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SEISMIC PROTECTION OF WIND TURBINES USING TUNED MASS DAMPERS

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ABSTRACT

The seismic efficiency of tuned mass dampers is numerically analyzed by means of a three-bladed 5 MW onshore reference wind turbine. The calculations are carried out by the aeroelastic dynamic horizontal axis wind turbine simulator FAST with its seismic and structural control codes. Time-histories of five historic earthquakes are used. These are Tokachi-Oki (1968), El Centro (1979), Northridge (1994), Kobe (1995) and Kocaeli (1999). The simulations are performed simultaneously with turbulent wind at 1-25 m/s mean speeds. The optimum TMD parameters are calculated using Den Hartog's criteria for natural damper frequency and damping ratio. A mass ratio of 5 % is chosen for the analyzed TMD.

The acquired results show that TMD can mitigate especially the periodic structural vibrations effectively. This effect is observed both for the wind and for the seismic loading, which shows that the seismic vibration mitigation effort of a TMD mainly depends on the frequency content of the earthquake. During El Centro earthquake, which causes mainly transient vibrations, the efficiency of TMD is not significant. From the analyzed other four earthquakes, particularly the seismic vibrations caused by the Tokachi-Oki earthquake are reduced remarkably, by which the turbine tower without TMD reaches its highest RMS and peak deflection.

INTRODUCTION

Because of its minor environmental impact, electricity generation using wind power is getting remarkable also in seismic active regions. As shown in Fig.1 large part of the south European coastal areas presents high seismic hazard and such wind conditions, which are sufficiently suitable for financial returns from modern wind turbines. According to the global report of the Global Wind Energy Council the power capacity of the installed wind turbines for instance in Turkey has reached in 2012 2.3 GW by increasing in one year period over 28 % (Fried et al., 2012). The safety and serviceability of these structures mainly depend on their design and analysis, which should include in

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addition to the primary wind loading also the seismic forces, as documented in norms and guidelines such as IEC Standard 61400-1.

Wind turbine tower oscillations induced by wind, wave and earthquake excitation risk the structural safety and cause material fatigue, which limits the lifespan of the wind turbine and creates inefficiencies from the economic perspective. To prolong the lifespan of a wind turbine, it is necessary to reduce the stress due to dynamic loads. Because of insufficient damping properties and filigree construction, it is preferable to use auxiliary vibration mitigation methods to control the dynamic loading of wind turbines. A common method for reducing oscillations is to integrate a tuned mass damper (TMD). A TMD in the form of a pendulum or liquid mass damper could be installed at the bottom of the drive train and tuned to the relevant natural frequency of the wind turbine tower.

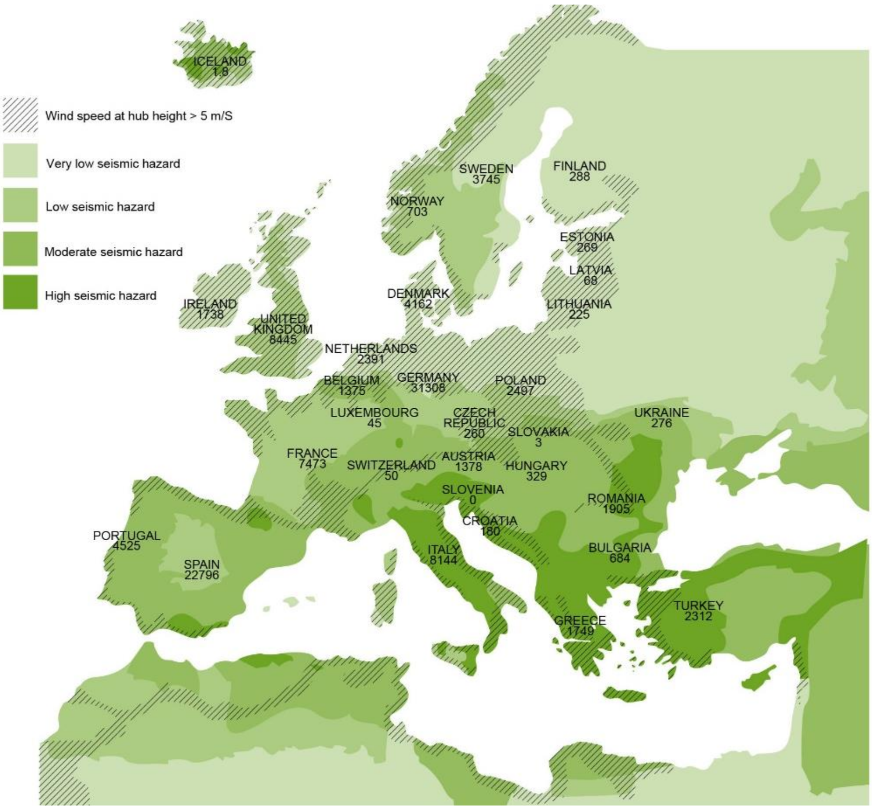

Figure 1. Seismic hazard map of Europe with annotation of suitable site for wind power installation (with average wind speed at 50 m from ground > 5 m/s) and of wind power installed in each country by end of 2013

VIBRATION MITIGATION OF WIND TURBINE TOWERS WITH TUNED MASS DAMPER

Auxiliary structural control methods can be classified as dampers and tuned mass dampers. Metallic dampers are one of the most applied strategies for conventional vibration control. These devices dissipate the oscillation energy of a structure through the inelastic deformation of metal and are especially suitable for seismically excited structures. However, one big obstacle of these damping systems is that, they cannot recover the large strains and thus a replacement after each major earthquake event is necessary.

