Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 117-127

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

PERFORMANCE ENHANCEMENT OF FLOATING OFFSHORE WIND TURBINES WITH TUNED LIQUID COLUMN DAMPER: A NUMERICAL STUDY

Amiya Pandit[1], and Michael O'Shea[2]

[1] ERI, Structural and Hydro-Environmental Dynamics Laboratory
University College Cork, Ireland
e-mail: apandit@ucc.ie

[2] School of Civil, Structural & Environmental Engineering
University College Cork, Ireland
email: michaeloshea@ucc.ie

Abstract

Floating offshore wind turbines (FOWTs) play a crucial role in producing clean, green energy and are a great source to harvest wind sources. These tall, slender and flexible structures are prone to constant vibrations under the action of wind and wave loading. Moreover, the excessive vibrations in spar-type FOWTs may impose fatigue, and the submerged mooring cables get corroded during the operational period, which can cause unexpected failure of spar FOWT in extreme environments. Therefore, in the present study, tuned liquid column damper is introduced to minimise the excessive vibration. Numerical simulations are carried out with 5MW NREL, spar type floating OWT, under the wind wave misalignment in OpenFAST. Moreover, corrosion modelling is carried out in the mooring cables by minimising the stiffness and diameter, and the effectiveness of TLCD placed at nacelle is verified. The results show that, TLCD is capable of minimising the excessive vibration in both healthy and damaged spar FOWTs.

Keywords: Floating wind, vibration, corrosion, Tuned liquid column damper, mis-aligned

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12396.25435

1 INTRODUCTION

Offshore wind turbine has become a great reliable source to harness clean energy. Over the years, the installation of the offshore wind turbines has significantly increased, specially the fixed offshore wind turbines. But fixed offshore wind is found to be uneconomical for deep waters. Therefore, floating offshore wind turbine (FOWT) is a viable and economical option to exploit deep ocean area. But the FOWT are more vulnerable to repetitive environmental load such as wind, wave, current, which cause unwanted vibration. The prominent forced vibrations can reduce the service life of FOWT and accelerate the risk of failure. FOWTs are a complex system, which shows intricate behavior under constant environmental loading. Hence, mitigation of the excessive vibrations is crucial for improving the overall dynamic performances of the FOWT. Therefore, different methods have been proposed to control the unwanted vibrations and it is categorized as active, semi-active or passive control systems.

Considering the fact that, the passive control systems do not require external power supply and sophisticated components such as high precision actuators like active control systems. Therefore, passive control systems are widely used and appreciated for its effectiveness. The potential of tuned mass dampers (TMD) [1], [2], [3], [4], [5], [6], [7], [8], [9] in controlling the vibrations of offshore wind turbine tower have been investigated and these studies have confirmed the efficacy of passive TMDs. But, the requirement of large damper stroke and mass of TMD make it challenging for installation. Other type possible damper, for example tuned liquid damper (TLD) [10], [11], [12], [13] tuned liquid column damper (TLCD) [14], [15], [16] pendulum damper [17], [18], [19], K-damper [20] have been installed in the offshore wind turbines to suppress the undesired vibrations in tower, platform and blades. The structural control modules, have shown excellent performance in the area of offshore wind.

Spar type FOWTs are still in the early stage and classified as the ballast stabilized foundation type. The mooring cables used in it connects the floater to the sea bed for maintaining the position at sea. But the mooring cables deteriorates over time and may influence the overall stability of the floater. One of the dominant mooring cable degradation is identified as the pitting corrosion [21], [22], which potentially promote the platform motion due to reduction in stiffness and elasticity. Thus, the wind/wave induced motions of the floating platform negatively influence the overall dynamics of the FOWTs, especially the tower. The excessive vibrations not only reduce the fatigue life but also lead to increase the maintenance cost as these FOWTs are installed in the deep water. Notably, the damage in the mooring cables influence the natural frequencies of the FOWT. This is also the case where passive damper compromises its potential in controlling the excessive vibrations in OWTs. Notably, when the device frequency mistuned from the primary structure, the dynamics of the OWTs suffers significantly. But TLCD, a U-shaped container, utilizes liquid that imparts external damping to the structure. It has the advantage of low cost, easy installation and allow flexible configuration.

