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Study on vibration attenuation and load reduction of wind turbines based on tuned mass damper

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ABSTRACT

The tuned mass damper (TMD) is introduced to the field of structural control of wind turbines. Taking the 5MW offshore wind turbines as a research case, the parameters of TMD are optimized via both theoretical analysis and numerical simulation. In the theoretical analysis, to grasp the key factors of the wind turbine in the aspect of structure dynamics, the turbine with TMD system is simplified with three degrees of freedom in longitude direction. The influence of the parameters of TMD such as damper ratio, frequency is investigated through frequency domain analysis of the transfer function between the total thrust force and displacement of the wind turbine. Based on the theoretical analysis, the TMD is further optimized using numerical simulation under a certain wind condition via the program FAST-SC, in which a more complicated model of the wind turbine is established. The results show that TMD can obviously affect the characteristics of the vibration and load of the wind turbine. By optimizing TMD, the vibration and load of the wind turbine can be substantially attenuated. For further applying the structural control of wind turbines using TMD, the performance of TMD is verified under some standard wind models from GL2010 including EOG, NWP, EWM, ECG, EDC, via FAST-SC. The result shows that the vibration and load suppressing capacity of the wind turbines by TMD system can reach above 10% in some operating cases, which make great significance for the structure control of wind turbine.

Keywords: tuned mass damper, 5MW maritime wind turbines, structure control

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INTRODUCTION

At present, the TMD has been widely used in the field of structure control for vibration attenuation and load reduction. A simple TMD consists of the mass (inertial force), the spring (elastic restoring force) and the damper (energy dissipation). Installing a TMD system on the structure can effectively reduce the vibration of the principal structures. There are already a lot of engineering cases of TMD system, but most of them are concentrated on architecture and bridge cases [1-4]. In recent years, the researchers at home and abroad also have done some simulation studies about the TMD system on the vibration control of the wind turbines[5-8]. Via the program "FAST-SC", the vibration and load of the offshore wind turbine with TMD are numerically studied [9-11]. The simulation results show that the passive control system using TMD can reduce the fatigue load of the tower bottom by about 10%. The study of Bossanyi et al.[12] shows that wind turbines using the generator torque control, blade pre-bending and TMD damping system technique can make the wind turbines load reduce by 20%, and make the tower cylinder design mass reduce by 10%. Zhang et al. [13] analyzed the dynamic responses of the wind turbines with TMD to the condition of typhoon. The result showed that TMD system could effectively reduce the extreme load of the wind turbines and could also reduce the tower top movement of the wind turbines by 15% under the condition of extreme wind.

TMD has provided a good way for the load reduction and vibration attenuation of wind turbines. But in the structural control of the wind turbines, the influence of the key factors of TMD on the vibration attenuation and load reduction is still not clear. In addition, many studies only focus on the performance of TMD under a single external wind condition, the effects in the enormous standard operating conditions are to be verified. In this study the 5MW wind turbine will be taken as a research object, the parameters of TMD are optimized via both theoretical analysis and numerical simulation, and the performance of the TMD system will be verified in many complicated wind conditions, to give more experience and knowledge for the application of TMD for vibration attenuation and load reduction in the structure control of wind turbine.

FREQUENCY DOMAIN ANALYSIS OF THE INFLUENCE OF TMD ON WIND TURBINE VIBRATION

Wind Turbine Dynamic Model with TMD

The prototype of the model adopted in this study is a 5MW offshore wind turbines designed by NREL, The fixed platform is used to eliminate the influence of the foundation. The main parameters of the wind turbine are shown in Table 1:

Table 1 Main parameters of the simulation model of the wind turbines

Rated Power(MW)	5
wind rotor	The upwind, clockwise rotation
number of blades	3
Control method	Variable pitch, variable speed, yaw
Drive System	Multistage gearbox speed growth
Wind rotor/hub diameter(m)	126、3
Hub height (m)	90
Cut-in, rated, cut-out wind speed (m/s)	3、11.4、25
Rated tip velocity ratio	80
cone angle, tilt angle (degree)	-2.5、5
Mass of wind turbines (T)	110
Nacelle mass (T)	240
Mass of tower (T)	347.5
Nacelle size(m)	18*6*6
Platform type	Fixed platform
The position of TMD	Nacelle

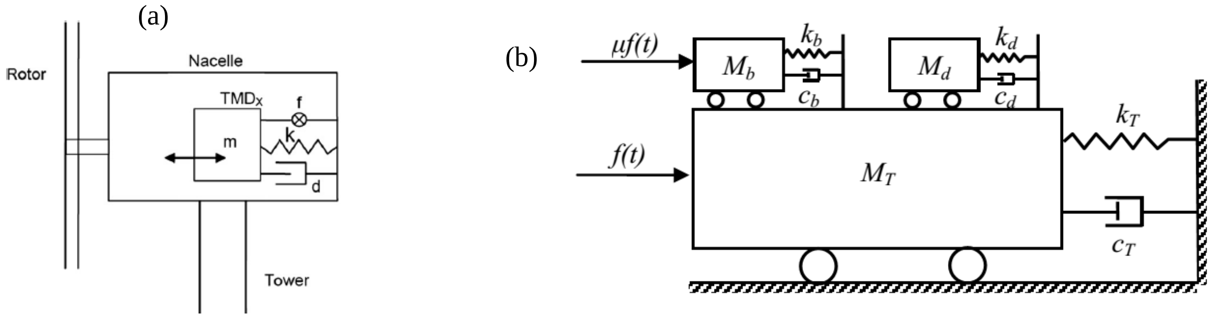


Fig. 1 (a) configuration of TMD, (b) simplified dynamic model of wind turbine with TMD