TMD consist of an auxiliary mass attached to the main structure. The tuned parameters enable the mass of the damper to oscillate with a phase shift against the motion of the structure, leading to damping forces on the primary structure. Pendulum damper or liquid mass dampers like tuned sloshing damper (TSD) and tuned liquid column damper (TLCD) are especially suitable for the control of the naturally low frequency vibrations of wind turbine towers. These damper systems are shown in Fig.2.

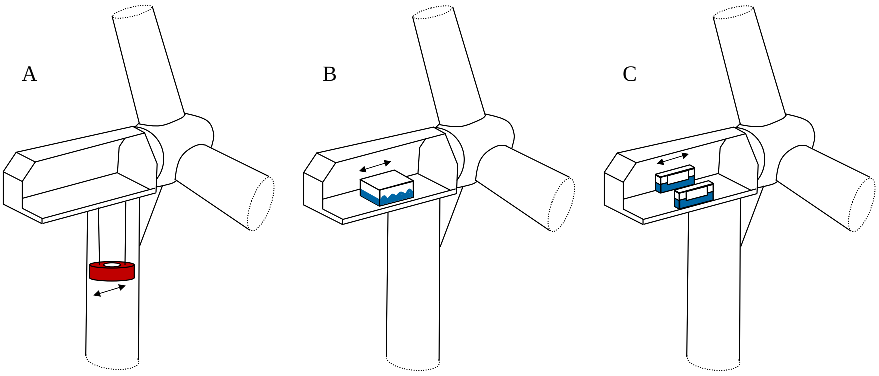

Figure 2. Examples of tuned mass damper (TMD) implications: Pendulum damper (A), tuned sloshing damper (B) and tuned liquid column damper (C) attached to a wind turbine

A pendulum damper consists of an auxiliary mass hanged on the structure by a pendulum. As the damper mass transfers its restore forces directly over the pendulum to the structure, it should be located on the structures segment with a maximum displacement. For the most of the wind turbines, the first mode tower bending vibrations are relevant and the maximum displacement occurs at tower top. Therefore, it is preferable to install the pendulum damper below nacelle and tune it to the fundamental tower frequency. Hydraulic dampers or friction plates supporting the damper mass can be used to increase the damping ratio of the pendulum damper.

Liquid mass dampers use mostly Newtonian fluids such as water. Due to their low prime and maintenance costs, liquid mass dampers are an interesting alternative to the mechanical mass dampers. These dampers have usually very low natural frequencies and can therefore easily be used for the mitigation of tower bending vibrations of wind turbines. TSD consist of an open tank filled with the damper liquid. The geometry of the tank defines the dynamic properties, especially the natural frequency of the damper. The restore forces caused by the sloshing of the liquid mitigate the vibrations of the structure. The oscillation energy dissipates by the sloshing and liquid-tank interaction effects. Depending on the desired damper mass TSD can be integrated at the bottom of the nacelle of a wind turbine.

TLCD patented by Frahm (Frahm, 1910) consists of a U-shape tank, which is filled with a Newtonian liquid. TLCD reduces the structural vibrations by means of restore forces caused by streaming of the liquid in the U-shape tank with a phase shift against the vibrations of the structure. The oscillation energy is dissipated by turbulence and friction effects, which are mainly caused by changes in sectional area of the tank by using an orifice. Due to its geometric versatility, TLCD can be easily integrated in the outer shell of the nacelle of a wind turbine (Altay et al. 2013a, 2014a and 2014b).

The dynamic behavior of a TMD is defined mainly by its frequency, damping ratio and mass. Usually 3-10 % of the modal mass of the structure is sufficient to mitigate vibrations. The natural frequency f_D of a TMD can be calculated using the equations of Table.1. Hereby as shown in Fig.3 L_{PD} is the length of the pendulum, L_{TSD} the length of the tank of TSD and L_{TLCD} the length of the liquid column of TLCD. H_{TSD} is the liquid depth in the TSD-tank and g the gravitational acceleration.

