SHAKING TABLE TEST OF OFFSHORE WIND TURBINE SUPPORTING STRUCTURE CONTROLLED BY TMD

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Abstract

Taiwan has launched a plan to develop offshore wind farms by using wind turbines in the Taiwan Strait. However, Taiwan's offshore wind farms are located in an earthquake prone area with sandy soil conditions. To ensure safety and reliability of the offshore wind turbines, it is important to protect the offshore wind turbine supporting structures subjected to seismic loadings. Vibration reduction of engineering structures using tuned mass damper (TMD) is a widely accepted strategy. Compared with other energy dissipation devices, the TMD system can be incorporated into the structure with less interference. To investigate important issues on offshore wind turbine supporting structures, in this study, a 1/25 scaled-down test model was fabricated to simulate the dynamics behavior of a typical 5MW wind turbine with jacket structure and pile foundations. Moreover, a large laminar shear box filled with sand and water was used to simulate the saturated soil condition of the offshore wind farm. The shaking table test was conducted at National Center for Research on Earthquake Engineering (NCREE) in Taiwan. During the test, the frequency of the test model (whole system) was identified firstly by a white noise excitation. The TMD system located on the nacelle of the turbine model was designed to tune the whole system's frequency for vibration reduction. Two artificial earthquake ground motions with the site (wind farm) characteristics were used as the excitations. The responses of the test model w/ and w/o the TMD system were compared. Shaking table test results demonstrate that the TMD system is effective in reducing the seismic responses of the test model. Therefore, the feasibility of using a TMD to reduce the seismic vibration of offshore wind turbine supporting structures was verified.

Keywords: offshore wind turbine supporting structures; tuned mass damper; shaking table test; seismic mitigation

1. Introduction

Taiwan has launched a plan to develop offshore wind farms by using wind turbines in the Taiwan Strait. However, Taiwan's offshore wind farms are located in an earthquake prone area with sandy soil conditions. To develop the offshore wind turbine supporting structure in deep water, the jacket-typed structure is the most economical way. To ensure safety and reliability of the offshore wind turbines, it is important to investigate the seismic behavior of the offshore wind turbine with jacket structure and its foundation during earthquakes. Furthermore, it is also important to protect the offshore wind turbine supporting structures subjected to seismic loadings, as well as the influence of soil liquefaction.

Vibration reduction of engineering structures using tuned mass damper (TMD) is a widely accepted strategy. Tuned mass damper (TMD) systems, which were first proposed by Frahm [1], and is a widely utilized strategy in the area of structural control, including high-rise buildings, observatory towers, building floors, railway bridges and pedestrian bridges against natural and man-made loadings [2-6]. A TMD consists of an added mass with properly functioning spring and damping elements to provide frequency-dependent damping in a primary structure. A TMD absorbs the vibration energy of a structure and dissipates it *via* the damping mechanism. The design and application of traditional linear TMDs are well developed [7-13].

In the researches on vibration reduction of wind turbines by using TMDs. Ghassempour et al. [14] deals with vibration mitigation via TMD in bottom-fixed offshore wind turbines. Focusing on a baseline 5-MW turbine mounted on a monopile, equipped with an omnidirectional TMD. Dinh and Basu [15] investigates the use of TMD and multiple tuned mass damper (MTMD) for vibration control of nacelle/tower and spar of spar-type floating wind turbines. Lackner and Rotea [16] proposed a new simulation tool to model passive, semi-active and active TMDs in wind turbines, with the considerations of fatigue, aerodynamics, structures and turbulence. Zhao et al. [17] conducted shaking table tests on a 1/13 scaled bottom-fixed monopile offshore wind turbine tower (test model) equipped with a bidirectional TMD. Control performance of TMD under different rotation speeds of the blades and ground excitations were investigated.