Wind turbine is a complicated system that consists of interacting devices with some degrees of flexibility; it can be modeled with different complicated levels. In order to grasp the key factors of the wind turbine dynamic characters and service for the vibration attenuation controller design, the turbine with TMD is simplified with three degrees of freedom in longitude direction. The blade and tower are continuous slender flexible structures. Considering only their first mode shape, the model can be transformed as Fig. 1. Although the whole turbine system is nonlinear, in a certain operating point it can be analyzed as linear system. With Lagrange method, the motion equation is

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=F(t) \quad (0)$$

Where, [M], [C] and [K] are mass matrix, damping matrix and stiffness matrix respectively. The generalized coordinates are

$$\{x\}=[x_T, x_d, x_b]^T \quad (0)$$

$$[M]=\begin{bmatrix} M_T & 0 & 0 \\ M_d & M_d & 0 \\ M_b & 0 & M_b \end{bmatrix},[C]=\begin{bmatrix} C_T & -C_d & 0 \\ 0 & C_d & 0 \\ 0 & 0 & C_b \end{bmatrix},[K]=\begin{bmatrix} K_T & -K_d & -K_b \\ 0 & K_d & 0 \\ 0 & 0 & K_b \end{bmatrix} \quad (0)$$

$$F(t)=\begin{bmatrix} -f(t) \\ 0 \\ -\mu f(t) \end{bmatrix} \quad (0)$$

Where M_T is the generalized mass of tower top which is composed of the lump mass of nacelle and continuous mass of tower. M_d is the mass of TMD, and M_b is the generalized mass of the blade. C_T is the structure damping of tower, C_b is the generalized damping of the blade, C_d is the damping of TMD which can be tuned and controlled for the vibration reduction, K_T is the generalized stiffness of tower, K_d represents the stiffness of TMD, K_b is generalized stiffness of blade. x_T, x_d and x_b denote the generalized displacement of the tower top, the nacelle and the blade, respectively. The detailed calculation method of generalized parameter for the flexible blade and tower with mode shape is described in [14]. $f(t)$ is the total thrust force on turbine, $\mu f(t)$ represents the generalized thrust for on the rotor blade, μ is the coefficient factor.

Table 2 generalized parameter of the wind turbine

M_T (kg)	M_d (kg)	M_b (kg)	K_T (N/m)	K_d (N/m)	K_b (N/m)	C_T N/(m/s)	C_d N/(m/s)	C_b N/(m/s)
4.29E5	2.00e4	2.61e3	1.45e6	6.40e4	5.026e4	6900	10000	114

Make Laplace transform of equation (1), then transfer function $H(s)_{x_T-f(t)}$ between tower top displacement x_T and thrust force $f(t)$ can be got.

$$H(s)_{x_T-f(t)}=\frac{X_T(s)}{F(s)}=\frac{A(s)}{B(s)} \quad (0)$$

Where,

$$A(s)=1+\frac{\mu K_b}{\left(M_b s^2+C_b s+K_b\right)} \quad (0)$$

$$B(s)=\left(M_T s^2+C_T s+K_T\right)+\frac{(C_d s+K_d)M_d s^2}{\left(M_d s^2+C_d s+K_d\right)}+\frac{K_b M_b s^2}{\left(M_b s^2+C_b s+K_b\right)} \quad (0)$$

Frequency domain characteristics of the wind turbine with different parameters of TMD system

TMD system is a vibration system containing masses, springs and dampers, so its relevant design parameters contain the mass (m), the spring stiffness (k) and the damping (c). The combined action of those parameters determines the vibration characteristics and damping effects of TMD system. Additionally, the installation location of the TMD in the wind turbines may also change its response towards the principal structure and subsequently influence the damping effect of TMD system. In engineering application, the inherent frequency and damping ratio are the commonly used parameters to determine TMD's performance. They are respectively:

$$\omega=\sqrt{\frac{k}{m}} \quad (1)$$

$$\zeta=\frac{c}{2\sqrt{km}} \quad (2)$$

The first parameter ω which is introduced above is called the inherent frequency under non-damping status of the system. The second parameter ζ is called damping ratio. According to the definition, the natural frequencies have the dimension of angular velocity, but the damping ratio is a parameter without dimension.

In order to find the right key parameters for the TMD system, the frequency domain analysis is made with different damping ratio and inherent frequencies. Fig. 2 shows the Bode diagram of the transfer function $H(s)$ for the wind turbine with TMD systems. A maximum magnitude can be observed at the frequency of 0.28 from the Bode diagram, which gives an approximate value of the inherent frequency of the wind turbine. When the damping ratio ζ =0.07, the maximum amplification of the transfer function can be suppressed significantly, but there exist two peak values around the frequency of 0.25, as shown in Fig. 2(a). When the damping value is 0.14, the maximum magnitude is substantially reduced, which means that, at this damping ratio the vibration and load can be more effectively attenuated by TMD. When the damping value is bigger than 0.14, the maximum dynamic amplification increases with damping ratio and performance of the TMD becomes worse. Fig. 2(b) presents the effect of TMD with different inherent frequencies. As can be observed, when the frequency of TMD is 0.266 or 0.285 which is close to the natural frequency of the tower, the maximum amplification is successfully decreased by TMD and the response is generally well.