The goal of this study is to examine the effectiveness of TLCD, taking into account pitting corrosion damage scenarios in the mooring cables of the floating offshore wind turbines. The magnitude of damages in all the three mooring cables are limited to 25 %. The advantage of this approach is to measure the sensitivity of TLCD for the operational range of the FOWTs. Therefore, a numerical model of the coupled FOWT with TLCD is established in OpenFAST. Consequently, numerical simulations are carried out for healthy and damaged structures under mis-aligned wind-wave loading.

The rest of the paper is structures as follows: Section 2 describes the mathematical modelling of the coupled FOWT with TLCD. Section 3 discusses the vibration issue with the damaged mooring cables under different met ocean condition. Section 4 presents the results where a comparative analysis is performed. The conclusions are summarized in section 5.

2 FLOATING OFFSHORE WIND TURBINE COUPLED WITH TLCD

The nonlinear model of 5 MW NREL spar-supported FOWT is developed in OpenFAST in this investigation. A multibody dynamic model of spar FOWT is developed using Kane's method. The equation of motion derived by Kane's method is more readily solvable. Moreover, the wind turbine simulation tool OpenFAST employs Kane's method, which offers significant advantages over the Euler-Lagrangian formulation. It is necessary that each component must be defined in its local coordinate for accurate modeling of multibody systems. The blades have more than one coordinate system assigned to them. For a detailed modelling of the blades, they are referred to their coned coordination system followed by the pitched coordinate system. Similarly, the platform and tower rotations occur simultaneously about more than one axis. The Kane's equation of motion for a simple holonomic multibody system can be given by Equation (1)

$$F_k + {F_k}^* = 0 \text{ for } k = 1,2, \ldots N \tag{1}$$

where N is the total number of degrees of freedom required to describe the complete kinematics of the OWT. The generalized active force and inertia force for the k^{th} degree of freedom is given by Equation (2)-(3)

where $$F_k = \sum_{i=1}^{N} [{E_{Vk}}^{X_i}.\ F^{X_i} + {E_{wk}}^{N_i}.\ M^{N_i}] \tag{2}$$

$${F_k}^* = -\sum_{i=1}^{N} [{E_{Vk}}^{x_i}.\left(m^{N_i}{}^{E}a^{X_i}\right) + {E_{wk}}^{N_i}.E_{H^{N_i}}] \tag{3}$$

For the wind turbine model, the mass of the of the platform, tower, yaw bearing, nacelle, hub, blades and generator contributes to the generalized inertia forces. Generalized active forces applied directly to the wind turbine systems, forces that ensure constraint relationship between various rigid bodies and internal forces within flexible members. Forces applied directly on the offshore wind turbine system include aerodynamic forces on the blades and tower, hydrodynamic forces on the platform, mooring forces on platform, gravitational forces, generator torque and high-speed shaft brake. The gearbox friction force is neglected in the investigation. The internal forces within flexible members include elasticity and damping in tower, blades and drive train.

Table 1. Gross properties of the NREL spar-type FOWT

	NREL 5-MW OC3-Hywind spar type FOWTS	
Basic description	Max rated power	5 MW
	Rotor diameter	126 m
	Hub height	90 m
	Cut-in, Rated, Cut-out wind speed	3m/s, 11.4m/s, 25m/s
	Cut-in, Rated rotor speed	6.9 rpm, 12.1 rpm
	Tower structural damping ratio	1%
	Rotor Mass	110,000 kg
	Tower Mass	249,718 kg
	Nacelle Mass	240,000 kg

2.1 The TLCD model description

TLCD consists of one horizontal and two vertical columns partially filled with liquid. As shown in Figure (1), the cross-sectional area of the horizontal and vertical column is denoted as A_h and A_v respectively. The density of the liquid is given by ρ. The liquid is considered to be incompressible. The equivalent length of the TLCD is given by Equation (4)

$$L_E = \alpha B + 2L_v \tag{4}$$

but when $\alpha = 1$, $L_E = L$.

where α is the ratio of cross-sectional area of vertical column to the horizontal column (A_v/A_h). The total mass of the liquid inside the TLCD is calculated using Equation (5)

$$m_l = \rho A_h(\alpha B + 2L_v) \tag{5}$$

The natural frequency of the TLCD is given by Equation (6)

$$\omega_{TLCD} = \sqrt{\frac{2g}{L_E}} \quad \text{rad/s} \tag{6}$$

The head loss can be considered as the overall head loss induced by flow passing through the orifice.

