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A monitoring system for wind turbines subjected to combined seismic and turbulent aerodynamic loads

Breiffni Fitzgerald* and Biswajit Basu

Department of Civil, Structural & Environmental Engineering, Trinity College Dublin, Dublin, Ireland

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Abstract. Research to date has mainly focused on structural analysis and design of wind turbines considering turbulent aerodynamic loading. The combined effects of wind and seismic loading have not been studied by many researchers. With the recent expansion of wind turbines into seismically active regions research is now needed into the implications of seismic loading coupled with turbulent aerodynamic loading. This paper proposes a monitoring procedure for onshore horizontal axis wind turbines (HAWTs) subjected to this combined loading regime. The paper examines the impact of seismic loading on the 5-MW baseline HAWT developed by the National Renewable Energy Laboratory (NREL). A modified version of FAST, an open-source program developed by NREL, is used to perform the dynamic analysis.

Keywords: seismic analysis; wind turbines; FAST

1. Introduction

Due to the rapid growth and expansion of wind turbine technology worldwide, turbines are now being deployed in earthquake prone regions. Consequently, structural engineers must now concern themselves with designing wind turbines that can adequately resist loading from extreme natural hazards such as earthquakes. China is one example of a seismically prone region that has seen dramatic growth in wind power production with an increase in installed capacity of 4600% over the last decade (Katsanos *et al*. 2016). Furthermore, many seismically prone areas such as California, Italy and Spain already have large installed capacities of wind power. Therefore it is becoming more important to consider seismic actions on wind turbines and this is an area of research that has grown in interest in recent years.

A considerable amount of work has been done on vibration control of wind turbines in recent years. Dueñas-Osorio and Basu (2008) showed that excessive acceleration of wind turbine components can lead to unavailability of wind turbines and recommended the use of structural control strategies to mitigate vibrations. Murtagh *et al*. (2008) and Murtagh and Basu (2007) pioneered the application of passive structural control schemes for wind turbines. Further work on passive control was carried out by Colwell and Basu (2009), Lackner and Rotea (2011), Zhang *et al*. (2014, 2015, 2016), Dinh and Basu (2015) and Basu *et al*. (2016). Semi-active control has been investigated by Arrigan *et al.* (2011, 2014) and Dinh *et al*. (2016). In recent years active control of

*Corresponding author, Assistant Professor, E-mail: fitzgeb7@tcd.ie

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wind turbines has received much attention from researchers. Staino *et al*. (2012) developed an active controller to suppress edgewise vibrations in wind turbine blades. Staino and Basu (2013) also investigated the impact of blade rotor speed variations on blade vibration and designed active controllers to suppress this. Fitzgerald *et al.* (2013) developed active tuned mass dampers to control blade vibrations. Fitzgerald and Basu (2014) proposed an innovative active tendon control system for wind turbine blades and in further studies examined the effects of soil-structure interaction on structural control schemes (Fitzgerald and Basu (2016)). Basu *et al*. (2014) have investigated active control using flexible alternating current transmission systems (FACTS) devices. Stewart and Lackner (2011) have also studied active control of wind turbine components. For a more thorough review of structural control schemes applied to wind turbines see Staino and Basu (2015).

Although it is clear that many controllers have been developed for wind turbines the literature is still somewhat sparse on the question of structural health monitoring schemes. Many schemes are well known for monitoring large civil infrastructure such as those developed by Basu *et al*. (2008) and Nagarajaiah *et al*. (2009). However, there are not many studies that have developed monitoring schemes for wind turbines. Fitzgerald *et al.* (2010) proposed a damage detection scheme for wind turbine blades using short time Fourier transforms and real-time monitoring of blade vibration signals. Recently, Hu *et al.* (2015) proposed vibration-based structural health monitoring of a wind turbine system. This monitoring has the capacity to detect possible structural damage. The authors recommended that further research be carried out in order to ascertain damage in extreme load conditions, such as earthquake and wind gust.

Not only is the literature on monitoring of wind turbines sparse but there are almost no studies found which investigate the combined effects of combined turbulent aerodynamic loading and seismic loading on wind turbines. Dai *et al.* (2014) proposed a rapid seismic analysis methodology for existing wind turbine tower structures with a synergy of field testing and finite element modelling. Simplified reduced order models of HAWT towers were developed and updated based on field vibration measurement data from existing wind turbine tower structures in a Chinese seismic environment. This study did not include the effects of rotating blades and did not consider the wind fluctuation. Soil-structure interaction was also ignored. Indeed the authors recommended that future studies should undertake a more comprehensive assessment with more realistic load combinations (i.e., combined turbulent aerodynamic and seismic loads) considered. Kim *et al.* (2014) presented a procedure for seismic fragility analysis of offshore wind turbines. Push-over analysis was proposed to find the critical value of nacelle displacement. This analysis is static and the effects of dynamic turbulent aerodynamic loads were not considered in this study.

This paper investigates the effects of combined turbulent aerodynamic and seismic loads on HAWTs. The paper also proposes a monitoring strategy for HAWTs located in seismically prone regions. The 5-MW baseline HAWT developed by the National Renewable Energy Laboratory (NREL) is used for this purpose. A modified version of FAST, an open-source program developed by NREL, is used to perform the dynamic analysis.

2. Earthquake ground motions

In this study, the combined effects of turbulent aerodynamic loads and seismic loads on multi-megawatt onshore wind turbines have been studied. Two types of ground motions have been considered: The first is synthetically generated ground acceleration that is compatible with the

Eurocode 8 design spectrum ground acceleration and the second is obtained from real earthquake records downloaded from the USGS archive.

2.1 Synthetic ground acceleration (spectrum compatible)

Using SeismoMatch software (SeismoMatch 2016) input seismic ground motions are adjusted to the elastic design response spectrum of Eurocode 8 (2004). SeismoMatch is an application capable of adjusting earthquake accelerograms to match a specific target response spectrum, using the wavelets algorithm proposed by Abrahamson (1992) and developed and refined by Hancock *et al.* (2006). Seismomatch has been used in many recent studies (Ganjavi and Hao 2013, Hajirasouliha *et al.* 2013, Shahi *et al.* 2016, Tesfamariam *et al.* 2013) to obtain spectrum-compatible earthquakes. Using the wavelets algorithm a realistic representation of earthquake energy content is generated by Seismomatch.

One earthquake record has been downloaded from the USGS archive for the purposes of generating a spectrum-compatible accelerogram. Non-stationary characteristics have been modelled using the time-history of the real earthquake record. Pertinent data from the earthquake is summarised in Table 1. Fig. 1 shows the acceleration time history of the original earthquake considered.