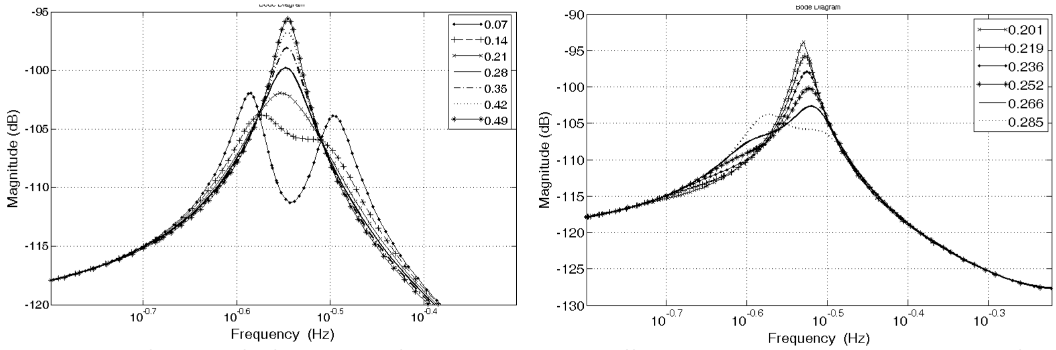


Fig. 2 Bode diagram of the transfer function *H(s)* for TMD systems with different (a) damping ratios and (b) inherent frequencies.

THE OPTIMIZATION OF TMD UNDER A CERTAIN WIND CONDITION USING "FAST-SC"

It should be noted that wind turbine is a complicated nonlinear model with many flexible structures. And the Characters of thrust forces is also complicated. Thus, to make the optimization of the TMD a step further, a more complicated model is essential for the optimization of TMD. Based on the simplified dynamic model in the previous section, an approximate range is given out for the optimization of TMD. In this section, a full wind turbine model is established by FAST-SC, and the optimization of TMD parameters will be further studied.

FAST-SC simulation platform

FAST is a program that is currently developed and maintained by NREL[15]. In 2005, the program FAST passed the assessment of Germanischer Lloyd Wind Energie and were identified as suiting "for the design and certification of the computational load of wind turbines". Based on the FAST software, the University of Massachusetts put forward an advanced version FAST-SC(SC for structural control), in which the TMD model variance was added. So using FAST-SC program, the structure dynamic simulation of large wind turbines configured with the TMD can be conducted [9-11].

In the present study, only the wind turbines load and vibration related freedoms are retained, including the freedom of 3-order in the flapwise direction of the rotor, the freedom of 2-order in the edgewise direction of the rotor, the freedom of 2-order in the fore-after direction of the tower, the freedom of 2-order in the side-side direction of the tower as well as the freedoms of the TMD system etc.. In addition, the fixed maritime foundation is adopted in this study for the offshore wind turbine. The TMD System is configured in the direction of x axis and is installed in the nacelle, with the tower top center as the tactic balance location of the TMD. To confine the displacement of the mass, the braking locations are set at ±7m respectively away from it. The braking rigidity and braking damper at this spot are respectively set to be 50KN/m and 500KNs/m.

Optimization of the damping ratio

In the optimization, the mass of the preliminary selection of modulation damper is 20000 kg, which can not only ensure that the TMD system has certain effects of damping vibration, but also avoid the additional load which is caused by too much mass of the modulation damper. The frequency f is chosen around the natural frequency of the main structure 0.28, which can be obtained from the simply frequency domain analysis in Fig. 2(b). To ensure the frequency the initial stiffness (k) of its spring is set to be 64,000N/m according to Eq. (8). Therefore, there is a one to one correspondence between the c and ζ. Via FAST-SC program, the vibration and the dynamic load of the wind turbine is simulated under five different damper ratios from 0.14 to 0.42. Fig. 3 shows the time traces of the displacement of the tower top in the axis direction under different damper ratio. As can be indicated, the TMD system can significantly reduce the amplitude of the vibration of the tower top and the damper ratio can obviously influence the effect of vibration reduction. When the damper ratio ζ=0.14, the vibration amplitude of tower top is substantially lower than the other damper ratios. Comparing with the TMD System which has a high damping ratio ζ=0.40, its inhibiting effect on the tower vibrating amplitude is about 10% higher. Fig. 4 shows the bending moment of x axes at the bottom of tower. The suppression of the moment of the tower bottom is similar to that of the vibration of the tower top. Therefore, the TMD system whose damping ratio ζ is 0.14 has better dampening effect than the TMD system whose damping ratio is higher.

In order to further determine the optimized damping ratio and eliminate interference caused by exceptional cases, we chose the variation range of damping ratio ζ between 0.08 and 0.20, the calculation interval of 0.03. Fig. 5 shows the displacement of tower top under the five damper ratios. The results show that under the TMD system with relatively low damping ratio, the vibration inhibition effect of the tower top made by the change of damping ratio has been inconspicuous, but we can still know from Fig. 5 that the vibration inhibition effect of the TMD system is the best when the damping ratio (ζ) is 0.14. Therefore, with the analysis of simulation experiment, under the situation that the mass and frequency of TMD system is the same and the installation position is fixed, comparing with the TMD system with high damping ratio, the TMD system with lower damping ratios has a much more obvious effect on the vibration and load reduction of the wind turbines; But for the lower damping ratio TMD system, the influence of changing the damping ratio on the vibration attenuation effect of wind turbines is not obvious.