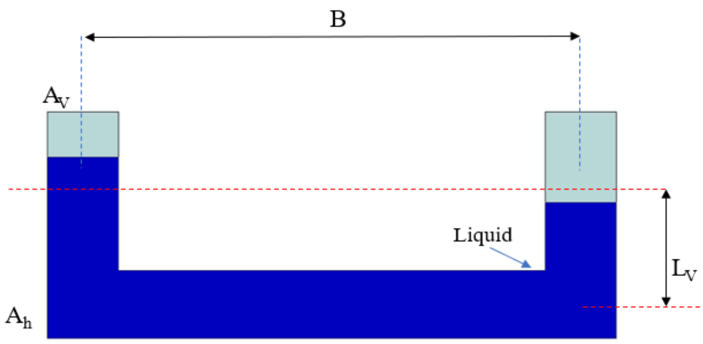


Figure (1). Typical TLCD used in the nacelle of spar type FOWT.

2.2 Dynamic loading

Morison's representation is used to estimate the hydrodynamic loads on the spar of the floating wind turbine. Strip theory in conjuction with Morison's equation can be used to compute the linear wave inertia forces and nonlinear viscous drag forces. The total load on the platform is then obtained by integrating the elemental forces along the depth of the platform.

The force associated with a strip dz of the platform is given by Equation (7)

$$dF^P{}_i(Z,t) = -C_{A\rho}\left(\frac{\pi D(z)^2}{4}\right)\ddot{q}_i(z,t)dz + C_{M\rho}\left(\frac{\pi D\left(\frac{\pi D(z)^2}{4}\right)}{4}\right)a^f{}_i(z,t)dz +$$

$$\frac{1}{2}C_{D_P}D(z)\left(v_i{}^f(z,t)-v_i{}^p(z,t)\right)\left|v_i{}^f(z,t)-v_i{}^p(z,t)\right|dz \quad (7)$$

where the superscript P denoted the platform and dF^P is the elemental force on the platform.

The three-dimensional wind fields are generated using *TurbSim* package provided by National Renewable Energy Laboratory (NREL), USA. The aerodynamic load on the wind turbine are estimated using steady state blade element momentum (BEM) theory. The *TurbSim* package enable producing the turbulent wind filed while varying the turbulence intensity levels and characteristics wind speeds.

The details of met ocean conditions adopted in the present investigation is listed in Table (2).

Table 2. Met-ocean conditions

Load cases	Mis alignment	Wind speed (m/s)	Wave period (s)	Wave height (m)
LC1	57.95	8.24	8.46	1.67
LC2	43.57	20	8.79	3.11

3 REPLICATION OF DAMAGE SCENARIO IN THE FOWT

In this study, pitting corrosion in the mooring cables is considered as a damage scenario taking into account the reduction in stiffness of the mooring cables. This can prompt the entire FOWT system to shift towards new equilibrium or highlights shifts in dynamic response of the structure due to the degradation. Therefore, modifications in the different modules of OpenFAST are incorporated and simulations are performed under diverse met ocean conditions. Both displacement and acceleration signals are compared for healthy and damage state of the FOWTs for the sensitivity analysis. To mimic the effect of pitting corrosion mooring line's elasticity is reduced by 25%.

4 RESULTS AND DISCUSSIONS

The TLCD employed at the nacelle of the FOWT to control the tower vibration under the effect of mis-aligned wind wave loading. The 3D wind field for the 8.24 m/s, and 20 m/s are shown in the Figure 2. The tower fore-aft and side-side natural frequency is calculated as 0.48 Hz and 0.49 Hz respectively. It is well known that for better effectiveness of TLCD, a higher mass ratio is suitable, but in the present study the mass ratio is kept 1% (3500kg). Two different environmental cases are considered where the choice of α and $\frac{B}{L}$ are studied. Figure (3) shows the distribution of standard deviation calculated from the tower fore-aft (FA) displacement. For each load case, different value of α=[0.5, 0.6, 0.7] and $\frac{B}{L}$ =[0.7, 0.8, 0.9] are considered for parametric optimization. The simulations are carried out for 675s but initial 75s are removed while