Table 1. Equations for the calculation of natural frequencies of tuned mass dampers

Pendulum damper	Tuned sloshing damper	Tuned liquid column damper
$f_D = \frac{1}{2\pi}\sqrt{\frac{g}{L_{PD}}}$	$f_D = \frac{g}{2L_{TSD}} \tanh \frac{\pi H_{TSD}}{L_{TSD}}$	$f_D = \frac{1}{2\pi}\sqrt{\frac{2g}{L_{TLCD}}}$

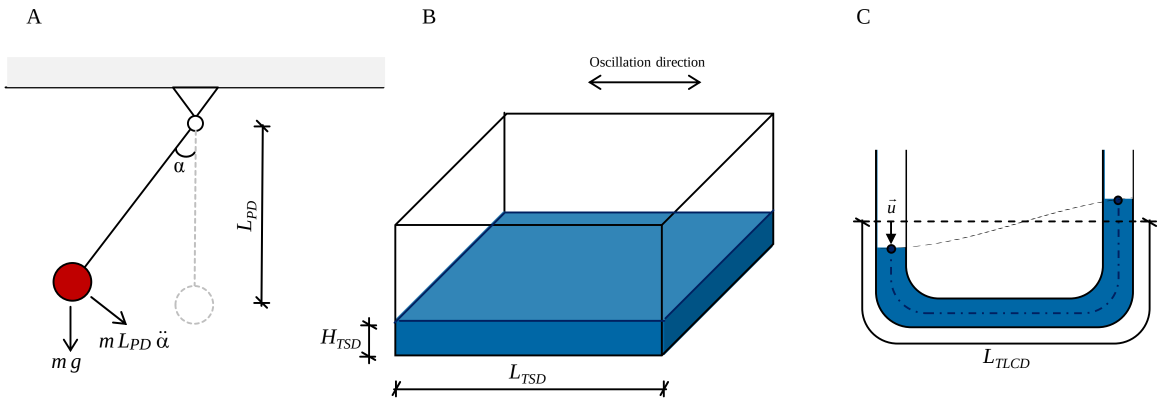

Figure 3. Geometric parameters for the calculation of natural frequencies of tuned mass dampers: Pendulum damper (A), tuned sloshing damper (B) and tuned liquid column damper (C)

For effective vibration mitigation, the natural frequency and damping ratio of the TMD must be tuned to the dynamic properties of the main structure. Most common method is the criteria developed by Den Hartog from the resonance curves of a harmonically excited two degrees of freedom system (Den Hartog, 1947). The optimal natural frequency of the TMD is calculated by using Eq.(1). Eq.(2) give the optimal damping ratio of the TMD. Hereby f_M is the natural frequency of the relevant mode of the structure, which is significant for the vibration of the structure. For the wind turbines, it is preferable to use the fundamental frequency of the fore-aft tower-bending mode, which is mainly relevant for the fatigue behavior of the structure. The mass ratio of a TMD m_D to the modal mass of the structure m_M is defined as μ and influences both of the optimization equations. In addition, other criteria can also be used, such as criteria of Warburton (Warburton and Ayorinde, 1980).

$$f_{D,opt} = \frac{f_M}{1+\mu} \tag{1}$$

$$D_{D,opt} = \sqrt{\frac{3\mu}{8(1+\mu)^3}} \tag{2}$$

SEISMIC PROTECTION OF THE REFERENCE WIND TURBINE WITH TUNED MASS DAMPER

The seismic efficiency of the TMD is numerically analyzed by means of a three-bladed 5 MW onshore reference wind turbine. Table.2 shows the system properties as defined by U.S. Department of Energy's National Renewable Energy Laboratory (Jonkman et al., 2009).

Table 2. System properties of the reference wind turbine

Rating / configuration	5 MW / 3 Blades
Control	Variable speed, collective pitch
Cut-in, rated and cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in and rated rotor speed	6.9 rpm, 12.1 rpm
Hub height	90 m
Rotor diameter	126 m

The modes and the dynamic properties belonging to the first two tower fore-aft bending modes are shown in Fig.4. Hereby the damping ratio is given as constant for all modes. As shown in Fig.5 the first fore-aft natural frequency is between the one- and three-per-revolution frequencies of cut-in and cut-out wind speeds. As the fundamental tower frequency is critically close to the three-per-revolution of the turbine, resonant tower vibrations can be expected especially at low wind speeds. The modal mass of the wind turbine can be calculated from the tower for-aft bending mode by using the Eq.(3).

Hereby *m(x)* and *η(x)* are the tower mass and modal coordinates of the tower mode distributed over the tower height *h*. The nacelle and rotor masses $m_{Nacelle}$ and m_{Rotor} are added as lumped masses to the modal mass of the turbine.