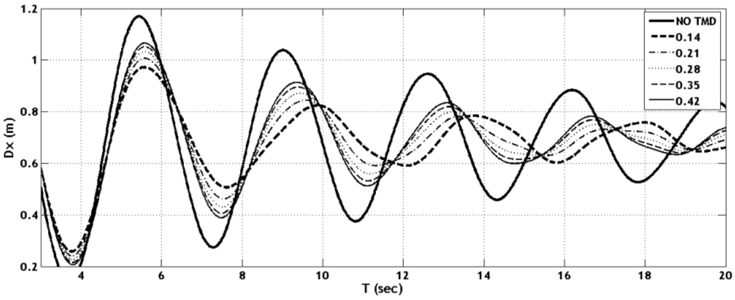


Fig. 3 Time traces of the displacement of the tower top in the axis direction under different damper ratio

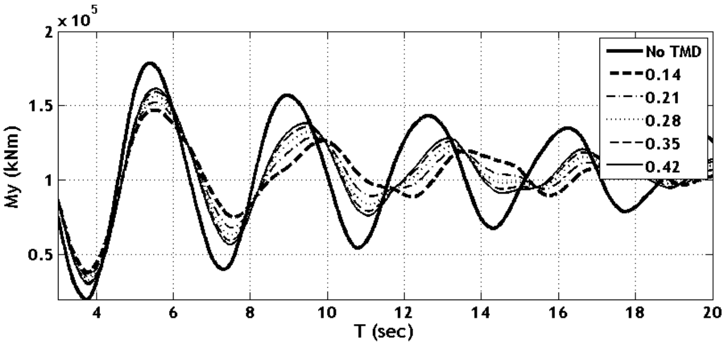


Fig. 4 Time traces of the bending moment of x axes at the bottom of tower under TMD Systems of different damping ratios

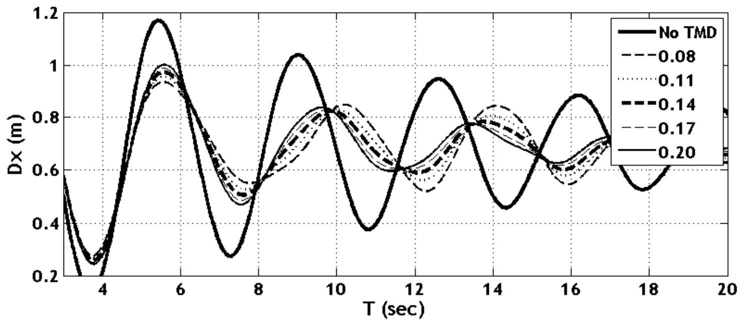


Fig. 5 Time traces of the displacement of the tower top in the axis direction under different damper ratio

Optimization of the frequency

As pointed out in the section 2, the inherent frequency of TMD system should be close to the main frequency of the structure so as to ensure the action of reverberation resonance can be generated. But for the wind turbine, the main structure contains some mechanical components with different inherent frequencies. In order to enhance the effect of the TMD for vibration reduction, the frequency f of TMD should be chosen close to around the natural frequency of the main structure, which can be obtained from the simply frequency domain analysis in Fig. 2(b), and is approximately 0.28. We select the parameters mass of TMD system as 20,000 kg (m=20,000 kg), damping ratio ζ as 0.14. Five different frequencies ranging from 0.12 to 0.28 is tested with the increment of 0.04. Fig. 6 and Fig. 7 show the movement of the tower top and the moment of the tower bottom under the TMD system with different frequencies. The results indicate that a slight change of inherent frequency in TMD system can lead to relatively big changes of vibration features and loading features of wind turbines. Compared with damping ratio, the vibration attenuation performance of TMD which is applied to wind turbines is more sensitive to the change of inherent frequency. Therefore, the optimization of frequency of the TMD system is of great significance to improve the vibration attenuation performance of TMD system. From the ultimate displacement of tower top and the ultimate load of the tower bottom, it can be concluded that among the five different frequencies the vibration attenuation performance of TMD system with the frequency of 0.24 Hz is the best. Comparing with the inherent frequency of the tower, the optimal frequency of the TMD should be a little smaller and it is only about 87% of the frequency obtained from the simple frequency domain analysis in this study.

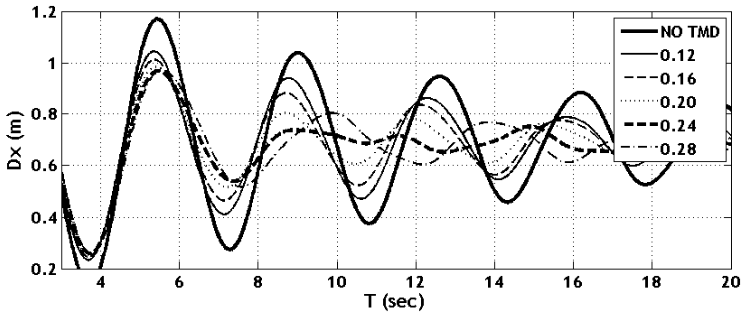


Fig. 6 Displacement of the tower top in the axis direction for the wind turbine using TMD with different frequencies

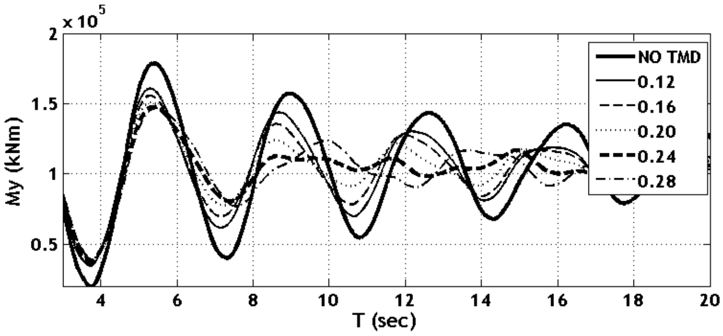


Fig. 7 The bending moment of x axes at the bottom of tower under TMD Systems of different frequencies.

