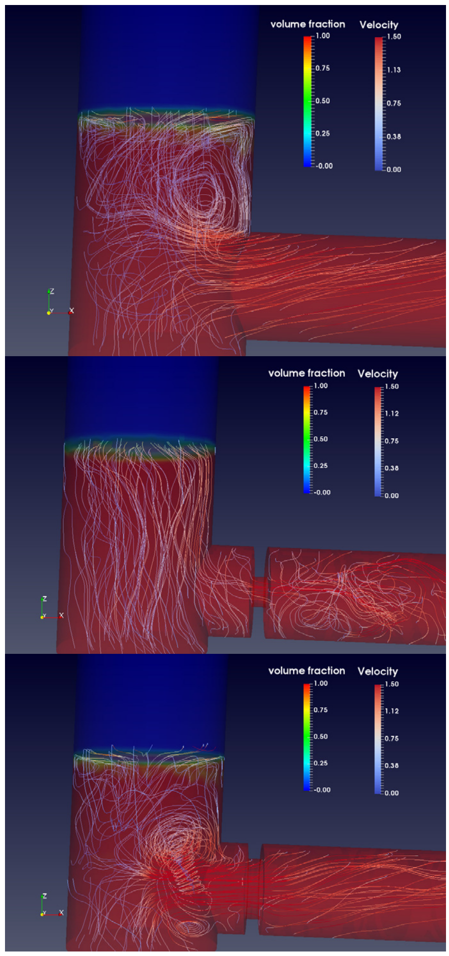

Figure 8 Free surface contours and the streamline of the upstream column under the prescribed motion A = 5 deg, $\omega = 0.5\omega_0$

6.2 Coupled floating-sloshing modelling (semi-submersible platform with/without TLMCD)

Moving from the sloshing only modelling to a coupled floating-sloshing system, Figure 9 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-

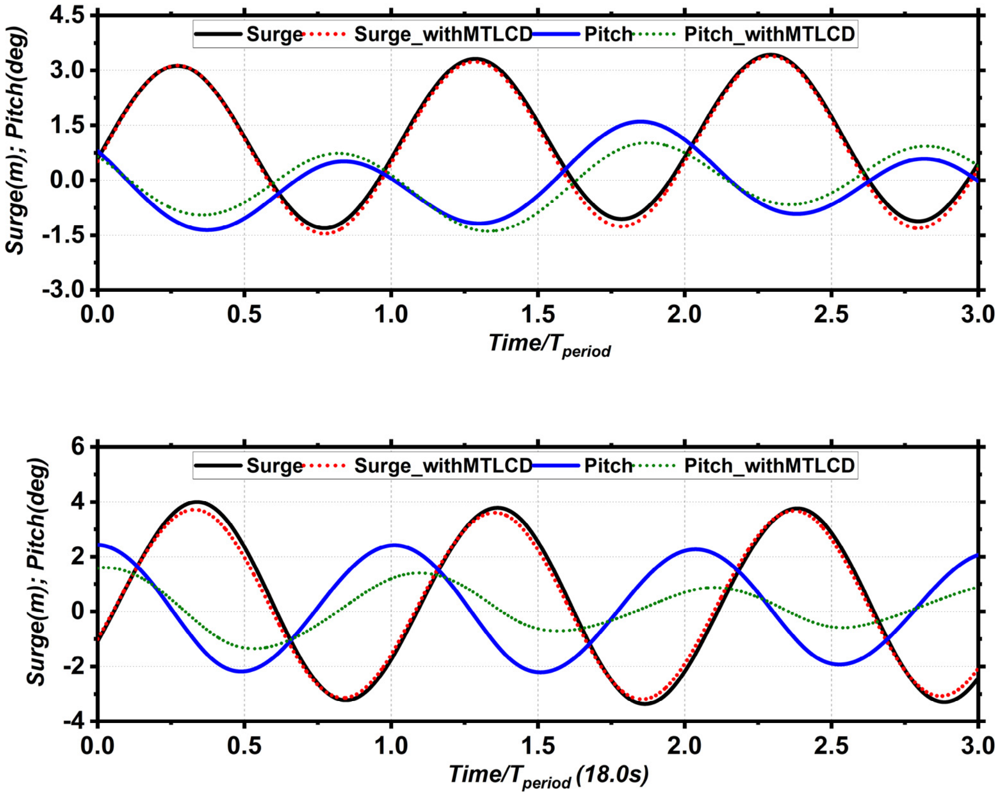

Figure 9 Surge and pitch motions for different semi-submersible configurations with different incident wave periods, top: T=12.1s; bottom: T=18.0s

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.