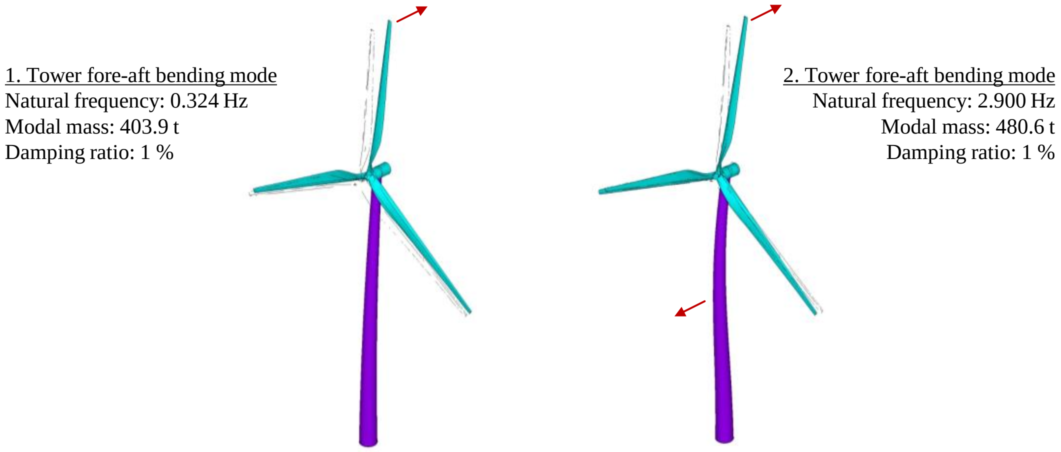

Figure 4. Dynamic properties of the reference wind turbine

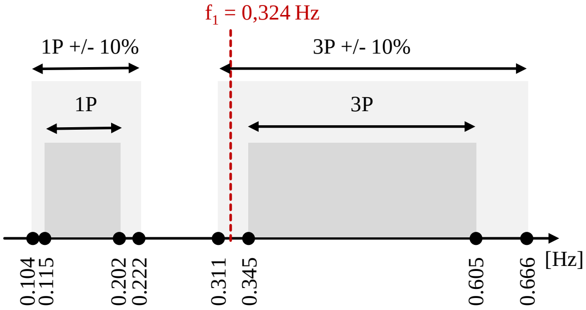

Figure 5. One- and three-per-revolution frequencies of the reference wind turbine

$$m_{modal} = \int_0^h m(x)\eta^2(x)dx + m_{Nacelle} + m_{Rotor} \tag{3}$$

The simulation of the seismically excited reference wind turbine is carried out by NREL's open source FAST (Jonkman, 2013) and FAST-Seismic (Prowell and Asarch, 2012) combined with the expansion FAST-SC (Lackner, 2012), which is developed by University of Massachusetts. The code FAST (Fatigue, Aerodynamics, Structures and Turbulence) can simulate aero elastic dynamic horizontal axis onshore and offshore turbines with turbulent wind loading. The seismic calculations of the reference wind turbine are carried out simultaneously with turbulent wind loading for wind speeds 1 to 25 m/s with 1 m/s step, which are generated by FAST's stochastic inflow turbulence simulator TurbSim (Kelley and Jonkman, 2013). The relevant simulation parameters of the wind field are documented in Table.3.

Table 3. Simulation parameters of the wind field

Simulation time	1030 s
Time step	0.05 s
Number of grid-points	31 x 31
Grid dimension	145 x 145 m
Turbulence model	Kaimal
Turbulence type	Normal turbulence model
Wind profile type	Power law
Height of the ref. wind speed	90 m
Mean wind speeds	1-25 m/s

In order to calculate the seismic loading of the wind turbine modeled in FAST environment FAST-Seismic simulates an actuator mass connected to the base of the turbine (Fig.6). The actuator force $f_g(t)$ is calculated by Eq.(4). Hereby k_{act} is the stiffness of the actuator calculated by Eq.(5) and c_{act} the actuator damping coefficient calculated by Eq.(6). Tuning the stiffness and the damping the realized motions $x_{g,0}$ and $\dot{x}_{g,0}$ get closer to the desired seismic motions $x_{g,seis}$ and $\dot{x}_{g,seis}$. In Eq.(5) and Eq.(6) m_{tf} is the total mass of the wind turbine with its foundation and Ω_{act} is the actuator circular frequency, which should be 10 times the highest frequency of the turbine. In Eq.(6) D_{act} is the damping ratio of the actuator and equals to 60 to 70 %, which lets the actuator mass to oscillate near the critical damping case and have an optimum step response. The relevant simulation parameters of FAST-Seismic are listed in Table.4. In order to reduce the numeric failure the time step of the main simulation is reduced after the simulation of the wind field from 0.05 s to 0.005 s.

$$f_g(t) = k_{act}(x_{g,seis} - x_{g,0}) + c_{act}(\dot{x}_{g,seis} - \dot{x}_{g,0}) \tag{4}$$

$$k_{act} = m_{tf}\Omega_{act}^2 \tag{5}$$

$$c_{act} = 2m_{tf}D_{act}\Omega_{act} \tag{6}$$

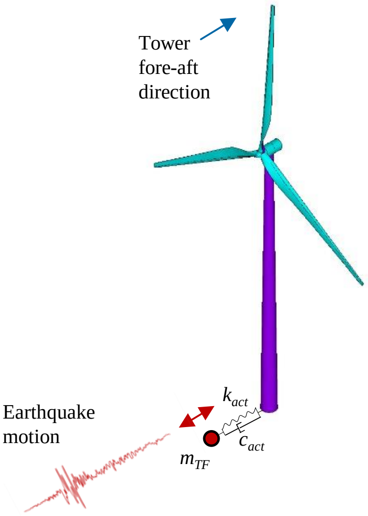

Figure 6. Simulation of seismic wind turbine loading with an actuator mass

Table 4. Simulation parameters of the seismic loading

Simulation time	1000 s
Time step	0.005 s
Earthquake starting time	500 s
Actuator circular frequency	75.4 rad/s
Actuator damping ratio	65 %

As listed in Table.5 five historic earthquakes are used to calculate the seismic efficiency of the TMD. The recorded accelerograms are applied both in the fore-aft and side-to-side tower direction at the same time. The time histories of the earthquakes are shown in Fig.7.