Table 1 Earthquake ground motion for generation of spectrum-compatible earthquake

Earthquake	**Year**	**Location**	**Magnitude (M_w)**	**PGA (*g*)**
Kocaeli	1999	Turkey	7.5	0.20

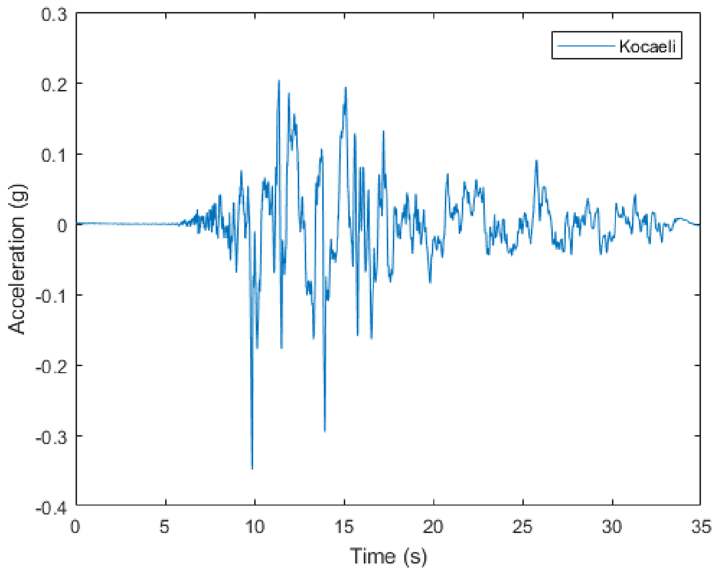

Fig. 1 Original ground acceleration for generation of spectrum-compatible earthquakes

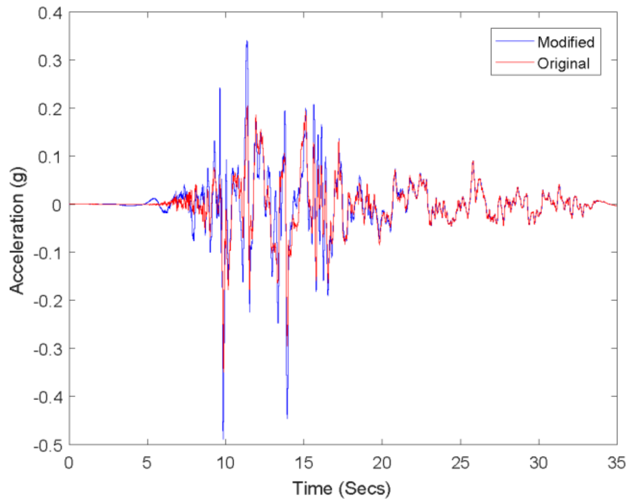

Fig. 2 Kocaeli - comparison of original acceleration and modified spectrum-compatible acceleration

The proposed method for generating a fully nonstationary spectrum compatible earthquake is now applied to the target response spectrum defined in Eurocode 8 (2004). In this numerical example Type B soil (deposits of very dense sand, gravel, or very stiff clay ground) and Type 1 seismicity has been selected. The maximum ground acceleration a_g has been set as 0.35 g. Fig. 2 compares the acceleration time histories of the original Kocaeli earthquake and the modified spectrum-compatible acceleration generated by Seismomatch. Fig. 3 shows a comparison between the target response spectrum (Eurocode 8), the original response spectrum and the modified mean response spectrum of the Kocaeli earthquake ground acceleration.

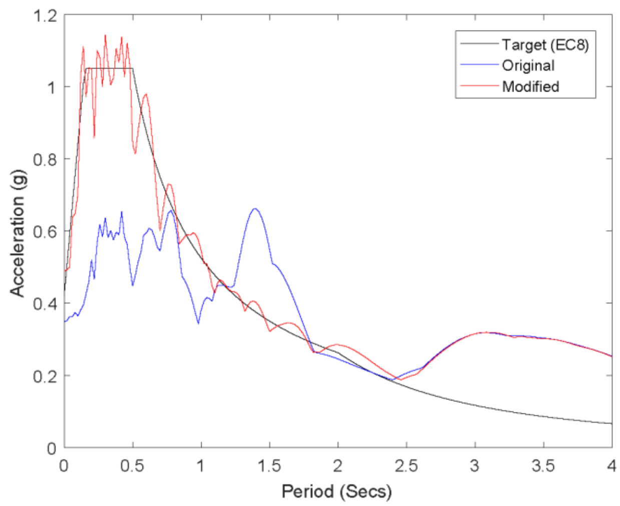

Fig. 3 Kocaeli - comparison of earthquake ground acceleration spectra

Table 2 Earthquake ground motions

Earthquake	Year	Location	Magnitude (M_w)	PGA (g)
El Centro	1940	California, USA	6.9	0.36

2.2 Ground acceleration from recorded seismic events

One further earthquake record, the El Centro earthquake, has been downloaded from the USGS archive for the purposes of this study. Pertinent data from the earthquake is summarised in Table 2. Fig. 4 shows the acceleration time history of the El Centro earthquake.

3. Wind turbine model - FAST

Jonkman JM & Buhl ML Jr. (2005) at the National Renewable Energy Laboratory (NREL) in the US have developed the combined modal and multi-body code FAST (Fatigue, Aerodynamics, Structures and Turbulence). FAST is the leading industry tool for simulating the coupled dynamic response of wind turbines. FAST joins aerodynamics models, control and electrical system (servo) dynamics models, and structural (elastic) dynamics models to enable coupled nonlinear aero-hydro-servo-elastic simulation in the time domain. The FAST tool enables the analysis of a range of wind turbine configurations, including two- or three-blade horizontal-axis rotor, pitch or stall regulation, rigid or teetering hub, upwind or downwind rotor, and lattice or tubular tower. Onshore or offshore (fixed-bottom or floating substructures) turbines can be modelled.

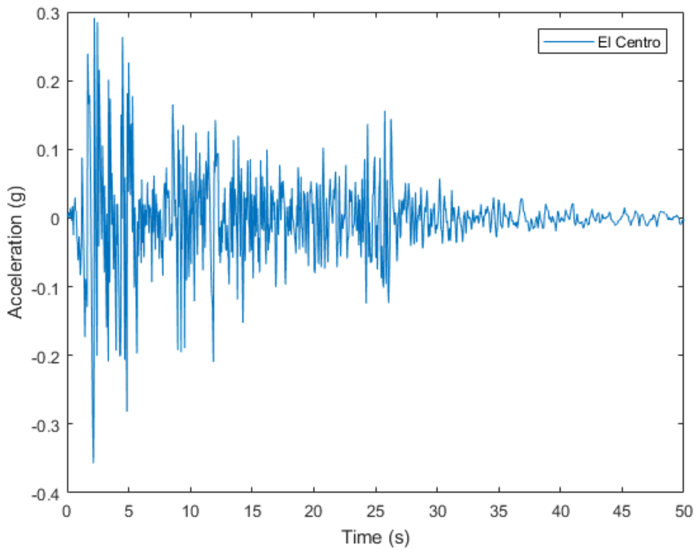

Fig. 4 Accelerogram of El Centro earthquake record

Table 3 Properties of NREL 5-MW baseline HAWT Hancock *et al.* (2006)

NREL 5-MW baseline wind turbine properties		
Basic description	Max. rated power	5-MW
	Rotor orientation, configuration	Upwind, 3 blades
	Rotor diameter	126 m
	Hub height	90 m
	Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
	Cut-in, rated rotor speed	6.9rpm, 12.1 rpm
Blade (LM 61.5 P2)	Length	61.5 m
	Overall (integrated) mass	17 740 kg
	Second mass moment of inertia	11 776 kg m^2
	1^{st} in-plane mode natural frequency	1.0606 Hz
	1^{st} out-of-plane mode natural frequency	0.6767 Hz
	Structural-damping ratio(all modes)	0.48%
Hub + Nacelle	Hub diameter	3 m
	Hub mass	56 780 kg
	Nacelle mass	240 000 kg
Tower	Height above ground	87.6 m
	Overall (integrated) mass	347 460 kg
	1^{st} Fore-Aft mode natural frequency	0.324 Hz
	1^{st} Side-to-Side mode natural frequency	0.312 Hz
	Structural-damping ratio(all modes)	1%

In this work, a modified version of FAST, following Asareh and Prowell (2011), has been used to apply combined turbulent aerodynamic loads and seismic loads to wind turbines. Turbulence has been generated from the NREL program TurbSim developed by Jonkman (2009). In this study, combined turbulent aerodynamic and seismic analysis of the 5-MW reference wind turbine developed by Jonkman *et al.* (2009) at the NREL has been examined. These loading conditions have been chosen to show the effect of the combination of turbulent aerodynamic and seismic loading conditions on wind turbine towers. Details of the 5-MW reference wind turbine are provided in Table 3.