To investigate important issues on jacket typed offshore wind turbine supporting structures, in this study, a 1/25 scaled-down test model was fabricated to simulate the dynamics behavior of a typical 5MW wind turbine with jacket structure and pile foundations [18-21]. Moreover, a large laminar shear box filled with sand and water was used to simulate the saturated soil condition of the offshore wind farm. The shaking table test was conducted at National Center for Research on Earthquake Engineering (NCREE) in Taiwan. During the test, the frequency of the test model (whole system) was identified firstly by a white noise excitation. The TMD system located on the nacelle of the turbine model was designed to tune the whole system's frequency for vibration reduction. Two artificial earthquake ground motions (called Hua-lien earthquake and Chi-Chi earthquake) with the site (wind farm along offshore area of Chang-Hua) characteristics were used as the excitations. The responses of the test model w/ and w/o the TMD system were compared.

2. Shaking Table Test Program

2.1 Test setup and input ground accelerations

Figure 1 depicts the test setup and the sensor placement of the shaking table test. A 1/25 scaled-down test model was fabricated to simulate the dynamics behavior of a typical 5MW wind turbine with jacket structure and pile foundations. It is noted that the mass block on the top of the test model represents the mass of the nacelle and blades. A large laminar shear box filled with sand and water was used to simulate the saturated soil condition of the offshore wind farm. The shaking table test was conducted at National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Figure 1 also shows that accelerometers and motion capture reflective markers for optical mocap are placed on the shaking table, on the wind turbine supporting structure and on the TMD. Additionally, one LVDT was used to measure the the TMD stroke.