Table 5. Historic earthquakes used for the numerical calculations

Name of the earthquake	Year	Recording station
Tokachi-Oki	1968	Hachinohe
El Centro	1979	Bonds Corner
Northridge	1994	Tarzana
Kobe	1995	KJMA
Kocaeli	1999	Düzce

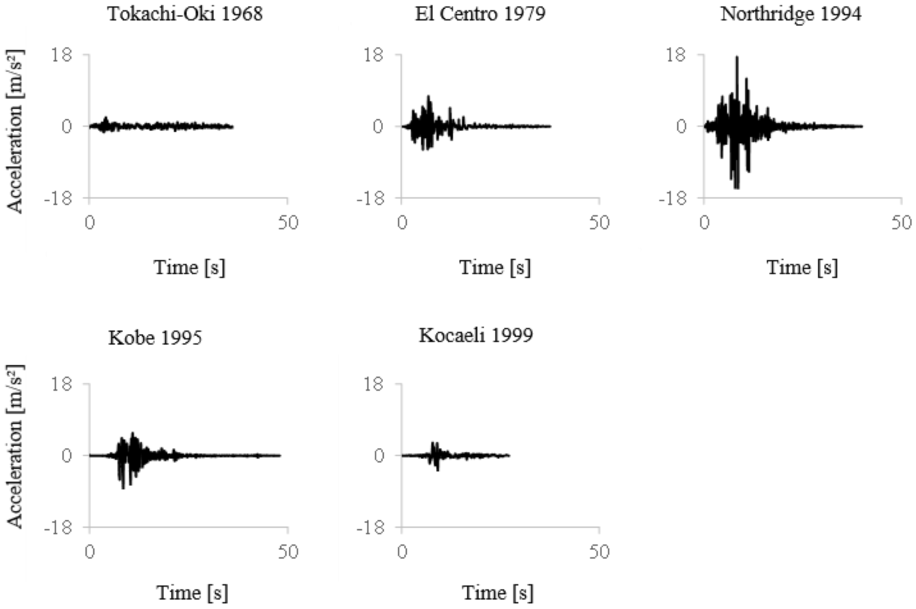

Figure 7. Time histories of the simulated five historic earthquakes

FAST-SC is a modified version of FAST and can simulate the TMD by additional degrees of freedom and lumped masses connected to the nacelle and platform of the FAST-model by a spring-dashpot. The TMD of the analyzed onshore wind turbine are assumed to be connected to the nacelle. The tuning frequency corresponds with the fundamental fore-aft tower bending frequency and is calculated by using the optimization criteria of Den Hartog as introduced before. The dynamic properties of the analyzed TMD are documented in Table.6. The mass ratio between the TMD and the modal mass of the wind turbine is chosen as 5 %.

Table 6. Simulation parameters of the tuned mass damper

Damper mass	20.2 t
Mass ratio	5 %
Spring stiffness	75.7 kN/m
Damping coefficient	10.0 kN s/m
Natural frequency	0.308 Hz
Damping ratio	12.7 %

The seismic TMD-efficiency is evaluated by the RMS value of the tower top deflection of the reference wind turbine, which corresponds to the fatigue damage of the structure. From the RMS values a reduction factor for the TMD is calculated by using the Eq.(7).

$$R = \left(1 - \frac{RMS_{with\,TMD}}{RMS_{without\,TMD}}\right) \cdot 100 \tag{7}$$

The time-histories of the turbine tower deflections of Tokachi-Oki and El Centro earthquakes are shown in Fig.8 and 9 for the cut-in, rated and cut-out wind speeds. In order to eliminate the static tower deflection, which cannot be reduced by the TMD, a high-pass filter is applied with a cutoff frequency at 0.1 Hz. As required by the norms and guidelines of wind turbines the last 600 s of the total 1000 s simulation time is used for the evaluation. The starting phase from 0 to 400 s of the simulations includes nonrealistic tower deflections resulting from transient effects. Earthquakes are simulated 100 s after the start of 600 s time histories.

