Accepted manuscript doi:
10.1680/jstbu.17.00168

Accepted manuscript
As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer
The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an ‘uncorrected proof’ PDF will replace the ‘accepted manuscript’ PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record
The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue’s Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Downloaded by [University of Manchester Library] on [10/03/18]. Copyright © ICE Publishing, all rights reserved.

Accepted manuscript doi:
10.1680/jstbu.17.00168

Submitted: 30 October 2017

Published online in 'accepted manuscript' format: 23 February 2018

Manuscript title: Numerical study of vibrations induced by horizontal-axis wind turbine on a steel building

Authors: Nina Gluhović[1], Milan Spremić[1], Marko Pavlović[2] and Zlatko Marković[1]

Affiliations: [1]Department of Materials and Structures, University of Belgrade Faculty of Civil Engineering, Belgrade, Serbia; [2]Delft University of Technology, Faculty of Civil Engineering and Geosciences, Delft, The Netherlands

Corresponding author: Nina Gluhović, Department of Materials and Structures, University of Belgrade Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia. Tel.: +381 11/3218-626.

E-mail: nina@imk.grf.bg.ac.rs

Abstract

One of the most important acceptance issues regarding implementation of small-scale wind turbines in urban environments is related to human comfort. Turbine-induced vibrations can have a big influence on small-scale turbine implementation for urban wind harvesting. A typical five-storey steel-framed office building with a roof-mounted, horizontal-axis wind turbine was numerically analysed. The aim of the work was to investigate the increase in vibration after the installation of the turbine. Comparison was made between floor vibrations caused by wind action on the building only and by wind action on the building and turbine combined. The results were then compared with requirements given in EN, ISO and BS design codes. The main outcome of the analysis is that the installation of the turbine did not compromise the building's serviceability.

Keywords: Buildings, structures & design; Composite structures; Wind loading & aerodynamics

1. Introduction

Demands for higher energy efficiency and use of renewable energy resources are constantly increasing. Harvesting of wind energy as a renewable energy resource by use of small-scale wind turbines in urban built environments becomes an attractive solution in addition to large on-shore and off-shore wind farms. Installation of small-scale wind turbines in urban regions can gain higher energy efficiency, considering that energy production takes place at the place of its consumption.

According to Wineur (2005) small wind turbines are defined as turbines that are specially designed for built environment, and can be located on buildings or on the ground next to buildings. While, wind turbines located in urban environments on the ground next to buildings has the capacity less than 100 kilowatts (kW) (Wineur, 2005), small-scale wind turbines mounted on buildings has capacity generally between 1 kW and 20 kW (Smith *et al.*, 2012).

Besides the high sensitivity of wind turbine efficiency due to variations in wind conditions, such as average wind speed, three-dimensional wind speed profile and turbulent wind flow (Smith *et al.*, 2012), implementation of wind turbines in urban environments has often been compromised by public resistance. Some of the most important issues regarding implementation of wind turbines in urban environments are related to the noise pollution and increased vibrations in buildings. Due to the lack of open free areas in urban regions, installation of wind turbines at buildings is the most possible solution. In case of installation of small-scale wind turbines on existing facilities the increase of structure vibrations can compromise their installation. Human perception of floor vibrations and uncompromised serviceability of equipment in buildings are the two most important acceptability criteria considering increased floor vibrations. Human response to floor motion is very complex phenomenon and it is often related to the combination of factors such as: magnitude of motion, the surrounding environment and the type of human activity which takes place at that moment. Increased vibrations in building structure due to mounting of small-scale wind turbine can be overcome with implementation of different types of dampers in supporting structures. Polyurethane foam insulation with open cells characterized by high elasticity, obtained by applying specific types of catalysts and polyols, has specific dynamic properties and are successfully used as acoustic insulators when it is necessary to protect the structure from so-called structure-born or impact noise and vibration (Pavlović *et al.*,2011). The usage of different types of insulators will be determined by limit values of vibration frequencies which should not be transferred to the supporting structure from small-scale wind turbine.