4. Numerical simulations

Wind turbines are traditionally designed for turbulent aerodynamic loading conditions with no reference to seismic loads. The aim of this work is to examine the effect of the combined aerodynamic and seismic loading on the performance of the wind turbine tower and to develop a monitoring strategy to protect wind turbines from the harmful effects of seismic loads.

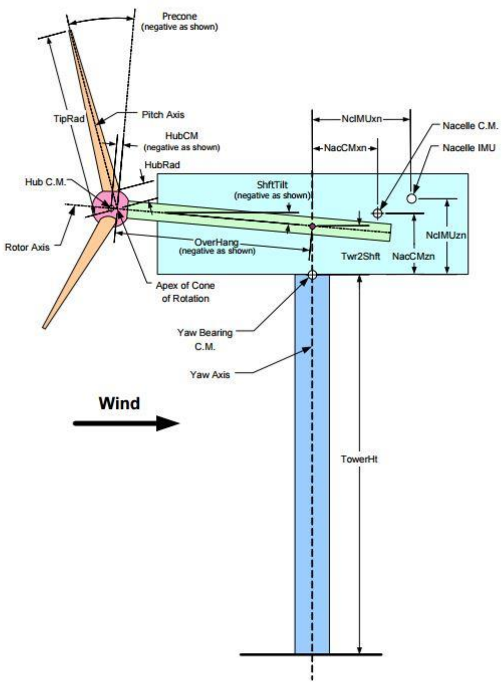

Fig. 5 FAST model with degrees of freedom illustrated

4.1 Design Loads

The 5-MW onshore turbine is subjected to its design load corresponding to a mean wind speed of 12 m/s with turbulence intensity of 10%. A 500-second simulation time is considered with 0.002-second time steps. The fore-aft response of the turbine tower is investigated. Fig. 6 shows the displacement and acceleration time histories in the fore-aft direction when the turbine is subjected to its design load. The maximum displacement is 1.086 m and the maximum acceleration is 1.974 m/s^2. Fig. 7 shows the fore-aft base shear force and bending moment time histories when the turbine is subjected to its design load. The maximum shear force is 1970 kN and the maximum bending moment is 179200 kNm.

4.2 Tower response to combined turbulent aerodynamic and seismic loading-spectrum compatible earthquake loading

The effects of combined turbulent aerodynamic and seismic loading of the 5-MW reference wind turbine are now examined. The turbine is subjected to its design aerodynamic load and seismic loading is introduced during the simulation in addition to this. In the first instance the spectrum compatible earthquake loading developed in Section 2.1 has been used. Earthquake shaking initiating at 250 seconds allows initial transient behaviour to diminish. Fig. 8 compares the design fore-aft displacement time history with the time history when seismic loading is also considered. The maximum fore-aft displacement of the tower top is 1.316 m when a spectrum compatible earthquake is also acting. This is an increase of 21% due to the earthquake loading. Fig. 9 zooms in on the dynamic response when the earthquake is applied (i.e., 205-300 seconds).

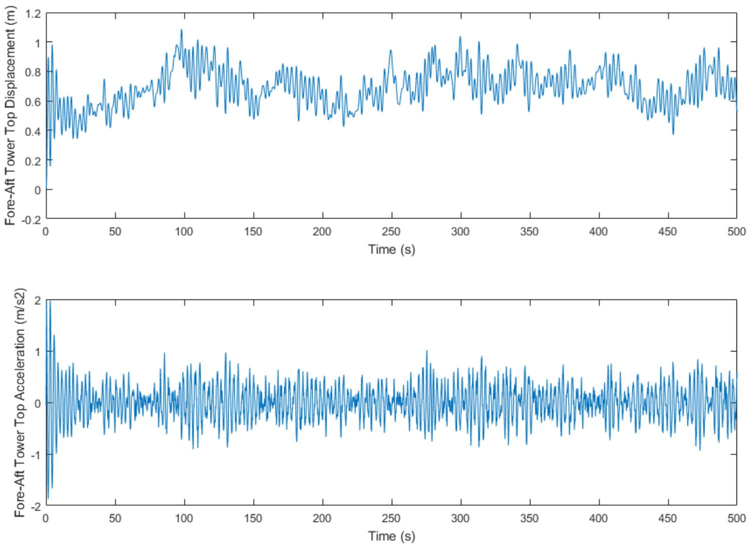

Fig. 6 Fore-aft displacement and acceleration due to design load

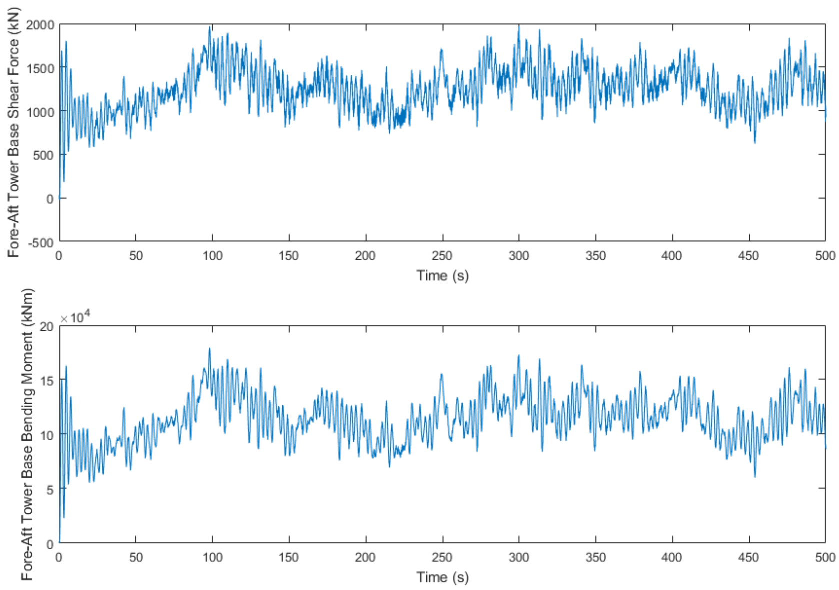

Fig. 7 Fore-aft shear force and bending moment due to design load

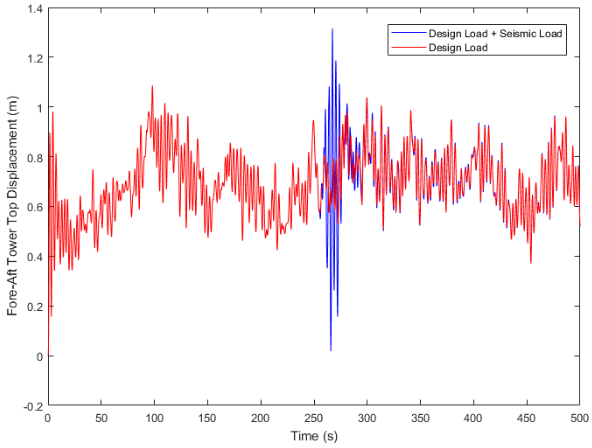

Fig. 8 Fore-aft tower top displacement comparison (spectrum compatible earthquake)