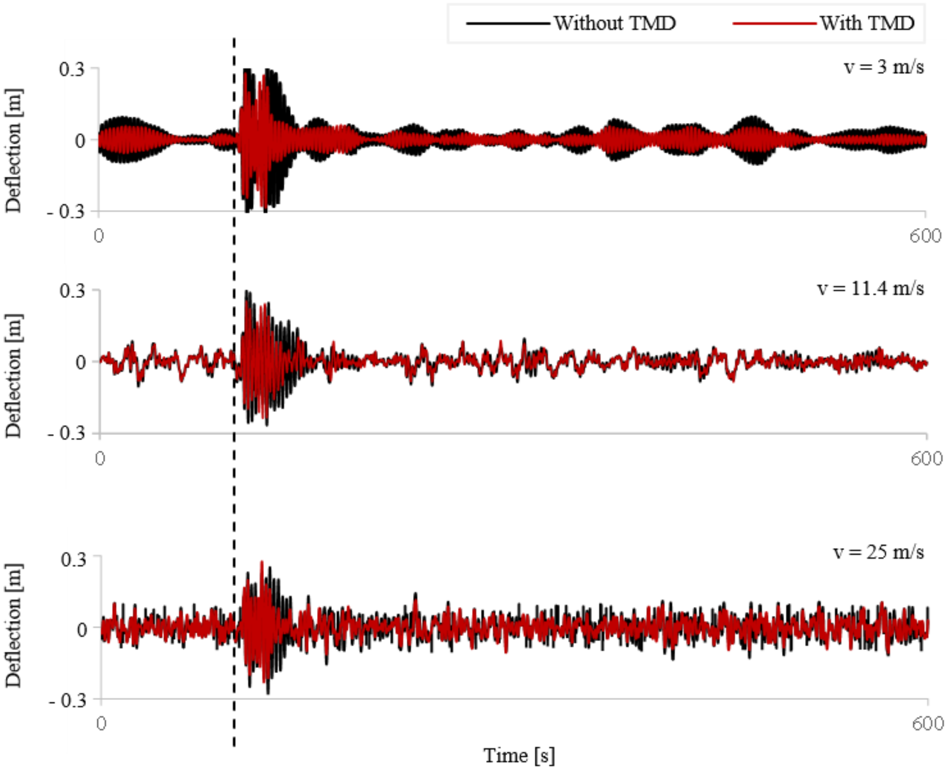

Figure 8. Time histories of the tower deflections of the reference onshore wind turbine – Tokachi-Oki Earthquake

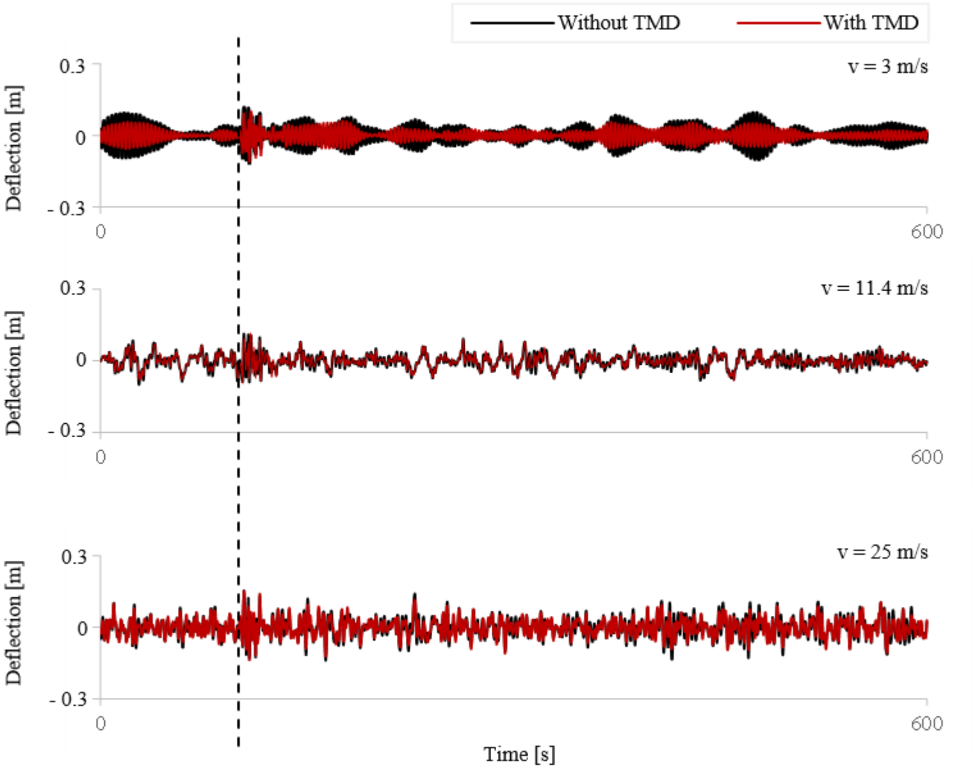

Figure 9. Time histories of the tower deflections of the reference onshore wind turbine – El Centro Earthquake

The RMS values of the tower deflection time histories are shown in Fig.10. Fig.11 compares the RMS values of the tower response with and without TMD. The reduction factors calculated from the RMS values are documented in Fig.12.