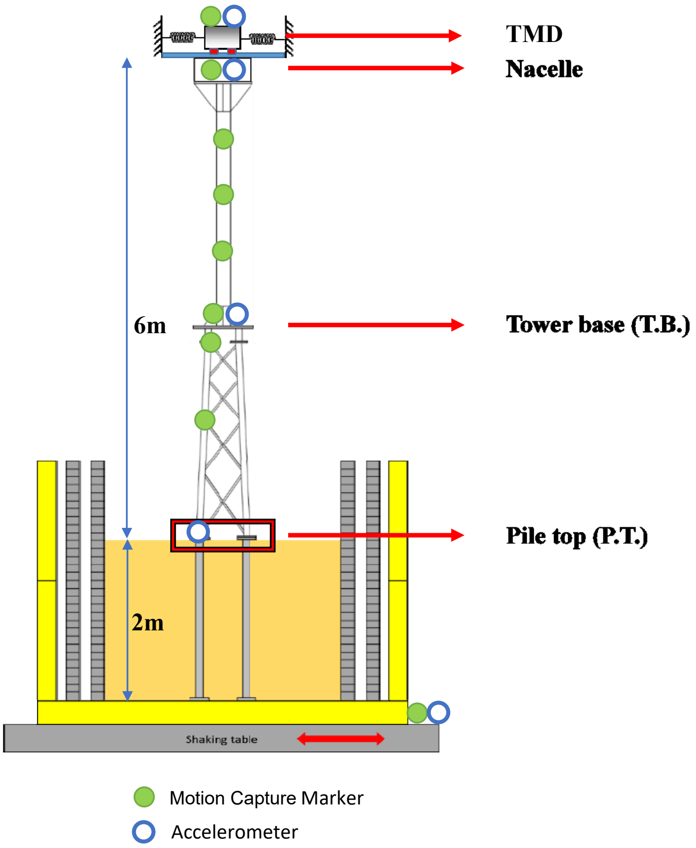


Fig. 1 – Shaking table test setup

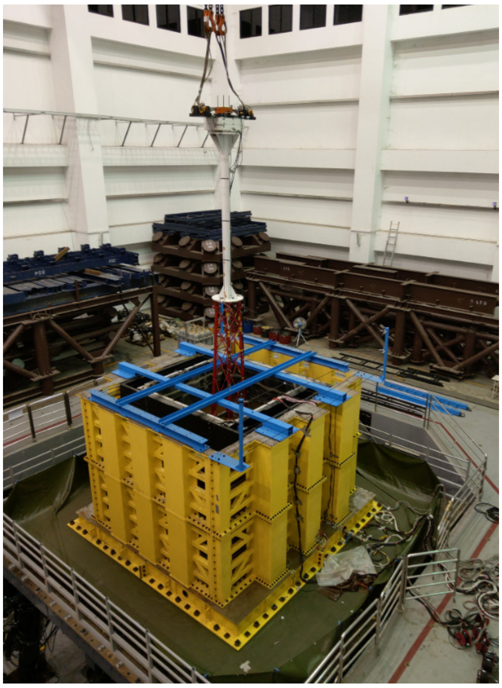
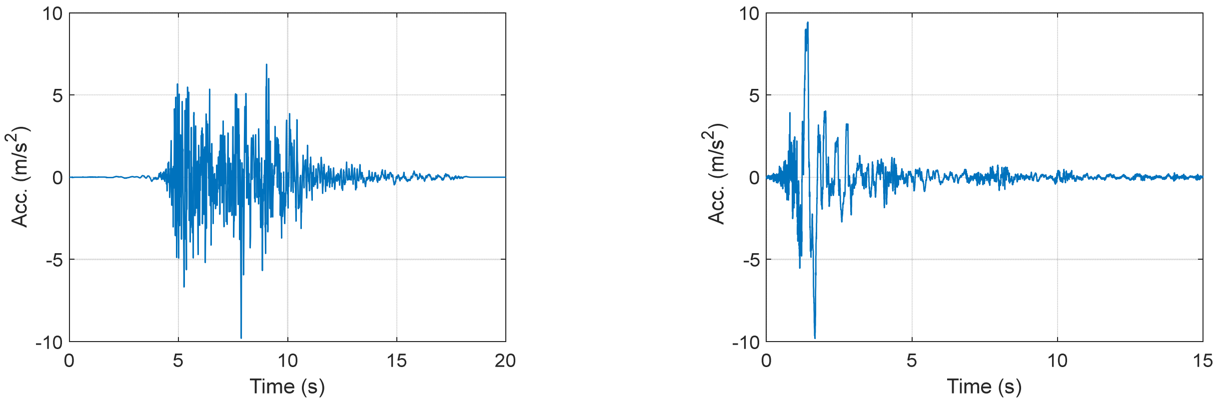


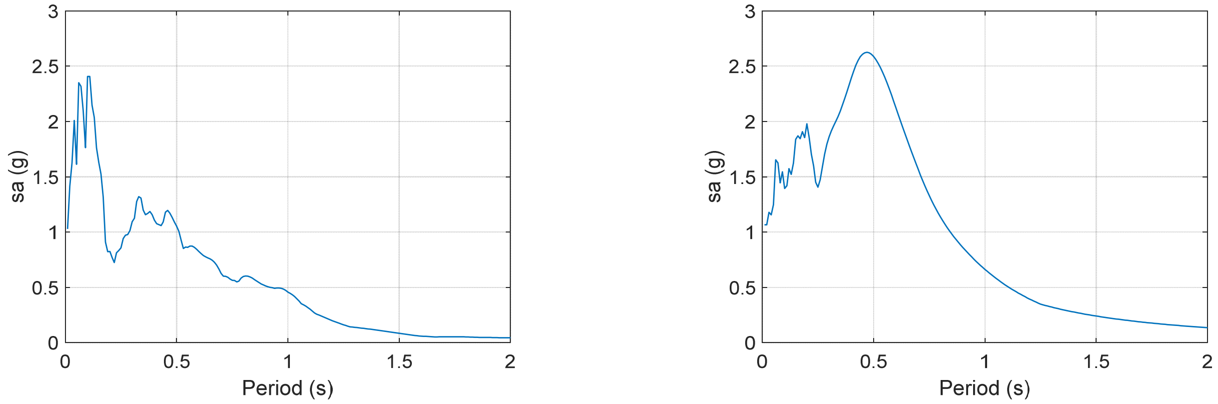
Fig. 2 – Picture of shaking table test

Two artificial earthquake ground motions, called Chi-Chi earthquake and Hua-lien earthquake were used as the excitations. Both ground accelerations were scaled based on the site characteristics (wind farm along offshore area of Chang-Hua). Figure 3 shows the waveform of the two ground motions, while Figure 4 shows the corresponding response spectrum.