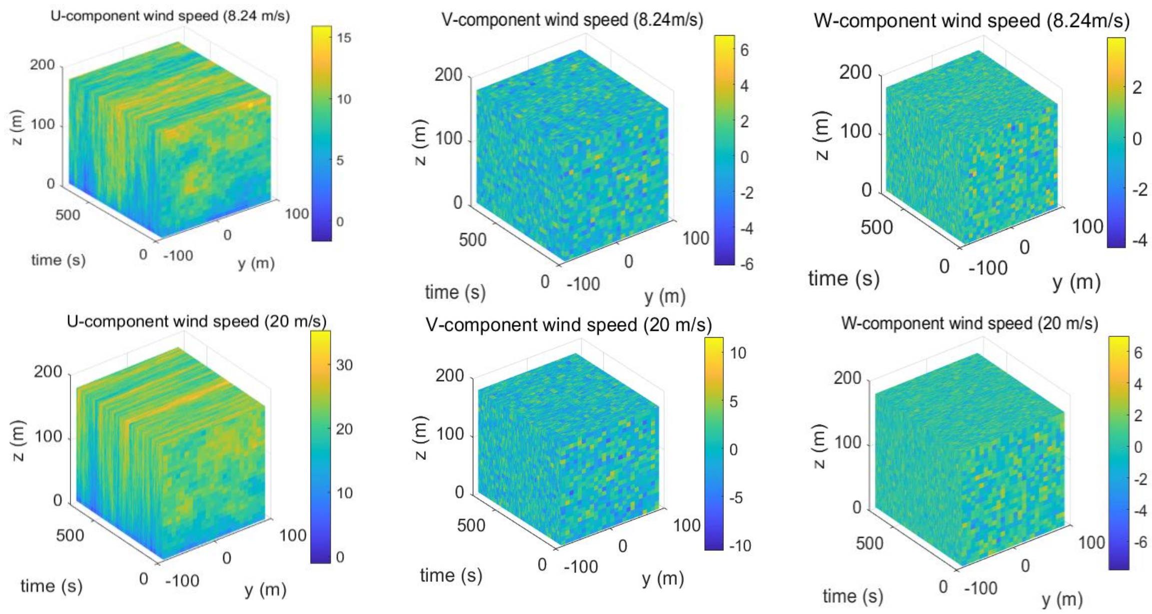
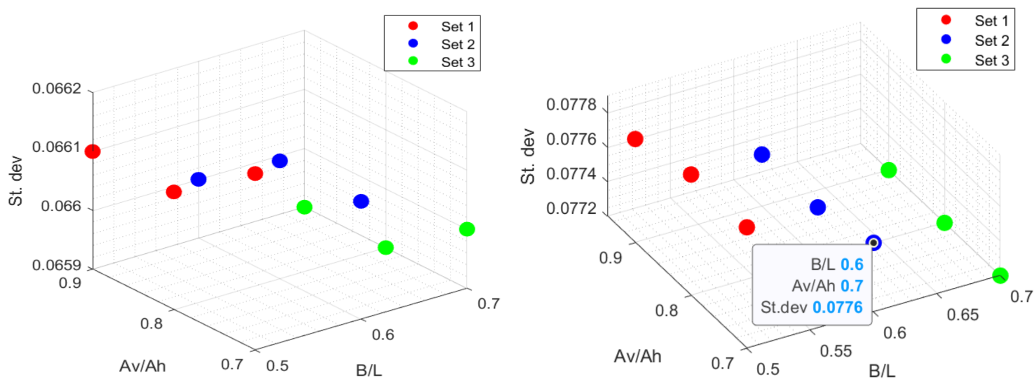
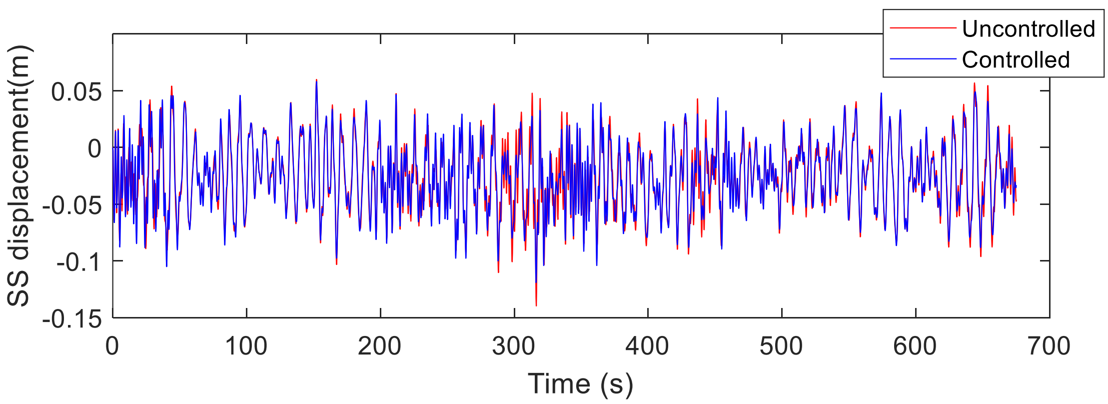