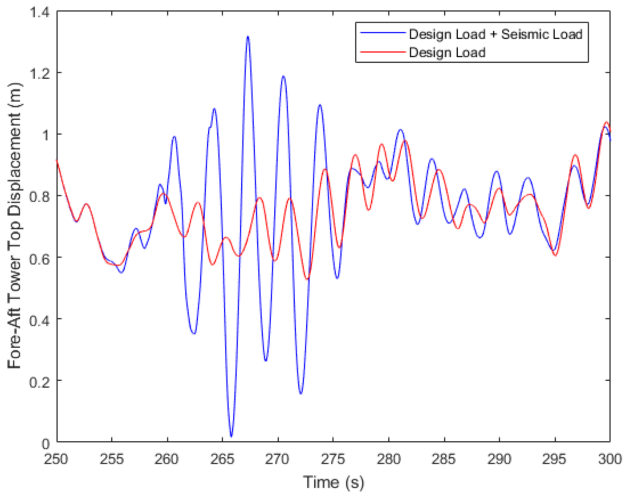

Fig. 9 Fore-aft tower top displacement comparison (spectrum compatible earthquake) – zoomed in

Fig. 9 compares the design fore-aft acceleration with the acceleration obtained when seismic loading is also considered. The maximum fore-aft acceleration of the tower top is 2.797 m/s^2 when a spectrum compatible earthquake is also acting. This is an increase in acceleration of 42%. Fig. 10 zooms in on the acceleration response when the earthquake is applied (i.e., 205-300 seconds).

The base shear force and base bending moment is now examined. These are key parameters in the design of wind turbines. Fig. 11 compares the design fore-aft base shear force with the force obtained when seismic loading is also considered. Fig. 12 zooms in on the response. The maximum base shear is 3229 kN (increase of 64%).

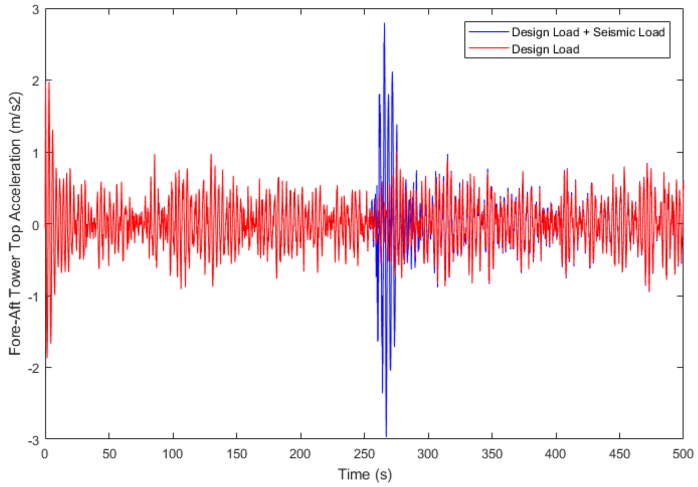

Fig. 10 Fore-aft tower top acceleration comparison (spectrum compatible earthquake)

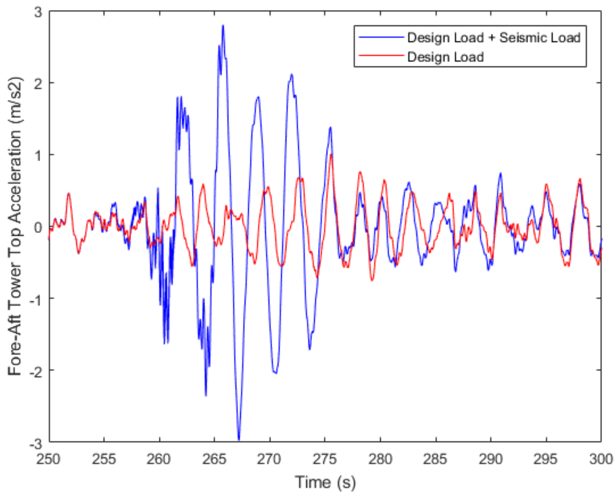

Fig. 11 Fore-aft tower top acceleration comparison (spectrum compatible earthquake) – zoomed in

Fig. 13 compares the design fore-aft base bending moment with the moment obtained when seismic loading is also considered. The maximum base moment is 219100 kNm when a spectrum compatible earthquake is also acting. This is an increase of 22% due to the earthquake loading. Fig. 14 zooms in on the response

It is clear that when the turbine is loaded with a spectrum compatible earthquake it is subjected to much higher loads than the design loads.

4.3 Tower response to combined turbulent aerodynamic and seismic loading-real earthquake loading

Real earthquake loading is now considered in addition to the design aerodynamic loading. The El Centro earthquake outlined in Section 2.2 will be used for this purpose. Earthquake shaking is again initiated at 250 seconds allowing transient behaviour to diminish.

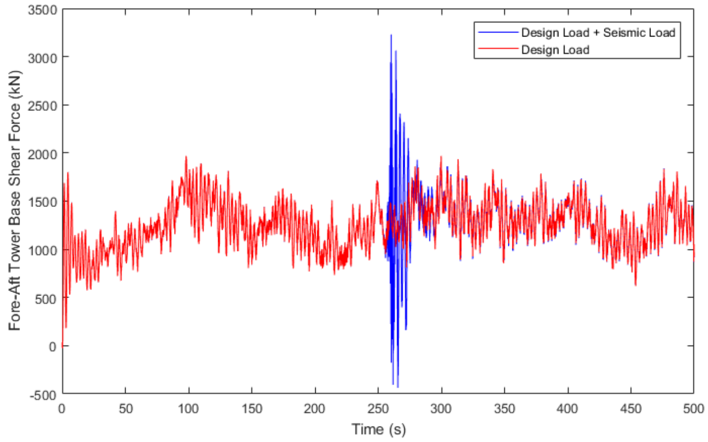

Fig. 12 Fore-aft base shear comparison (spectrum compatible earthquake)