Installation position of TMD

Table 3 shows optimized parameters of TMD such as mass of system, stiffness, damping, frequency, damping ratio, etc.. This section will further determine the installation position of TMD system. Since TMD is installed in the nacelle, the horizontal position of TMD system in the static state should be ensured in the center of tower top so as to reduce the unbalanced loading of vibration and only the vertical distance relative to the center of tower top is taken into consideration.

Table 3 The Parameter Setting After Optimization of TMD System

m/kg	k/(N/m)	c/(Ns/m)	ω/(rad/s)	f/Hz	ζ
20000	45479	8445	1.508	0.24	0.14

Set the vertical height of TMD to the center of tower top as 1--5 meters respectively, get the vibration features and loading features of key parts of wind turbines under TMD system at different height through numerical simulation by FAST program. Fig. 8 shows the movement of tower top in the *x* direction under TMD system at different position, indicating that the change of TMD position exerts inconspicuous influence on the vibration features of tower top. Therefore, the installation position of damper in the nacelle is not the key factor that influences the vibration attenuation performance of TMD system. Hence, for the sake of installation, the position of 2 meters above the tower top is selected in this study.

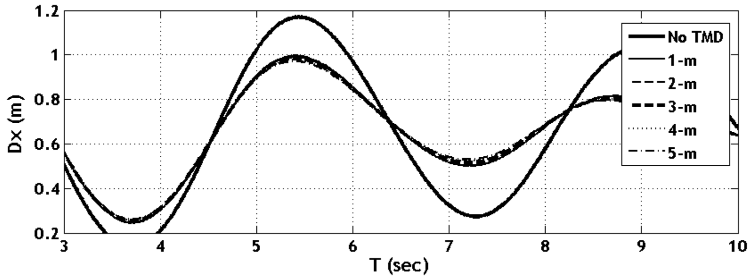


Fig. 8 the tower top movement (a), the tower top tailwind movement (b) and the tower top side-wind movement under the condition that TMD system is in different locations

VERIFICATION OF THE PERFORMANCE OF TMD SYSTEM UNDER DIFFERENT WIND SITUATIONS

The studies of the above section have determined the optimized parameter configuration of TMD system. The optimized parameter will be adopted in this section. The dynamic response of the wind turbine under different wind models will be simulated using the program of FAST-SC, to verify the performance of TMD system on vibration attenuation and load reduction under some more complicated external conditions, aiming to accumulate experiences for further studying and applying the structural control of wind turbines using TMD.

The external wind conditions

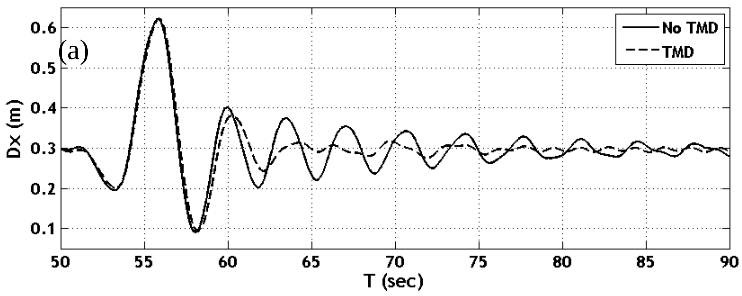
Five standard wind models from the GL certification 2010 are introduced in the present verification, which are Extreme Operating Gust (EOG), Extreme Wind-speed Model (EWM), Normal Wind Profile (NWP), Extreme coherent Gust (ECG) and Extreme Direction Change (EDC). In the EOG and NWP wind model, the two starting wind speeds of 8m/s and 15m/s of the extreme operating gust at the hub height is considered---the smaller one is below the rated wind speed, and the bigger one is above the rated wind speed. The vertical wind shear factor is 0.2. The wind speeds adopted in the simulation are shown in Table 2.

Table 2 The design conditions under different wind models

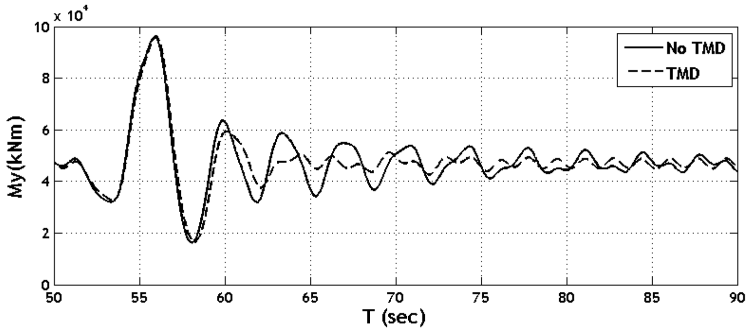
Case number	1	2	3	4	5	6	7
Wind model	EOG		NWP		EWM	ECG	EDC
wind speed at the height of hub (m/s)	8	15	8	15	56	10	20

The performance of TMD system under EOG

The extreme operating gust is added to the steady wind at the time of 50s to ensure the simulation for the wind turbine under the steady wind is fully developed, and the duration time is 10.5 seconds, and the total time of simulation is 100 seconds. Fig. 9(a) shows the movement of the tower top in the x direction under EOG with the starting wind speed of 8m/s at the hub height. As can be observed that under extreme operating gust conditions at low wind speeds, the TMD system can substantially affect the vibration and load characteristics of the wind turbine. Through TMD, conspicuous vibration attenuation can be obtained. To reveal the effect of TMD on the load furthermore, the bending moment of tower bottom is shown in Fig. 9(b). A similar suppression of the load at the bottom of the tower can be observed as the vibration of the tower top. At the wind speed, TMD system's inhibitory power on vibration can reach up to 15%, and the average load-weakening degree can also reach up to 10%. Hence, at the low wind speed both the vibration and load of the wind turbine can be greatly attenuated by TMD.