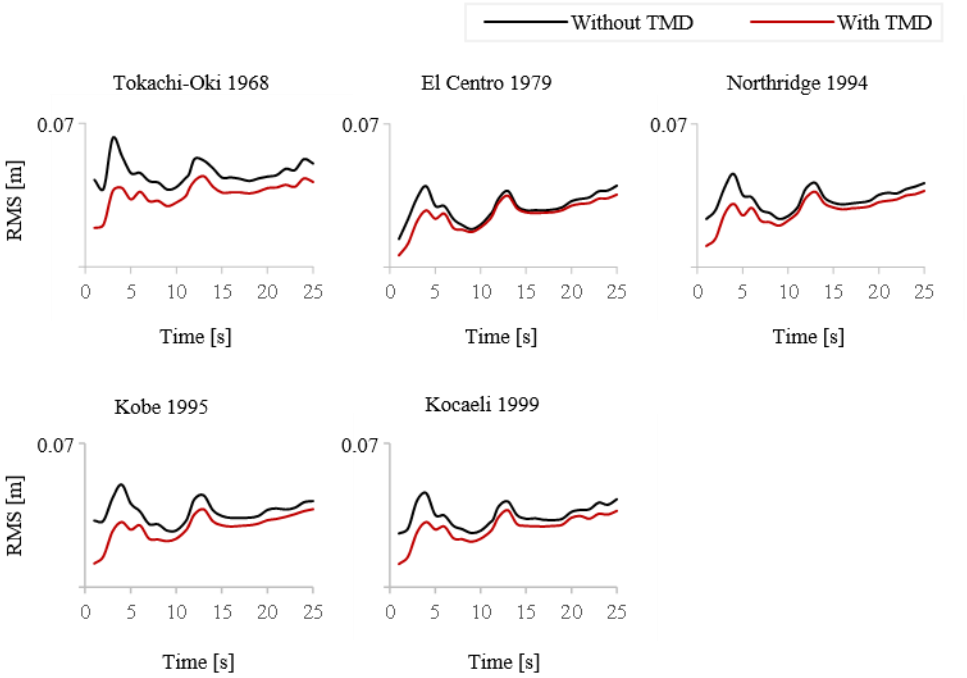

Figure 10. RMS values of time histories of the tower deflections of the reference onshore wind turbine

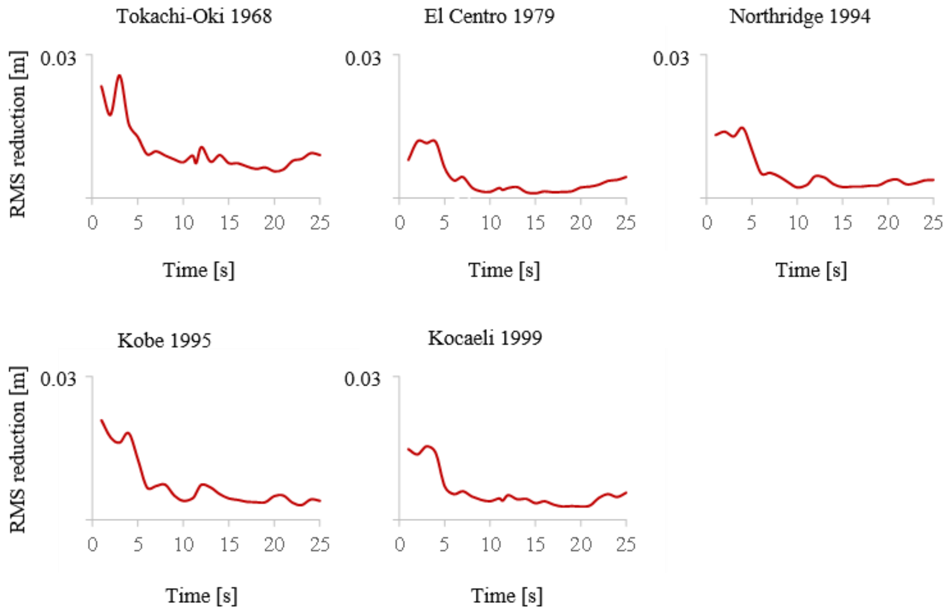

Figure 11. Change of RMS values of time histories of the tower deflections of the reference onshore wind turbine