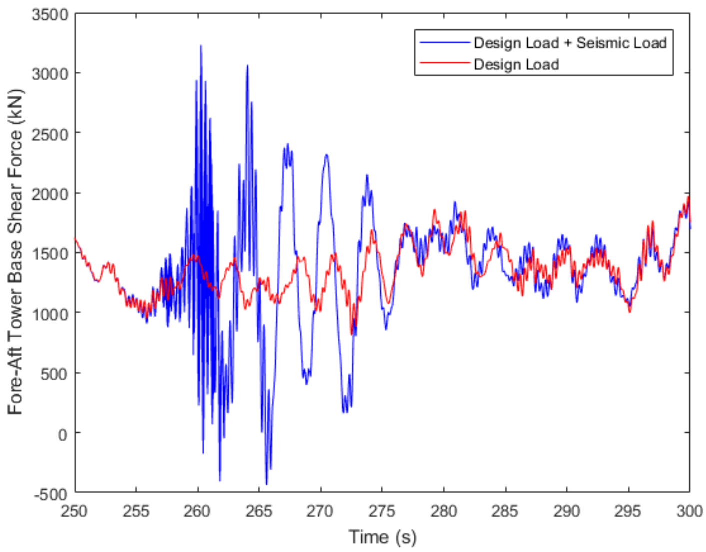

Fig. 13 Fore-aft base shear comparison (spectrum compatible earthquake) – zoomed in

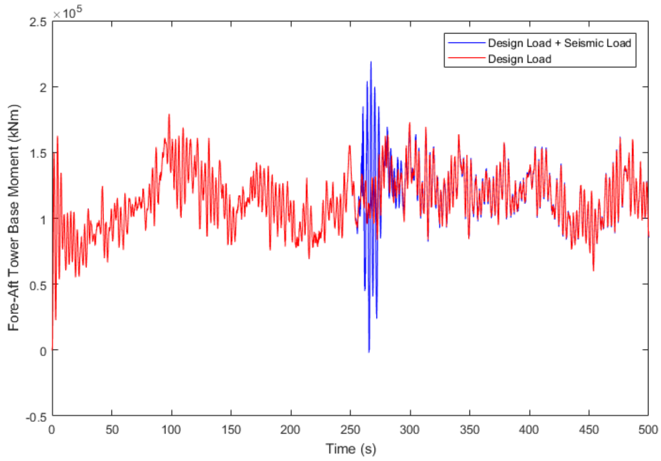

Fig. 14 Fore-aft base moment comparison (spectrum compatible earthquake)

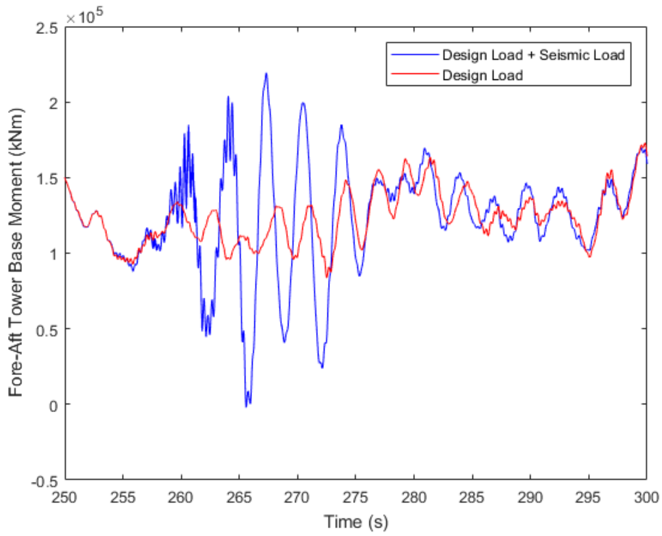

Fig. 15 Fore-aft base moment comparison (spectrum compatible earthquake) – zoomed in

Fig. 15 compares the design fore-aft displacement time history with the time history when the El Centro earthquake is also considered. The maximum fore-aft displacement of the tower top did not increase when the earthquake was also acting. However, there are increases in the peak-to-peak vibration response of the tower of over 105% when the earthquake loading is applied. Fig. 16 shows the displacement response zoomed in over the time when the earthquake was applied.

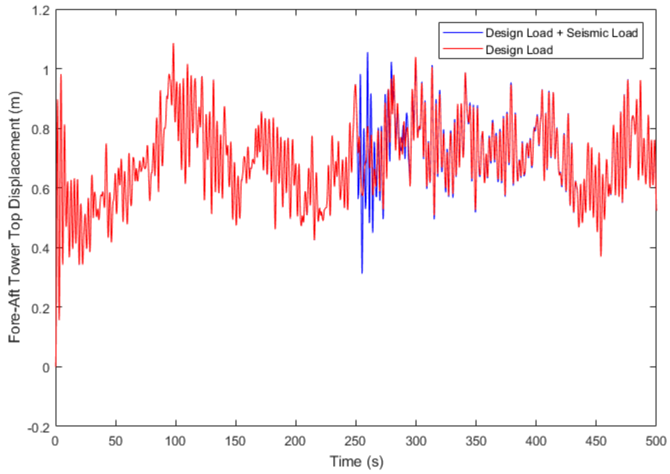

Fig. 16 Fore-aft tower top displacement comparison (El Centro)

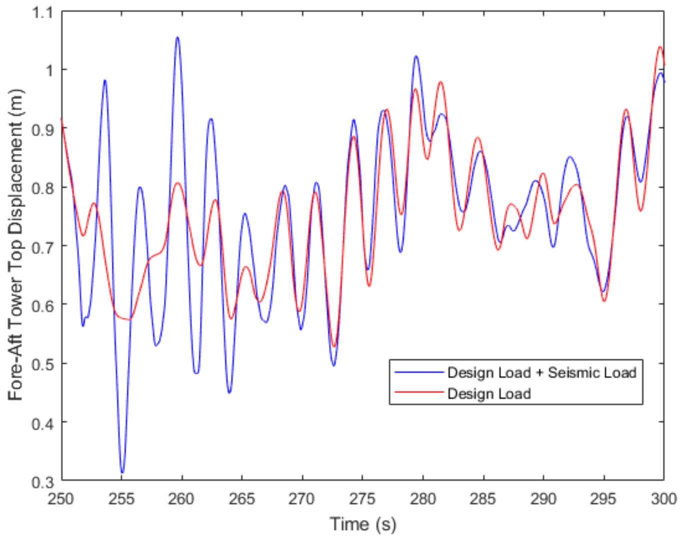

Fig. 17 Fore-aft tower top displacement comparison (El Centro) – zoomed in

Fig. 17 compares the design fore-aft acceleration with the acceleration when the El Centro earthquake is also considered. There are increases in the peak-to-peak vibration response of the tower of over 175% when the earthquake loading is applied. Fig. 18 shows the acceleration response zoomed in over the time when the earthquake was applied.