(a)



(b)

Fig. 9 Performance of the TMD under EOG wind model with the starting wind speed of 8m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom.

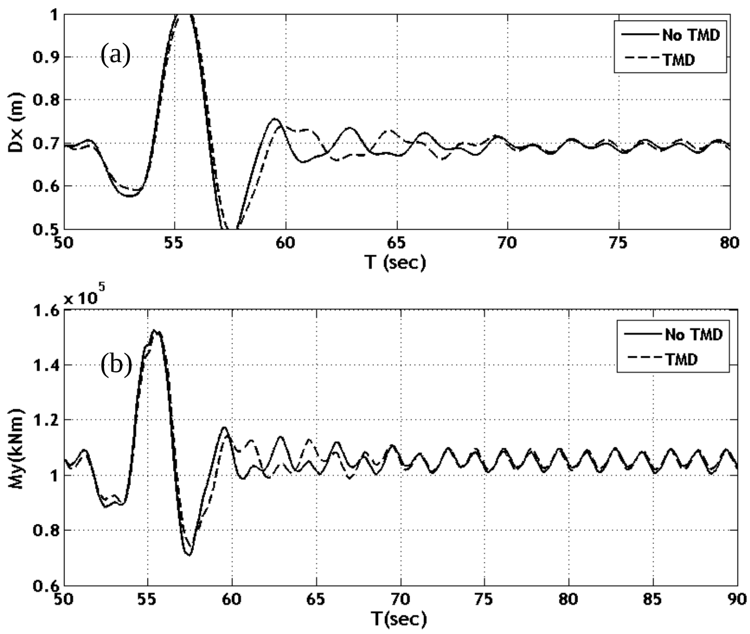


Fig. 10 Performance of the TMD under EOG wind model with the starting wind speed of 15m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom.

Fig. 10 shows the movement of tower top and the bending moment load at the tower bottom under the EOG with the starting wind speed of 15m/s at the hub height. As is shown in the Fig. 10, under extreme operating gust conditions at a high wind speed, the TMD system has the unanimous effect on vibration and load of the wind turbine to a certain extent, but vibration attenuation effect is inconspicuous. From the comparative analysis of Fig. 9-10, we can see that under the extreme operating gust, TMD system has certain inhibitory effects on the vibration and load of the wind turbine. Its vibration-damping effect is better under lower wind speed than under higher wind speed.

The performance of TMD system under the NWP wind condition

NWP is a simple steady wind model, in which the wind shear in the height direction is considered. According to the GL2010, the wind shear factor of 0.2 is selected here for the standard wind farm. Similarly as the EOG, two wind speeds of 8m/s and 15m/s are mainly considered here, with the simulation time period of 200 seconds. Fig. 11 and Fig. 12 exhibit the vibration and load properties under NWP of 8m/s and 15m/s, respectively. Both the displacement of the tower top and the moment of the tower bottom only reduce a little. From the results, it can be concluded that the TMD system has a certain suppressing effect on the vibration and load for the wind turbine, but its suppressing effect is much lower than that under the situation of EOG, among which the vibration reducing performance under high wind speed is better than that under low wind speed. The suppressing effect on the tower top under the wind speed of 15m/s reaches 4%; and also the bending moment of the tower bottom can be reduced by 5% accordingly.

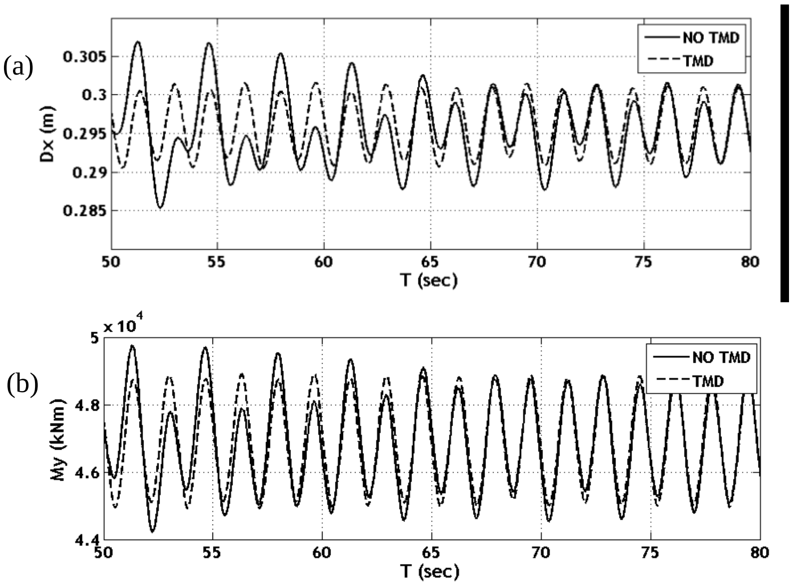


Fig. 11 Performance of the TMD under NWP wind model with the starting wind speed of 8m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom.