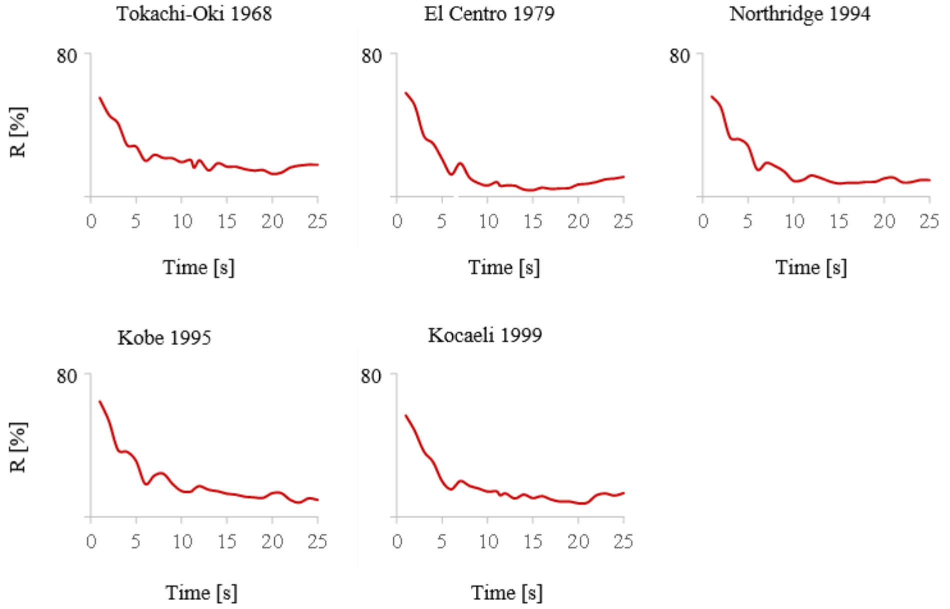

Figure 12. Reduction factors calculated from the RMS values of time histories of the tower deflections of the reference onshore wind turbine

Wind induced turbine tower vibrations, which can be classified as periodic and transient oscillations, depend on the speed and turbulence intense of the wind. Period vibrations occur mainly during normal wind conditions at low wind speeds, when the number of rotor revolution corresponds with the natural frequencies of the structure. These resonant character vibrations are notably relevant for the fatigue behavior of the turbine. As the fundamental frequency of the analyzed reference turbines tower fore-aft mode is quite near the cut-in wind speed 3 m/s induced three-per-revolution frequency, the tower responses near this wind speed mainly with periodic oscillations. As seen from the results TMD can mitigate these vibrations very effectively. This phenomenon remains regardless of the influence of the seismic effects. At higher wind speeds, the tower response becomes transient and the TMD loses its efficiency. This can clearly be seen from the shown time histories in Fig.8 and Fig.9.

Seismic tower vibrations of the wind turbine depends on the dynamic properties of an earthquake. Main parameters, which influence the tower response, are the time-span of the earthquake, the peak ground acceleration (PGA) and the frequency content of the earthquake. Each of the analyzed five historic earthquakes has different properties. Similar to other slender structures the seismic efficiency of a TMD attached on a wind turbine depends especially on the frequency content of the earthquake (Altay et al., 2014c). As seen from the time-histories although the PGA of Tokachi-Oki earthquake is significantly smaller than El Centro, the tower deflections caused by Tokachi-Oki earthquake are much larger. Fig.10, Fig.11 and Fig.12 show these effects with the comparison of RMS values clearly. The tower seismic responses are mostly periodic, except these of the El Centro earthquake, and therefore the reached vibration mitigation ratios are during these earthquakes more remarkable. Especially during Tokachi-Oki earthquake, TMD shows independently from the wind speed a general improvement of the turbine tower dynamics.

CONCLUSIONS

TMD can reduce especially structural vibration of periodic character. Consequently, the efficiency of the TMD depends mainly on the frequency content of the seismic loading. From the analyzed five historic earthquakes, TMD shows high efficiency especially during the Tokachi-Oki earthquake, which causes the most periodic turbine tower vibrations with the highest RMS and peak deflection. During earthquakes, which induce mainly transient vibrations the TMD efficiency is lower. Therefore, during the seismic design phase of a wind turbine with a TMD the local effects on earthquake seismic loading and their interaction with the dynamic structural properties of the turbine should always be considered.

FUTURE WORK

The earthquake induced transient vibrations of wind turbines can be reduced by improving the general damping properties of the turbine tower. Turbine dampers developed until now are to be positioned in inner side of the turbine tower and therefore they block the tower shaft and disturb the accessibility of the nacelle. In addition, the material costs and necessary maintenance effort make the application of these dampers difficult. Development of low-cost auxiliary dampers, which can be easily integrated in the filigree construction of the wind turbine, is going to be the main aim of the future work.

Depending on its operational way, dampers and TMD are divided into two groups: Passive dissipation systems, such as hysteretic metallic dampers and active systems with actuators, which induce supplemental forces on the host structure. These both methods can also be combined and used together. The so-called hybrid systems can function as a passive device in case of a failure of the active system. Both active and hybrid devices can reduce structural vibrations effectively. Nevertheless, the energy demand level of the actuators affects the application of these methods. Compared with other strategies the implementation of passive dissipation devices is more straightforward. However, the calibration and maintenance costs are great obstacles for these devices. In order to solve this problem, semiactive damping systems are developed (Altay et al. 2014c and 2013b), which can sense the actual condition of the structure and adapt their dynamic properties in real time. These adaptive devices offer a broad range of new application possibilities also for the seismic protection of wind turbine towers. Therefore, future work is concerned with the development and implementation of such systems for wind turbines.

ACKNOWLEDGMENTS

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