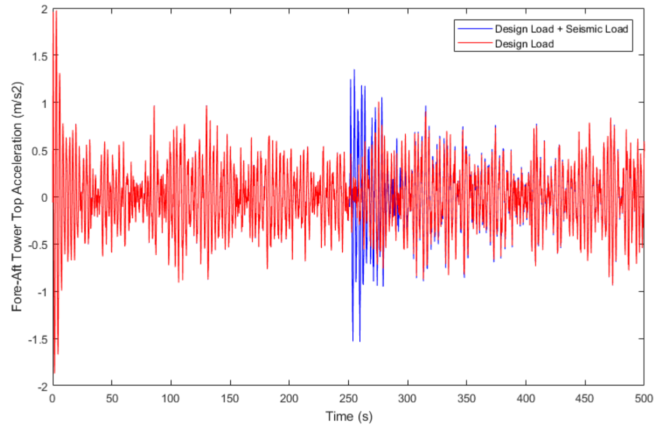

Fig. 18 Fore-aft tower top acceleration comparison (El Centro)

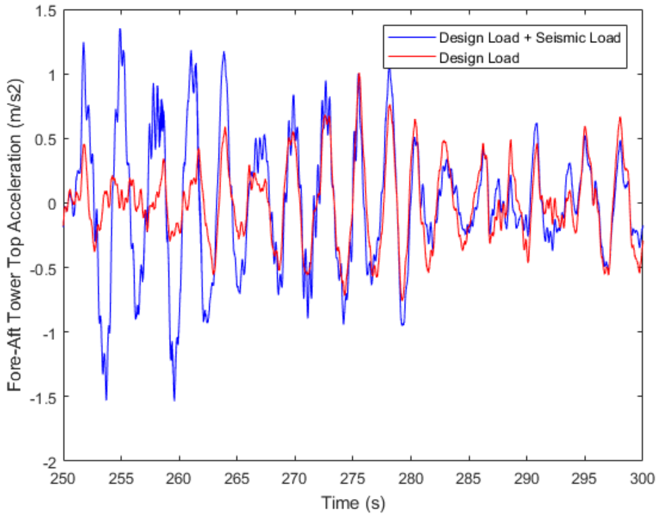

Fig. 19 Fore-aft tower top acceleration comparison (El Centro) – zoomed in

Fig. 19 compares the design fore-aft base shear force with the force obtained when seismic loading is also considered. The maximum base shear is 2163 kN when the El Centro earthquake is also acting. This is an increase of 10% due to the earthquake loading. The peak-to-peak vibration response is also greatly increased. Fig. 20 shows the base shear force time history zoomed in over the time when the earthquake was applied.

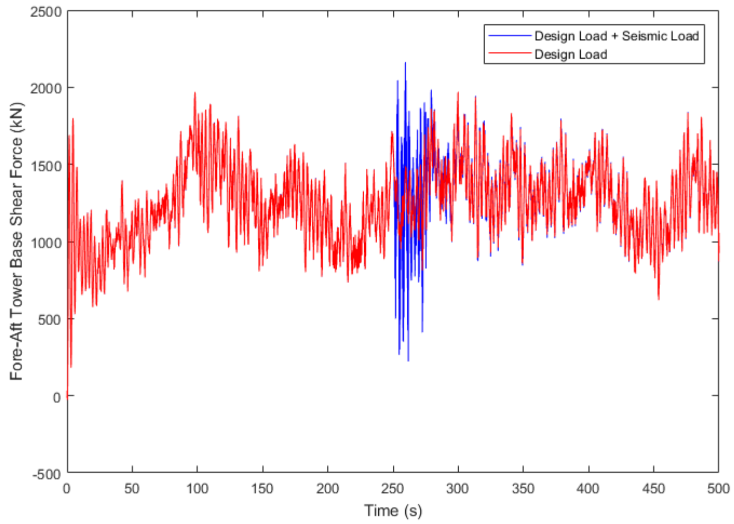

Fig. 20 Fore-aft base shear comparison (El Centro)

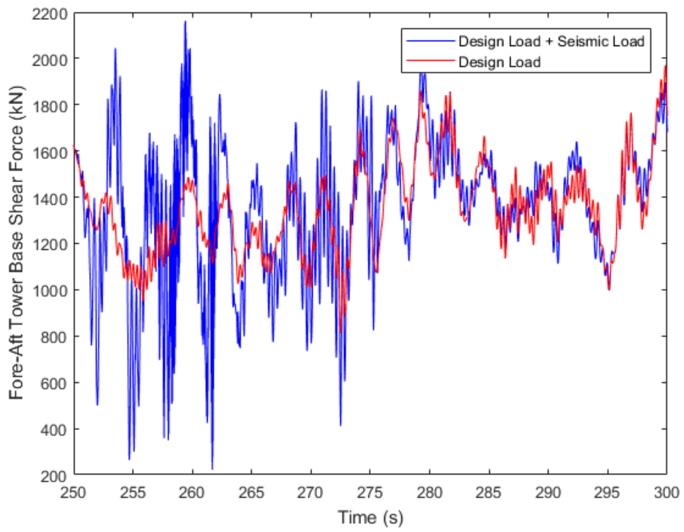

Fig. 21 Fore-aft base shear comparison (El Centro) – zoomed in

Fig. 21 compares the design fore-aft base bending moment with the moment obtained when seismic loading is also considered. There are increases in the peak-to-peak vibration response of the tower of over 150% when the earthquake loading is applied. Fig. 22 shows the base bending moment time history zoomed in over the time when the earthquake was applied.

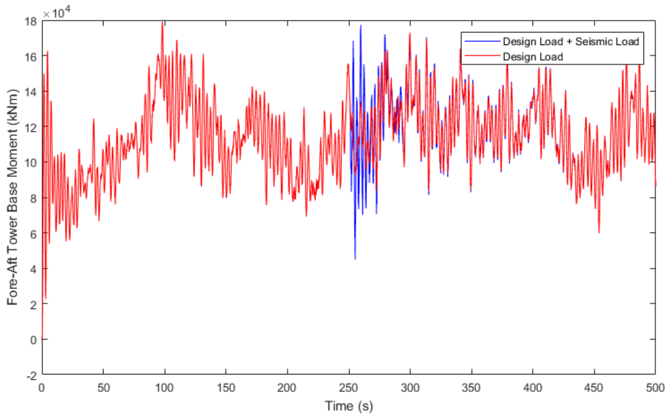

Fig. 22 Fore-aft base moment comparison (El Centro)

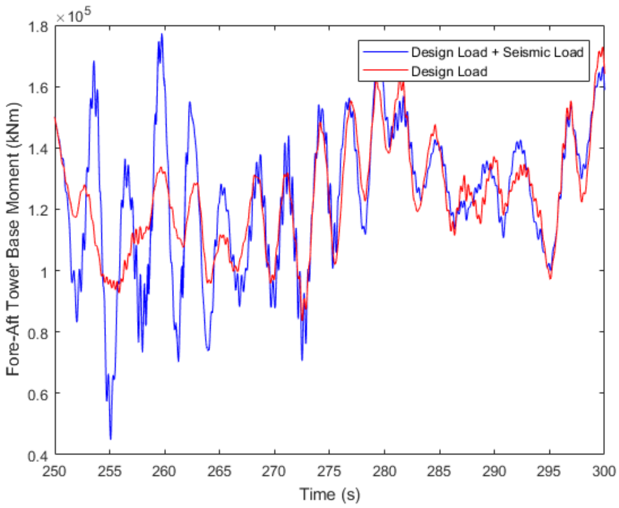

Fig. 22 Fore-aft base moment comparison (El Centro) – zoomed in

5. Monitoring

Monitoring and seismic vulnerability assessment of strategic structures is an important part of seismic emergency management. HAWTs are massive flexible structures and as such they are particularly sensitive to dynamic loads. The effect of combined seismic and turbulent aerodynamic loading is an increase in the turbine's tower displacements and base moments. This has been shown in the numerical simulations carried out. It has been demonstrated that the tower is subjected to higher stresses than the design stresses when seismic loading is present. This warrants further investigation in a subsequent study. As a preliminary finding we propose a multilevel monitoring scheme for HAWTs subjected to seismic loads.