(a) Chi-Chi (b) Hua-lien

Fig. 3 – Scaled ground motions (PGA scaled to 1g)



(c) Chi-Chi (d) Hua-lien

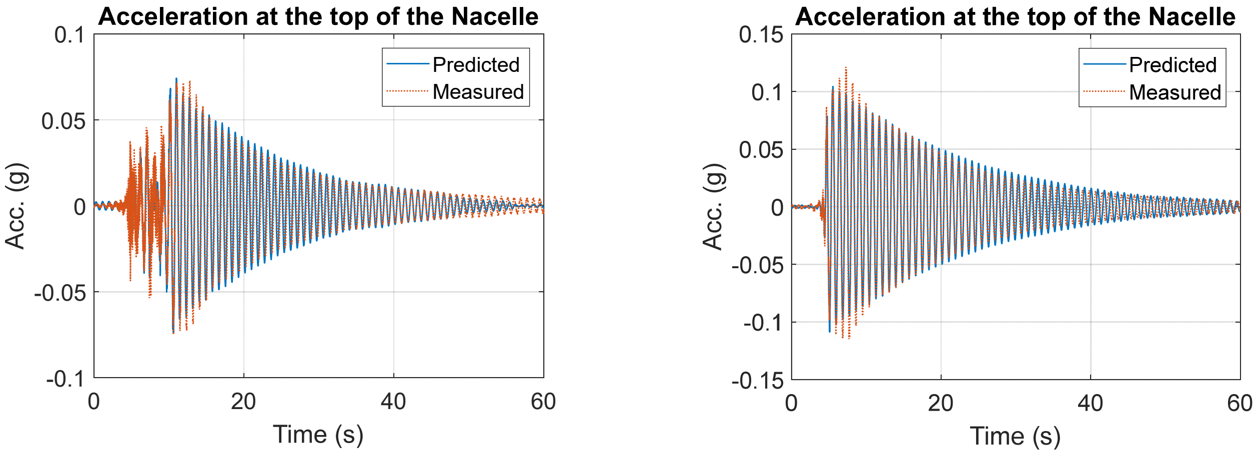
Fig. 4 – Response spectrums of the scaled ground motions (5% damping ratio)

2.2 System identification of the wind turbine supporting structure

Table 1 lists the modal parameters of the test model (w/o TMD), those parameters were identified by a white noise excitation with PGA scaled to 50 gal. Based on the identified modal parameters and the ground accelerations, the system responses can be predicted. Figure 3 compares the measured and the predicted nacelle accelerations with respected to the two ground motions (PGA=0.1g). It is shown the predicted accelerations is agree well with the measured accelerations, *i.e.,* the test data are reliable, and identified model is effective for analyzing the system dynamic responses.

Table 1 – Modal parameters of the test model (without TMD)

Mode	1st	2st	3st
Frequency (Hz)	1.15	10.47	23.94
Damping ratio (%)	0.94	4.08	6.29



(a) Chi-Chi (0.1g)

(b) HWA062 (0.1g)

Fig. 5 – Comparison of the measured and predicted nacelle accelerations (w/o TMD).

2.3 Optimization of TMD parameters

Simple formulas presented by Lin et al. [22] was used to determine the optimal TMD's parameters. The optimal TMD's parameters are determined by minimizing the mean-square displacement response ratio of the first mode, between the structure with and without installation of TMD under earthquake excitation. The optimal tuning frequency ratio, $r_{f,opt}$, and damping ratio, $\xi_{s,opt}$ take the forms as

$$r_{f,opt} = \left(\frac{a}{1+\mu}\right)^b; \quad a = 1.0 - \frac{\xi_1}{4}, \quad b = 1.35e^{3.2\xi_1} \tag{1}$$

$$\xi_{s,opt} = 0.46\mu^{0.48} \tag{2}$$

In Eq.(1), mass ratio μ and frequency ratio r_f are defined as

$$\mu = \frac{m_s}{m_p}; \quad r_f = \frac{f_s}{f_p} \tag{3}$$

where m_s and m_p represents the mass of the secondary system (TMD) and the primary system (wind turbine), respectively. f_s and f_p represents the frequency of the TMD and the wind turbine, respectively. Table 2 lists the physical parameters of the TMD (mass ratio =2.73%) and the test model, while Figure 6 shows the picture of the TMD, which is composed of mass blocks, springs, and linear guide rails.