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 9 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.

The surface elevation contour near the semi-submersible platform with the TLMCD is presented in Figure 10 under A=3.79m and T=12.1s. The current contours are shown as an example to present the relevance of the flow regime between the floating structure and the sloshing TLMCD. Figure 11 plots the corresponding pitch motion under one sampled wave period. It is seen that the nonlinear wave-structure interaction can be captured by using the present numerical tool. The free surface located at the inner TLMCD offset columns is not always aligned with the free surface elevation of the regular wave. For instance, at 5/6T, the water level located at two downstream TLMCD columns is higher than that at the upstream column. It is due to a phase lag between the incident wave forces and the dynamic response. Referring to Figure 11 at 5/6T, we can observe that the floater reaches the peak and this explains why the surface elevation varies inside and outside the semi-submersible floating platform.

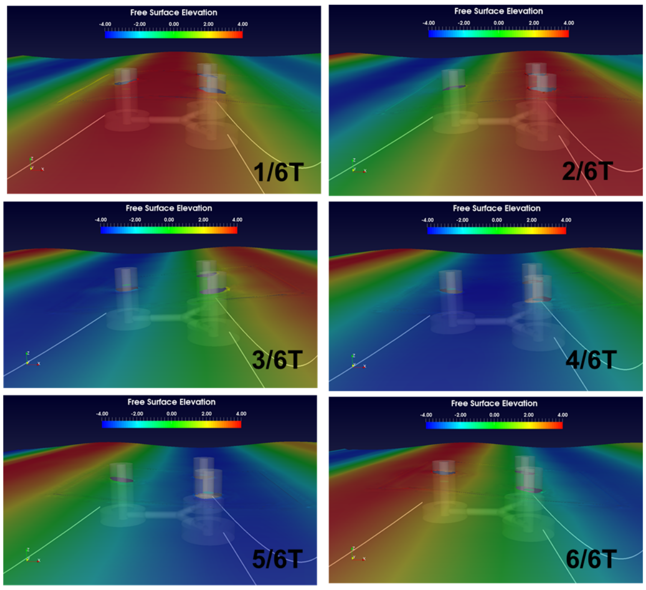

Figure 10 Wave elevation contour for one sampled wave period with A=3.79m, T=12.1s

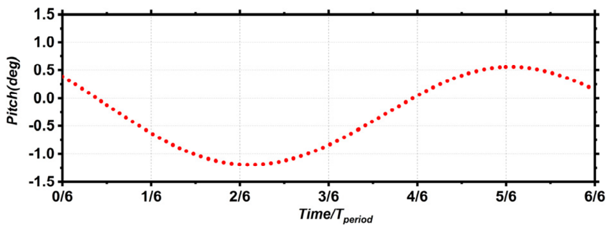

Figure 11 Pitch motion of the semi-submersible platform for one sampled wave period with A=3.79m, T=12.1s

7. CONCLUSION

The paper investigates the influence of the star-like three-column TLMCD on a semi-submersible FOWT under regular wave conditions. It starts with the verification of the passive-

control TLMCD system by calibrating the natural frequency for a benchmark case. The work is then extended to the sloshing only modelling to study the influence of the excitation frequency and the introduction of the nozzles to the TLMCD system. A fully coupled floating-sloshing modelling of a semi-submersible FOWT with the TLMCD is conducted under regular wave conditions. The comparison between the cases with and without the TLMCD TLMCD indicates that the presence of the TLMCD does not influence the translational motions such as surge and heave. However, as for the pitch motion, the TLMCD works well when the incident wave frequency is close to the pitch natural frequency of the system, evidenced by the decreased pitch amplitude. This desirable feature can lead to less fluctuations of the FOWT aerodynamic performance when the wind turbine is included. At the same time, when the incident wave frequency is not close to the pitch natural frequency, the introduction of the TLMCD has a minor effect, not causing additional motion responses to the entire FOWT system.

For practical applications, usually, TLCDs were placed on top of the floating substructure (Ha and Cheong, 2016) (Jaksic et al., 2015) for easy installation. In a recent work (Allen et al. 2018), a tuned mass damper has been integrated into a semi-sub platform to reduce its heave motions. As a first step, the aim of the present work is to demonstrate the applicability and effectiveness of applying a TMLCD system to control the hull motions of FOWTs and once this is proven we would next consider how to apply such passive control devices in practical usage, e.g., integrate the system into the internal space of semi-sub FOWT support structures.

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