At present, wind turbine monitoring is accomplished mainly through the Supervisory Control and Data Acquisition (SCADA) system. This has already been installed in wind farms in order to provide low-resolution monitoring and supervise wind turbine operation. The SCADA system monitors signals and alarms, usually at 10-min intervals to reduce the transmitted data bandwidth from the wind farm, and will usually includes the following parameters: active power, generator currents/voltages, wind speed, shaft speed, etc (Zaher *et al*. 2009). SCADA data are usually 10-min average data and the SCADA system was not initially designed for structural health monitoring purposes (Ng and Ran 2016). The low sampling rate is too low for implementing accurate fault diagnosis for wind turbine blades or towers. Although SCADA systems are already installed in wind farms we propose a purpose-designed wind turbine monitoring system. Various certification bodies have recommended purpose-designed structural monitoring schemes for wind turbines, e.g., Germanischer LIoyd (2007), and in recent years experienced condition monitoring practitioners develop such schemes, such as SKF, GE Bently Nevada and Gram and Juhl have developed commercial structural monitoring schemes for wind turbines (Ng and Ran 2016). Many of these commercially available schemes are vibration-analysis-based systems. For example, BLADEcontrol, designed by IGUS ITS GmbH (Germany), monitors wind turbine blade vibration by comparing spectra with historic spectra obtained from normal blades. Accelerometers bonded directly to the blades provide the vibration signal.

We propose a multilevel monitoring scheme that is based on the recording of ambient vibration data. There has been much work in recent years on structural monitoring using ambient vibrations. Mori and Spina (2015) developed a new method for seismic vulnerability assessment of buildings based on the experimental measurement of ambient vibrations. This method focused on the evaluation of the limit structural operational condition. The method can be used to decide whether seismic retrofitting is necessary. Cimellaro and De Stefano (2014) also used ambient vibrations to determine the dynamic characteristics (i.e., the natural frequencies, the mode shapes, and the damping ratios) of Mirandola Town Hall, a historical monumental palace which was damaged during 2012 Emilia earthquake. The measurement of ambient vibrations is readily achieved by installing low cost devices such as accelerometers on to the structures in question.

Wind turbines are very different from traditional civil engineering structures. They are the largest rotating machines on Earth, often operate in remote locations, rotate at low and variable speed and work under constantly varying loads. As a consequence, their vibration signals are dependent not only on their inherent structural properties, but also on the operating conditions (e.g., rotational speed, loading). Changes in the vibration characteristics of wind turbine components are therefore not necessarily indicative of a fault occurrence or structural damage. However, this work has shown that wind turbines subjected to seismic loading undergo significantly greater vibrations than can be expected in regular turbine operation.

Table 4 Earthquake ground motions

% Overstress	Condition	Corrective measures
<10%	Marginal	Scheduled maintenance
10-30%	Overstressed	Unscheduled maintenance
>30%	Extreme	Automatic shutdown and emergency maintenance

Therefore, in the case of seismic structural health monitoring of wind turbines it is adequate to use structural vibration as an indicator of a seismic event, provided sensible vibration thresholds are assumed. Though conventional structures under seismic loading are allowed to exceed linear design levels relying on ductility to dissipate the seismic loading energy by minor to moderate amounts of damage (Basu and Gupta 1995), wind turbines due to serviceability requirements are rarely allowed to be in the nonlinear regime. Hence, monitoring systems to detect early damage indicators (or levels of damage indicators) are necessary to be defined.

The first level of monitoring is for marginally overstressed HAWTs. This occurs if the effect of the earthquake is to increase the tower stresses by <10%. If this occurs the HAWT should be able to function as normal and should be inspected during its next scheduled maintenance. The next level of monitoring is for HAWTs that we class as overstressed. In this case the earthquake loading has increased the stresses in the tower by 10-30%. In this situation we propose that unscheduled maintenance should take place. The turbine may remain in operation until this has taken place. The third level of monitoring that we propose if for extremely overstressed HAWT towers. This occurs when the seismic load has increased tower stresses by over 30%. In this case there should be immediate shutdown of the wind turbine and emergency maintenance should be carried out as soon as possible. The turbine cannot be return to operation until this maintenance has taken place.

The multilevel monitoring scheme that we propose is summarised in Table 4.

The proposed monitoring scheme is based on real-time measurements of tower tip displacement and base moment. These can be readily calculated from acceleration measurements.

6. Conclusions

In this study the combined effects of turbulent aerodynamic loading and seismic loading on HAWT towers have been investigated. Real earthquakes and synthetically generated earthquakes (compatible with the Eurocode 8 design spectrum) were applied to the NREL 5 MW reference wind turbine in addition to turbulent aerodynamic loads. Simulations were carried out using a modified version of the FAST aeroelastic code. It was demonstrated for both real and synthetic (spectrum compatible) earthquakes that the seismic loading causes the turbine tower to undergo much greater vibrations than can be anticipated in design. Due to the increased expansion of wind turbines into seismically active regions in recent years a monitoring procedure for onshore HAWTs subjected to combined turbulent aerodynamic and seismic loading has been proposed in this paper.

Acknowledgments

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References

Abrahamson, N.A. (1992), “Non-stationary spectral matching”, *Seismol. Res. Lett.*, **63**(1), 30.

Arrigan, J., Pakrashi, V., Basu, B. And Nagarajaiah, S. (2011), Control of flapwise vibrations in wind turbine blades using semi-active tuned mass dampers”, *Struct. Control Health Monit.*, **18**(8), 840-851.