Figure (2) 3D wind field of turbulent wind speed

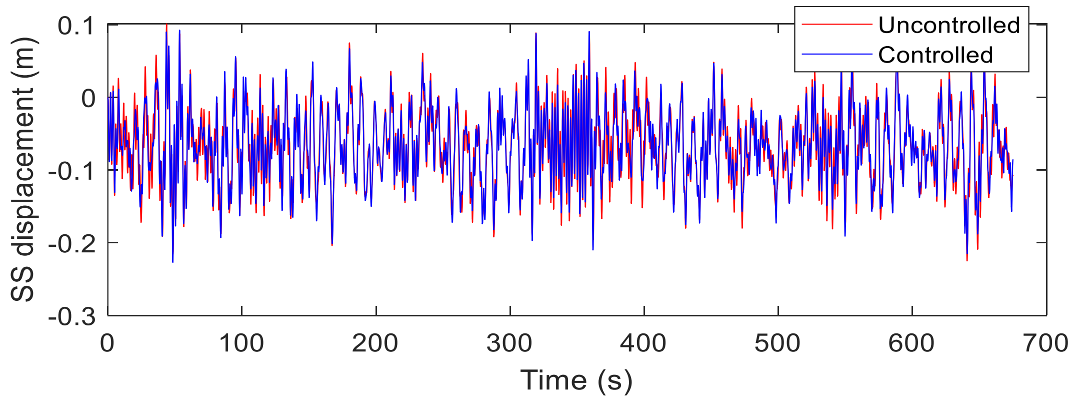


(a) (b)

Figure (3) Standard deviation in the fore-aft direction (a) LC1 (b) LC2



(a)



(b)

Figure (4) Temporal variation in tower side-side displacement with and without TLCD, α =0.5, $\frac{B}{L}$ =0.7 (a) LC1 (b) LC2

evaluating the value of standard deviation, in order to eliminate the effect of initial transition phase. The temporal variation of tower ss-displacement with and without TLCD is shown in Figure (4) which exhibits the vibration control performance of TLCD during the selected environmental loading. To conduct the parameter optimization the reduction ratio (RR) is evaluated, which is defined by Equation (8)

$$RR = \frac{\sigma_{Uncontrolled} - \sigma_{TLCD}}{\sigma_{Uncontrolled}} \quad (8)$$

where σ_{TLCD} and $\sigma_{Uncontrolled}$ are the standard deviations of tower side-side (ss) displacement with and without TLCD.

Table 3. Reduction ratio values in tower ss direction

Loading	$\frac{B}{L}$=0.5			$\frac{B}{L}$ ==0.6			$\frac{B}{L}$ ==0.7		
	α =0.7	α =0.8	α =0.9	α =0.7	α=0.8	α=0.9	α=0.7	α=0.8	α=0.9
LC1	1.35	1.35	1.35	1.69	1.69	2.03	1.69	1.01	2.03
LC2	3.23	3.23	3.63	3.63	3.99	4.04	4.64	1.81	4.84

From Table (3), the following observations is made: (a) For LC1, and LC2, as α increases for a specific value of $\frac{B}{L}$, the RR value is increased. It further illustrates that larger value of $\frac{B}{L}$ leads to better performance of TLCD. Figure (5) illustrates the influence of pitted corrosion on surge displacement. Figure (6), shows the frequency response of the platform surge under LC2. Figure (7) shows the time-history response of platform surge without and with TLCD subjected to LC2 when $\frac{B}{L}$=0.5 and α =0.9. The TLCD is found to suppress the platform surge displacement this means that tower vibration is suppressed. Therefore installation of TLCD on tower top is expected to improve overall dynamics of the FOWT.