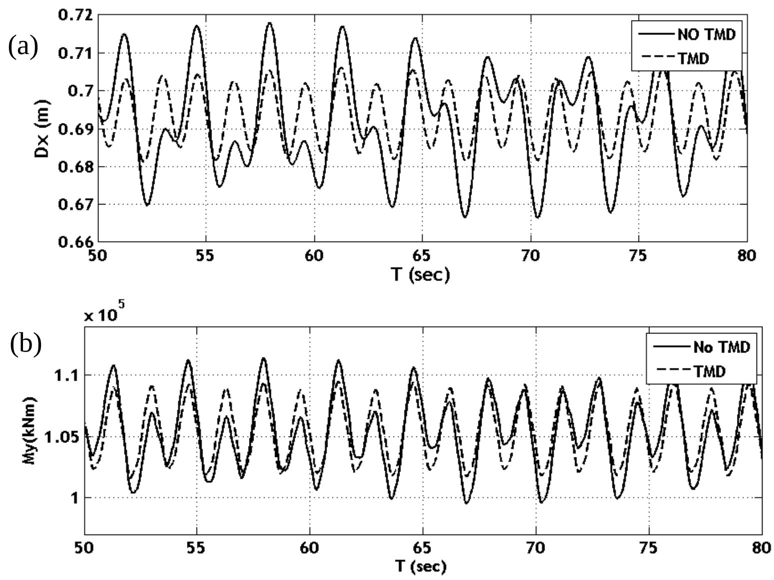


Fig. 12 Performance of the TMD under NWP wind model with the starting wind speed of 15m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom.

The performance of TMD system under EWM

The extreme wind speed of 56m/s at the height of hub with 1-year recurrence period is adopted. And the vertical wind shear exponent is 0.11. Under the extreme wind speed, only the state that the wind turbine parked and the wind rotor yawed parallel to the direction of the extreme wind is considered. 200 seconds are simulated using the FAST-SC program so as to make the wind turbine reach the stable condition. The vibration and load properties under NWM are exhibited in Fig. 13. Both the displacement of the tower top and the load of the tower bottom are greatly reduced by using the TMD system. Under the EWM with the wind speed of 56m/s, TMD system exhibits a great suppressing effect on the wind turbines' vibration and load, the suppressing effect on the displacement of the tower top will reach 60%, while weakening degree of tower bottom load will reach more than 60%. Because wind turbines can produce bigger vibration amplitude and load easier with high wind speed, TMD system has a huge significance on guarantee the wind turbines' stability with high wind speed.

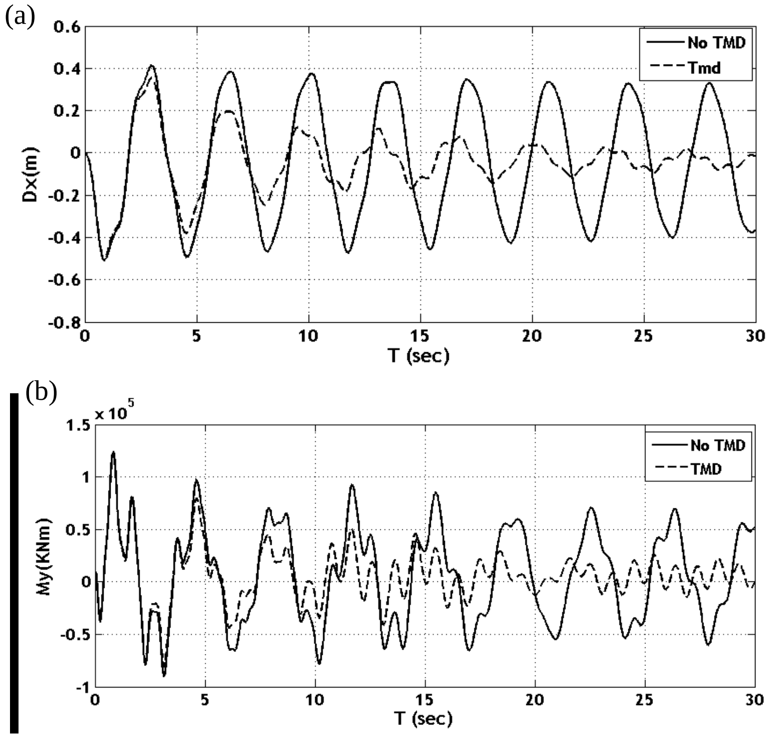


Fig. 13 Performance of the TMD under EWM wind model with the starting wind speed of 56m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom.

The performance of TMD system under ECG

The Extreme coherent Gust with a starting wind speed of 10m/s at the hub height is conducted in this section. The magnitude of the extreme coherent gust is 15m/s. The rise time of the gust is 10 seconds. The gust started at the time of 50s and ended at the time of 60s. A total time of 100 seconds is simulated using the program of FAST-SC. Fig. 14 show the time traces of the displacement of the tower top and the bending moment of the tower bottom under the ECG. From the Fig. 14, we can see that under the condition of extreme coherent gust, TMD system has certain inhibitory effects on the vibration and load of wind turbine, which can inhibit the vibration of the tower top by around 5%, while reduce the bending moment of the tower bottom by 7%. Contrasting the damping performance of TMD system under EOG, the inhibiting capacity of the TMD system against is weaker.