Arrigan, J., Huang, C., Staino, A., Basu, B. and Nagarajaiah, S. (2014), "A frequency tracking semi-active algorithm for control of edgewise vibrations in wind turbine blades", *Smart Struct. Syst*., 13(2), 177-201.
Asareh, M.A. and Prowell, I. (2011), "Seismic loading for FAST. Contract, 303(275), e3000", National Renewable Energy Laboratory, Golden, CO, USA.
Basu, B. and Gupta, V.K. (1995), "A probabilistic assessment of seismic damage in ductile structures", *Earthq. Eng. Struct. D*., **24**(10), 1333-1342.
Basu, B., Nagarajaiah, S. and Chakraborty, A. (2008), "Online identification of linear time-varying stiffness of structural systems by wavelet analysis", *Struct. Health Monit*., **7**(1), 21-36.
Basu, B., Staino, A. and Basu, M. (2014), "Role of flexible alternating current transmission systems devices in mitigating grid fault-induced vibration of wind turbines", *Wind Energy*, **17**(7), 1017-1033.
Basu, B., Zhang, Z. and Nielsen, S.R. (2016), „Damping of edgewise vibration in wind turbine blades by means of circular liquid dampers", *Wind Energy*, **19**(2), 213-226.
Cimellaro, G.P. and De Stefano, A. (2014), "Ambient vibration tests of XV century Renaissance Palace after 2012 Emilia earthquake in Northern Italy", *Struct. Monit. Maint*., **1**(2), 231-247.
Colwell, S. and Basu, B. (2009), "Tuned liquid column dampers in offshore wind turbines for structural control", *Eng. Struct*., **31**(2), 358-368.
Dai, K., Huang, Y., Gong, C., Huang, Z. and Ren, X. (2015), "Rapid seismic analysis methodology for in-service wind turbine towers", *Earthq. Eng. Eng. Vib*., **14**(3), 539-548.
Dinh, V.N. and Basu, B. (2015), "Passive control of floating offshore wind turbine nacelle and spar vibrations by multiple tuned mass dampers", *Struct. Control Health Monit*., **22**(1), 152-176.
Dinh, V.N., Basu, B. and Nagarajaiah, S. (2016), "Semi-active control of vibrations of spar type floating offshore wind turbines", *Smart Struct. Syst*., **18**(4), 683-705.
Dueñas-Osorio, L. and Basu, B. (2008), "Unavailability of wind turbines due to wind-induced accelerations", *Eng. Struct*., **30**(4), 885-893.
European Standard EN 1998-1:2004 (2004), "Design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings", Comité Européen de Normalisation, Brussels, Belgium.
Fitzgerald, B., Arrigan, J. and Basu, B. (2010), "Damage detection in wind turbine blades using time-frequency analysis of vibration signals", In Neural Networks (IJCNN), *Proceedings of the 2010 International Joint Conference on* (pp. 1-5). IEEE.
Fitzgerald, B. and Basu, B. (2014), "Cable connected active tuned mass dampers for control of in-plane vibrations of wind turbine blades", *J. Sound Vib*., **333**(23), 5980-6004.
Fitzgerald, B. and Basu, B. (2016), "Structural control of wind turbines with soil structure interaction included", *Eng. Struct*., **111**(2016), 131-151.
Fitzgerald, B., Basu, B. and Nielsen, S.R.K. (2013), "Active tuned mass dampers for control of in-plane vibrations of wind turbine blades", *Struct. Control Health Monit*., **20**(12), 1377-1396.
Ganjavi, B. and Hao, H. (2013), "Optimum lateral load pattern for seismic design of elastic shear-buildings incorporating soil-structure interaction effects", *Earthq. Eng. Struct. D*., **42**(6), 913-933.
Germanischer LIoyd (2007), Rules and Guidelines, IV Industry Services, 4 Guideline for the Certification of Condition Monitoring Systems for Wind Turbines.
Hajirasouliha, I., Asadi, P. and Pilakoutas, K. (2012), "An efficient performance-based seismic design method for reinforced concrete frames", *Earthq. Eng. Struct. D*., **41**(4), 663-679.
Hancock, J., Watson-Lamprey, J., Abrahamson, N.A., Bommer, J.J., Markatis, A., McCOY, E.M.M.A. and Mendis, R. (2006), "An improved method of matching response spectra of recorded earthquake ground motion using wavelets", *J. Earthq. Eng*., **10**(1), 67-89..
Hu, W.H., Thns, S., Rohrmann, R.G., Said, S. and Rcker, W. (2015), "Vibration-based structural health monitoring of a wind turbine system Part II: Environmental/operational effects on dynamic properties", *Eng. Struct*., **89**, 273-290.
Jonkman, B.J., Butterfield, S., Musial, W. and Scott, G. (2009), "Definition of a 5-MW reference wind turbine for offshore system development. Report No. NREL/TP- 50038060", National Renewable Energy Laboratory, Golden, CO, USA.
Jonkman, J.M. and Buhl, M.L. Jr. (2005), "FAST users guide. Report No. NREL/EL-500-38230", National

Renewable Energy Laboratory, Golden, CO, USA.
Jonkman, J.M. (2009), “TurbSim user’s guide: version 1.50. Report No. NREL/TP-500-46198”, National Renewable Energy Laboratory, Golden, CO, USA.
Katsanos, E.I., Thöns, S. And Georgakis, C.T. (2016), „Wind turbines and seismic hazard: a state-of-the-art review”, *Wind Energy*, **19**(11), 2113-2133.
Kim, D.H., Lee, S.G. and Lee, I.K. (2014), “Seismic fragility analysis of 5 MW offshore wind turbine”, *Renew. Energ*., **65**, 250-256, 2014.
Lackner, M.A. and Rotea, M.A. (2011), “Passive structural control of offshore wind turbines”, *Wind Energy*, **14**(3), 373-388.
Murtagh, P.J., Ghosh, A., Basu, B. and Broderick, B.M. (2008), “Passive control of wind turbine vibrations including blade/tower interaction and rotationally sampled turbulence”, *Wind Energy*, **11**(4), 305-317.
Murtagh, P.J. and Basu, B. (2007), « Identification of equivalent modal damping for a wind turbine at standstill using Fourier and wavelet analysis”, P*roceedings of the Institution of Mechanical Engineers*, Part K: Journal of Multi-body Dynamics, **221**(4), 577-589.
Mori, F. and Spina, D. (2015), “Vulnerability assessment of strategic buildings based on ambient vibrations measurements”, *Struct. Monit. Maint*., **2**(2), 115-132, 2015.
Nagarajaiah, S. and Basu, B. (2009), “Output only modal identification and structural damage detection using time frequency & wavelet techniques”, *Earthq. Eng. Eng. Vib*., **8**(4), 583-605.
Ng, C. and Ran, L. (Eds.). (2016), Offshore wind farms: technologies, design and operation. Woodhead Publishing.
SeismoMatch (2016), “A computer program for adjusting earthquake records to match a specific target response spectrum.”, *Available: http://http://www.seismosoft.com/seismomatch*
Shahi, R., Nam, N., Gad, E., Wilson, J. and Watson, K. (2016), “Seismic performance behaviour of cold-formed steel wall panels by quasi-static tests and incremental dynamic analyses”, *J. Earthq. Eng*., 1-28.
Staino, A., Basu, B. and Nielsen, S.R.K. (2012), “Actuator control of edgewise vibrations in wind turbine blades”, *J. Sound Vib*., **331**(6), 1233-1256.
Staino, A. and Basu, B. (2013), “Dynamics and control of vibrations in wind turbines with variable rotor speed”, *Eng. Struct*., **56**, 58-67.
Staino, A. and Basu, B. (2015), “Emerging trends in vibration control of wind turbines: a focus on a dual control strategy”, *Philos. T. R. Soc. A*, **373**(2035), 20140069.
Stewart, G.M. and Lackner, M.A. (2011), “The effect of actuator dynamics on active structural control of offshore wind turbines”, *Eng. Struct*., **33**(5), 1807-1816.
Tesfamariam, S., Stiemer, S.F., Dickof, C. and Bezabeh, M.A. (2014), “Seismic vulnerability assessment of hybrid steel-timber structure: Steel moment-resisting frames with CLT infill”, *J. Earthqu. Eng*., **18**(6), 929-944.
Zaher, A., McArthur, S.D.J., Infield, D.G. and Patel, Y. (2009), “Online wind turbine fault detection through automated SCADA data analysis”, *Wind Energy*, **12** (6), 574-593.
Zhang, Z., Li, J., Nielsen, S.R. and Basu, B. (2014), „Mitigation of edgewise vibrations in wind turbine blades by means of roller dampers”, *J. Sound Vib*., **333**(21), 5283-5298.
Zhang, Z., Basu, B. and Nielsen, S.R. (2015), „Tuned liquid column dampers for mitigation of edgewise vibrations in rotating wind turbine blades”, *Struct. Control Health Monit*., **22**(3), 500-517.
Zhang, Z., Staino, A., Basu, B. and Nielsen, S.R. (2016), “Performance evaluation of full-scale tuned liquid dampers (TLDs) for vibration control of large wind turbines using real-time hybrid testing”, *Eng. Struct*., **126**, 417-431.

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