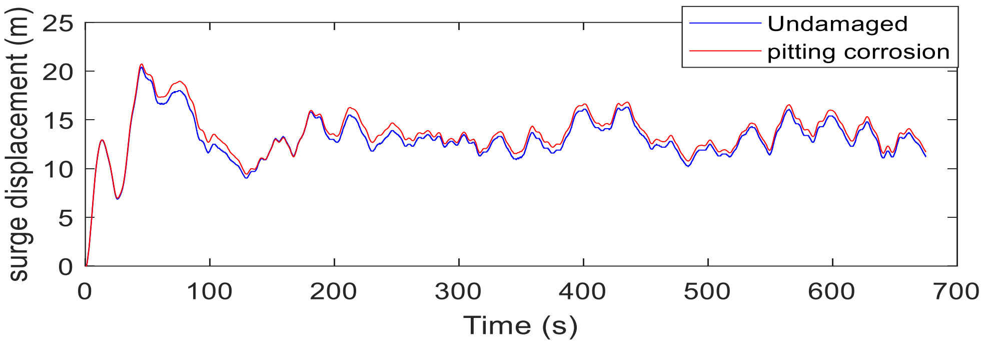


Figure (5) Temporal variation in platform surge displacement

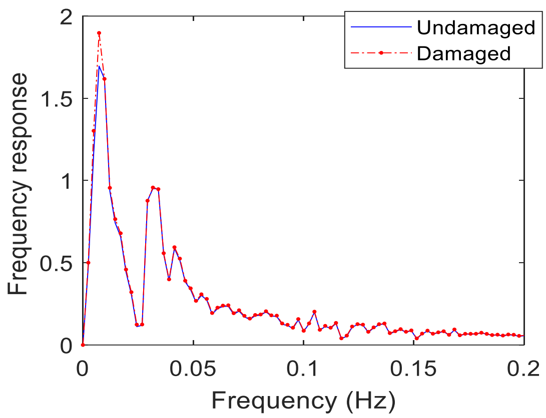


Figure (6) Frequency response function

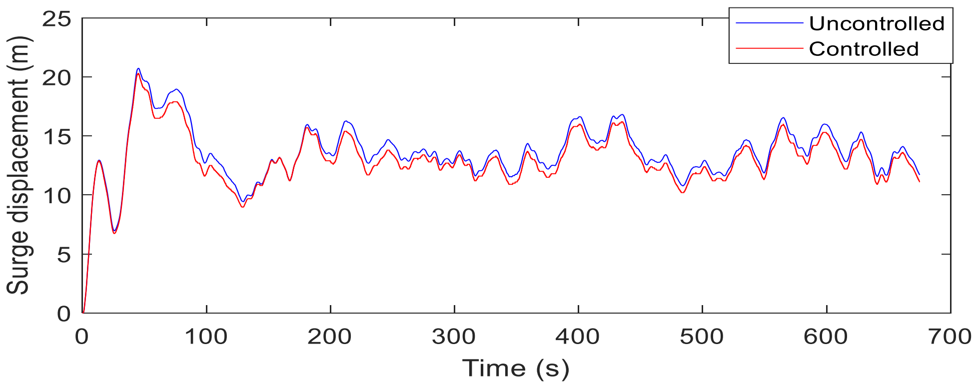


Figure (7) Temporal variation in platform surge displacement for damaged mooring cables

5 CONCLUSIONS

A comprehensive numerical investigation is carried out to determine the performance of TLCD for suppressing the tower side-side (ss) and platform motion when placed at the nacelle. A parametric optimization is carried out and it is revealed that TLCD with different cross-sectional areas significantly suppress the vibration even when there is damage in the mooring cables. The simulated results shows the robustness of passive TLCD, when there is mis-alignment in the wind-wave.

REFERENCES

[1] M.A. Lackner, M.A. Roteo, Passive structural control of offshore wind turbines. *Wind Energy*, **14 (3)**, 373-388, 2011.

[2] G.M. Stewart, M.A. Lackner, The impact of passive tuned mass dampers and wind-wave misalignment on offshore wind turbine loads. *Engineering Structures*, **73**, 54-61, 2014.