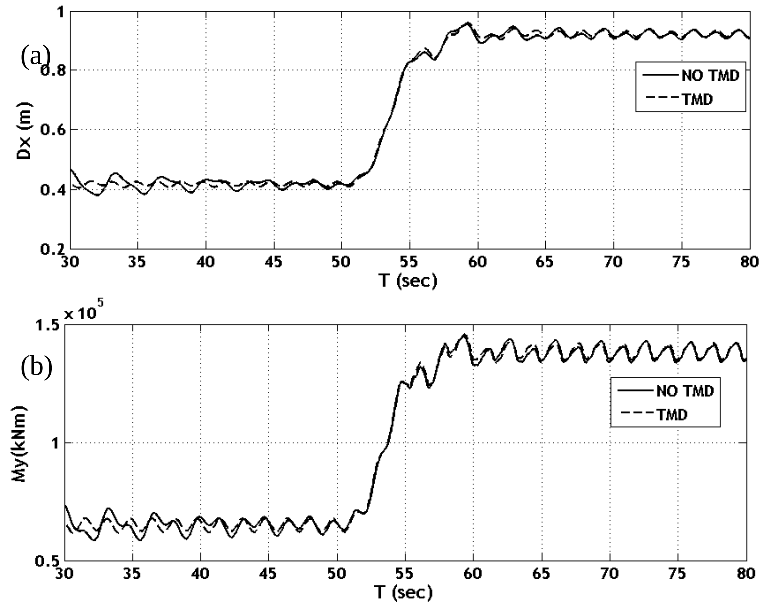


Fig. 14 Performance of the TMD under ECG wind model with the starting wind speed of 10m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom

The performance of the TMD system under EDC

For the wind model EDC, the starting wind speed of 20m/s at the hub height is adopted in this section. The EDC start at the time of 50s and last 6 seconds. The total simulation takes a total of 100 seconds. The vibration and load properties of the tower under EDC are shown in Fig. 15. It can be acknowledged that in the model of extreme wind direction change, TMD system will have certain inhibitory action on the vibration and load of the wind turbine, in which inhibitory action on tower top vibration in the axis direction can reach 5%, while inhibitory action on the bending moment of the tower bottom can only reach about 3%. Compared with the performance of the TMD system under steady wind, TMD has a better inhibitory effect on structural vibration and load fluctuation caused by shifting winds.

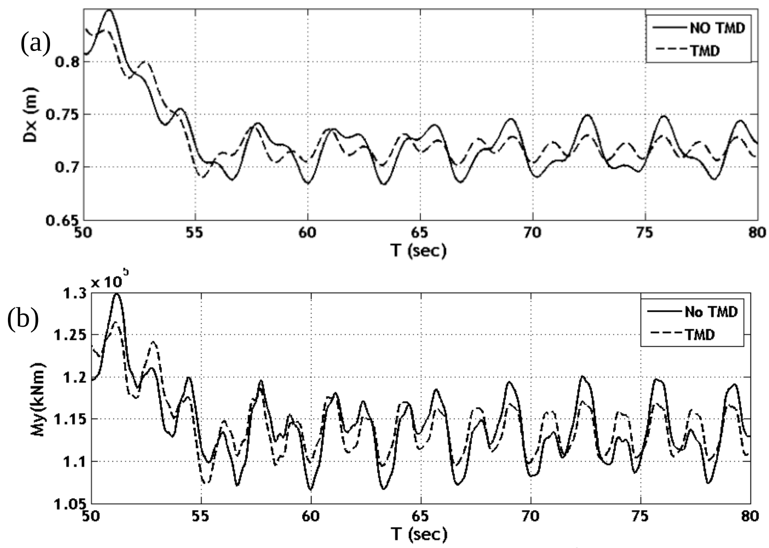


Fig. 15 Performance of the TMD under EDC wind model with the starting wind speed of 20m/s. (a) the movement of the tower top in axis direction and (b) the bending moment in the x direction at the tower bottom

CONCLUSION

This paper is dedicated to researching the TMD system's control over the vibration and load of wind turbines structure. The 5 MW maritime wind turbine is taken as the research target, and the key parameters of TMD system's damping performance is optimized through both theoretical analysis and numerical simulation. The effect of the TMD system is verified in various GL wind conditions via the program FAST-SC. The conclusions are as following:

(1) The simple model, in which the turbine with TMD system is simplified with three degrees of freedom in longitude direction, grasps well the key factors of the dynamic characters of the wind turbine. The frequency domain analysis shows that the key parameters including the frequency and the damping ratio of the TMD can significantly influence its dynamic characters, which gives an approximate range for the optimization. Based on the theoretical analysis, the parameters are further optimized using the software FAST-SC. It is found that the suppression of vibration and load are most sensitive to the changes in natural frequency and is least sensitive to the installation position of the damper. When the frequency f=0.24 and the damper ratio ζ=0.14, the best performance of TMD is obtained for the vibration attenuation and load reduction for the wind turbine.

(2) The TMD system has inhibition on the vibration and load of wind turbines under all the external wind model including the EOG, NWP, EWM, ECG and EDC. For the EOG, its inhibition ability on vibration and load in low wind speed is obviously superior than in high wind speed. At the starting wind speed of 8m/s, the suppression of vibration and load can achieve 10% or more. For the wind model of NWP, ECG and EDC, the TMD system has a relatively weak inhibition on the vibration and load while it has a much better damping capacity under the EWM. Under the EMW with a velocity of 56m/s, the attenuation can achieve up to 60%, which makes great significance for the survival of a wind turbine under very extreme environment, such as hurricane or tornado.

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