Table 2 – Physical parameters of the TMD and the test model

Component	Item	Value
Test model	Mass (m_p)	905 kg
	Frequency (f_p)	1.15 Hz
	Damping ratio (ζ_s)	0.94 %
TMD	Mass (m_s)	24.7 kg
	Spring stiffness (k_s)	1142 N/m
	Frequency (f_s)	1.09 Hz
	Maximum stroke (v_s)	±0.3 m

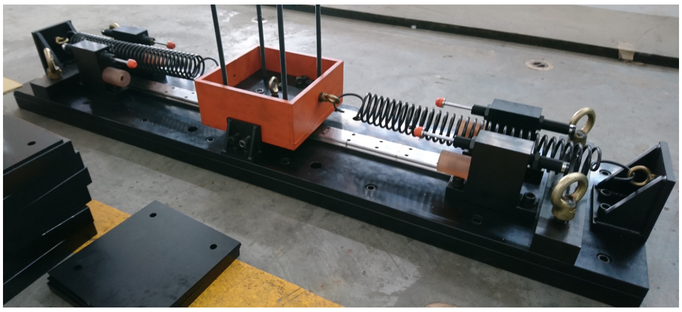
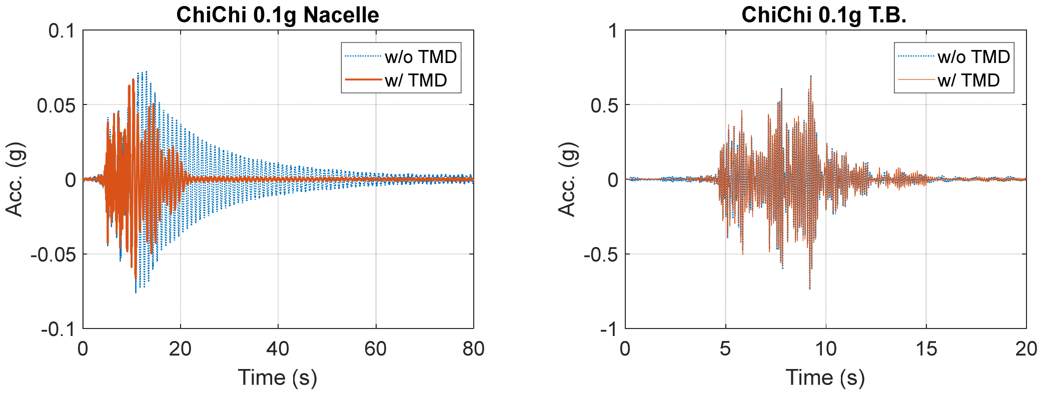