[3] Y. Si, H.R. Karimi, H. Gao, Modelling and optimization of passive structural control design for spar type floating wind turbine. *Engineering Structures*, **69**, 168-182, 2014.

[4] X. Tong, X. Zhao, S. Zhao, Load reduction of monopile wind turbine tower using optimal tuned mass dampers. *International Journal of Control*, **90 (7)**, 1283-1298, 2015.

[5] H, Zuo, K. Bi, H. Hao, Using multiple tuned mass dampers to control offshore wind turbine vibrations under multiple hazards. *Engineering Structures*, **141**, 303-315, 2017.

[6] M. Ghassempour, G. Failla, F. Arena, Vibration mitigation in offshore wind turbines via tuned mass damper. *Engineering Structures*, **183**, 610-636, 2019.

[7] J.J. Yang, E.M. He, Coupled modeling and structural vibration control for floating offshore wind turbine. *Renewable Energy*, **157**, 678-694, 2020.

[8] H, Zuo, Zhang. J, K. Bi, S. Zhu, H. Hao, Structural vibration control of spar-buoy floating offshore wind turbines. *Engineering Structures*, **294**, 116732, 2023.

[9] D. McNamara, A. Pandit, A. Malekjafarian, Optimized design of multiple tuned mass dampers for vibration control of offshore wind turbines. *Ocean Engineering*, **305**, 117912, 2024.

[10] J. Chen, C.T. Georgakis, Spherical tuned liquid damper for vibration control in wind turbines. *Journal of Vibration and Control*, **21 (10)**, 2013.

[11] Z. Zhang, A. Staino, B. Basu, S.R.K. Nielsen, Performance evaluation of full-scale tuned liquid dampers (TLDs) for vibration control of large wind turbines using real time hybrid testing. *Engineering Structures*, **126**, 417-431, 2016.

[12] M. Ha, C. Cheong, Pitch motion mitigation of spar-type floating substructute for offshore wind turbine using multilayer tuned liquid damper. *Ocean Engineering*, **116**, 157-164, 2016.

[13] Z. Zhang, B. Basu, S.R.K. Nielsen, Real time hybrid aeroelastic simulation of wind turbines with various types of full scale tuned liquid dampers. *Wind Energy*, **22 (2)**, 239-256, 2019.

[14] T. Buckley, P. Watson, P. Cahill, V. Jaksic, V. Pakrashi, Mitigating the structural vibrations of wind turbines using tuned liquid column damper considering soil-structure interaction. *Renewable Energy*, **120**, 322-341, 2018.

[15] A. Hemmati, E. Oterkus, M. Khorasanchi, Vibration suppression of offshore wind turbine foundations using tuned liquid column damper and tuned mass dampers. *Ocean Engineering*, **172**, 286-295, 2019.

[16] Z. Zhang, C. Hoeg, Dynamics and control of spar type floating offshore wind turbines with tuned liquid column dampers. *Structural Control and Health Monitoring*, **27 (6)**, 2020.

[17] C. Sun, V. Jahangiri, Fatigue damage mitigation of offshore wind turbines under real wind and wave conditions. *Engineering Structures*, **178**, 472-483, 2019.

[18] S. Chapain, A.M. Aly, Vibration attenuation in wind turbines: A proposed robust pendulum pounding TMD. *Engineering Structures*, **233**, 111891, 2021.

[19] J. Lin, Y. Wang, G. Zhang, Y. Liu, J. Zhang, Novel tuned mass dampers installed inside tower of spar floating offshore wind turbines. *Ocean Engineering*, **301**, 117412, 2024.

[20] A. Kampitsis, K. Kapasakalis, L. Via-Estrem, An integrated FEA-CFD simulation of offshore wind turbines with vibration control systems. *Engineering Structures*, **254**, 113859, 2022.

[21] C.S. Sakaris, Y. Yang, M. Bashir, C. Michailides, J. Wang, Structural health monitoring of tendons in a multibody floating offshore wind turbine under varying environmental and operating conditions. *Renewable Energy*, **179**, 1897-1914, 2021.

[22] S. Sharma, V. Nava, Condition monitoring of mooring systems for floating offshore wind turbines using convolutional neural network framework coupled with autoregressive coefficients. *Ocean Engineering*, **302**, 117650, 2024.