Fig. 6 – Picture of the TMD

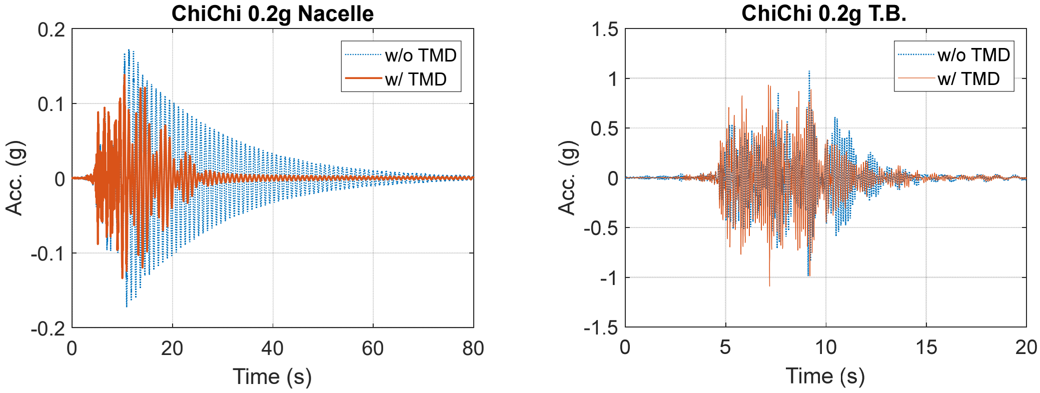
3. Test Results and Discussion

3.1 Comparison of time history responses

To demonstrate the control efficiency of the TMD, this subsection compares the experimental time history responses of the test model w/ and w/o TMD system. Figure 7 and 8 compare the acceleration responses of the test model under the Chi-Chi and Hua-lien earthquakes. It is noted that the soil liquefaction phenomenon is obvious when PGA is equal to 0.2g. The TMD is effective in reducing acceleration responses of the nacelle, while is less effective in reducing acceleration responses of the tower base. It is because the jacket structure is relatively stiffer than the tower structure, and the 1st mode of the test model shown in Table 1 is mainly contributed by the tower structure. The TMD system is designed to tune the 1st frequency of the test model for vibration reduction.

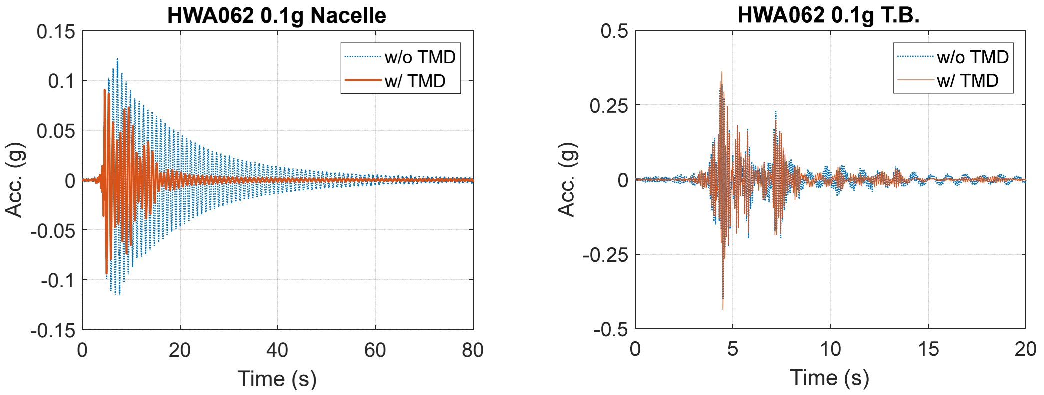


(a) Acc. of Nacelle (PGA=0.1g) (b) Acc. of tower base (PGA=0.1g)

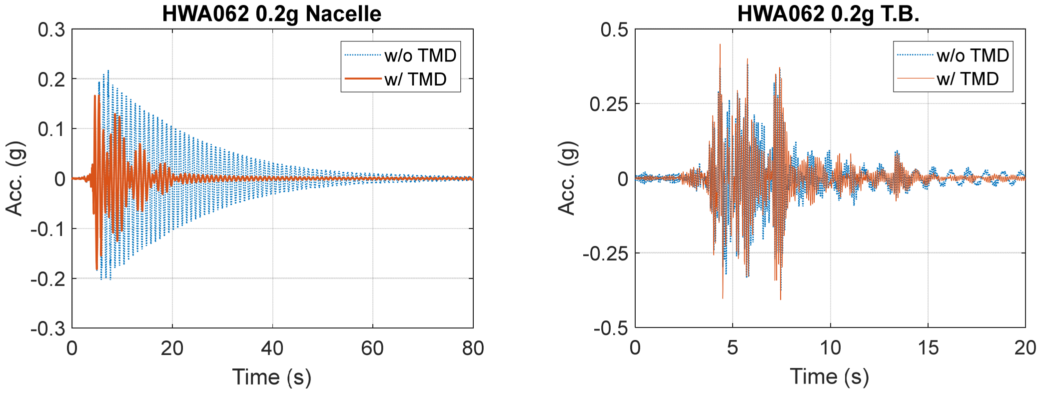


(c) Acc. of nacelle (PGA=0.2g) (d) Acc. of tower base (PGA=0.2g)

Fig. 7 –Acceleration responses of the test model w/ and w/o the TMD system (Chi-Chi earthquake)



(a) Acc. of nacelle (PGA=0.1g) (b) Acc. of tower base (PGA=0.1g)



(c) Acc. of nacelle (PGA=0.2g) (d) Acc. of tower base (PGA=0.2g)

Fig. 8 –Acceleration responses of the test model w/ and w/o the TMD system (Hua-lien earthquake)

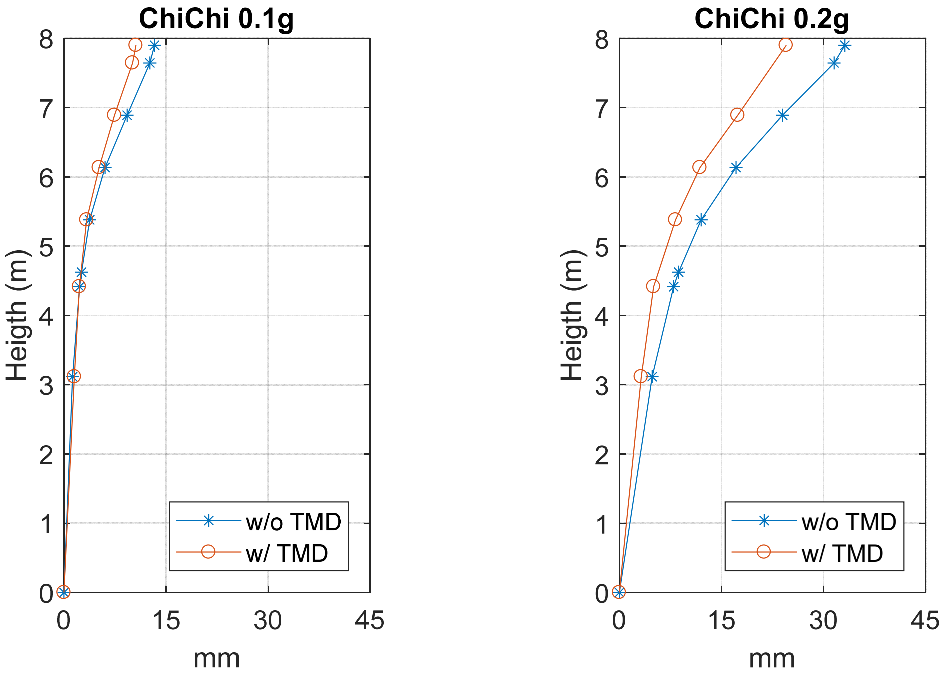
3.2 Comparison of peak and RMS responses

Table 3 lists the control performance of the TMD system when data for two selected earthquakes were applied. Table 3 shows that, although the TMD is less effective in reducing the peak displacement of the nacelle, it reduces the root-mean-square (RMS) displacement by 45-63%, as compared to the RMS responses of the uncontrolled system. Figure 9 compares the peak displacement (with respected to model height) of the test model subjected to the Chi-Chi earthquake, while Figure 10 compares the RMS displacement. The two figures reveal that: (1) Most of the lateral displacement is contributed by the tower structure. (2) The larger of PGA level, the beter the control performance.

Table 3 – Control performance of the TMD system

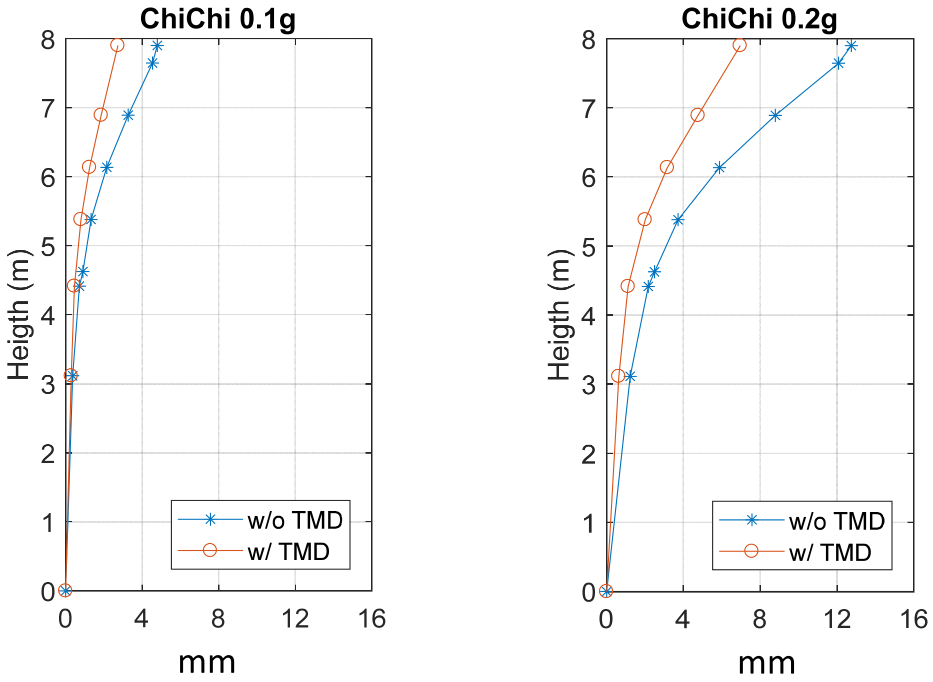
Displacement	PGA	TMD	Chi-Chi earthquake		Hua-lien earthquake	
			Nacelle	Tower base	Nacelle	Tower base
Peak (mm)	0.1g	w/o	13.69	2.30	21.96	3.44
		w/	10.63 (-22.4%)	2.26 (-1.7%)	16.67 (-24.1%)	2.85 (-17.2%)
	0.2g	w/o	33.13	7.98	39.76	7.78
		w/	24.51 (-26.0%)	5.03 (-37.0%)	36.13 (-9.1%)	6.85 (-12.0%)
RMS (mm)	0.1g	w/o	2.86	0.43	8.18	1.18
		w/	1.58 (-44.8%)	0.43 (-0.0%)	4.00 (-51.1%)	0.58 (-50.9%)
	0.2g	w/o	12.75	2.17	20.74	3.30
		w/	6.96 (-45.4%)	1.12 (-48.4%)	7.75 (-62.6%)	1.22 (-63.0%)

The value in parentheses shows the reduction ratio.



(a) PGA=0.1g (b) PGA=0.2g

Fig. 9 –Peak displacement with respected to model height (Chi-Chi earthquake)



(a) PGA=0.1g (b) PGA=0.2g

Fig. 10 –RMS displacement with respected to model height (Chi-Chi earthquake)

4. Conclusions

Taiwan has launched a plan to develop offshore wind farms by using wind turbines in the Taiwan Strait. However, Taiwan's offshore wind farms are located in an earthquake prone area with sandy soil conditions. Taiwan's offshore wind farms are located in an earthquake prone area with sandy soil conditions. To develop the offshore wind turbine supporting structure in deep water, the jacket-typed structure is the most economical way. To investigate the control performance of TMD systems on offshore wind turbine supporting structures, a 1/25 scaled-down test model was fabricated to simulate the dynamics behavior of a typical 5MW wind turbine with jacket structure and pile foundations. To consider the soil liquefaction effects, a large laminar shear box filled with sand and water was used to simulate the saturated soil condition of the offshore wind farm. A TMD system was designed and fabricated to reduce the 1st mode of the test model. Two artificial earthquake ground motions with the site (wind farm) characteristics were used as the excitations. Shaking table test results demonstrate that the TMD system is effective in reducing the seismic responses of the test model. Soil liquefaction doesn't cause a significant reduction in frequency of the structural system, therefore, the detuning effect of the TMD system is not obvious. The feasibility of using a TMD to reduce the seismic vibration of offshore wind turbine supporting structures was verified.

5. Acknowledgements

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