Mounting of small-scale wind turbines on the existing buildings in urban environments is also limited with poor understanding of building interactions, which is closely related to the specific building and wind turbine construction. According to Smith *et al.* (2012) main barriers for implementation of small-scale wind turbines in urban environments can be classified in five key areas: safety, wind resource, turbine technology, building interactions and non-technical obstacles. Poor understanding of building interaction is mostly reflected through concerns regarding excitation of resonance frequencies, increased vibrations in buildings and codes compliance. Based on the authors' knowledge, none of the current building design codes refers to the loadings from building mounted small-scale wind turbines. Also, major investigations concerning implementation of small-scale wind turbines in urban environments are related to the investigation of wind resources (Wineur, 2005), turbine technology and energy production (Encraft Warwick Wind Trials Project, 2009) and noise pollution.

Analysis of relative increase of floor vibrations in a steel building after installation of a small-scale wind turbine on the building's roof is presented in this paper. A five-storey steel building with steel-concrete composite floor deck structure is analysed with and without 5 m rotor diameter horizontal-axis wind turbine (HAWT) considering turbulent wind profile with average wind speed of 9, 12 and 15 m/s. The highest analysed average wind speed of 15 m/s is adopted approximately equal to the stop wind speed form small-scale wind turbines, according to Wineur (2005). Increase of floor vibrations is compared with current design requirements for floor vibrations, given in EN1990 (2010), EN1991-1-4 (2010), ISO 10137 (2007) and BS 6472-1 (2008).

2. Numerical models

Vibrations of the building are analysed by means of two independent numerical models. The first, aero-elastic, model of small-scale HAWT is analysed using multi-body analysis software package Ashes (Simis, 2013). It is used to obtain time-history load on building arising from operation of the turbine. The second model of steel building is analysed in Sofistik FE software (see https://www.sofistik.com) where time-histories of forces and bending moments from the first aero-elastic model are applied at two different positions at the building roof. Results of the building numerical analysis without small-scale wind turbine are compared with results obtained from building analysis with time-histories of forces and bending moments applied at the building roof. Also, enlargement of composite steel-concrete floor accelerations due to mounting of small-scale wind turbine are compared with accelerations caused by pedestrian walking without wind action on the building.

2.1 Modelling of small-scale horizontal axis wind turbine

Model of a 5 m diameter HAWT with 5 m hub height is developed using a multi-body analysis software package Ashes. Ashes software integrates finite element analysis (FEA) and blade element momentum (BEM) theory, providing the set of built-in templates of onshore and offshore wind turbines which can be further customized. The model of small-scale wind turbine which is used for numerical analysis presented in this paper is not incorporated in this software. Model of a small-scale HAWT is developed by scaling a standard NREL5MW onshore wind turbine with 126 m rotor diameter which model is incorporated in Ashes software package. Scaling of a NREL 5MW wind turbine is performed by local scaling of dimensions of different parts of wind turbine using 5/126=0.04 scaling factor. Rated power of small-scale wind turbine developed in Ashes is 2.4 kW and rated wind speed 9 m/s. Scaling of a NREL 5MW wind turbine with simple scaling of dimensions of all parts of wind turbine does not give always appropriate masses for different parts of scaled wind turbine. Scaled wind turbine should have similar mass distribution to those one achieved in the default turbine NREL 5MW, incorporated in Ashes software. Mass of the support tower and RNA structure (rotor-nacelle assembly) in comparison to the mass of whole wind turbine is approximately 50% each. Mass scaling models developed by NREL National Renewable Energy Laboratory (Fingersh*et al.*, 2006) show a good agreement with mass arrangement between different parts of NREL 5MW wind turbine modelled in Ashes.

Mass scaling of blades, using blade mass scaling relationship for LM Glasfiber blades shows difference less than 1% in comparison with NREL 5 MW wind turbine developed in Ashes, as shown in Figure 1.

Mass scaling models for small-scale wind turbines are not yet developed, as shown in Figure 1. Usage of scaling models presented in Figure 1 for small-scale wind turbines leads to the inaccurate results and irregular arrangement of masses which does not reflect real conditions for small-scale wind turbines. Therefore, scaling of NREL 5MW default wind turbine is performed through dimensions scaling with scale factor 0.04 and user defined masses for different parts of wind turbine. Mass of one blade is estimated based on the air foil geometry and blade length to approximately 80 kg and mass of the whole wind turbine is approximately 553 kg. Adopted rotor mass for small-scale wind turbine developed in Ashes software shows good agreement with rotor mass of wind turbines from different manufacturers with similar rated power according to Cace *et al.,* (2007).

Small scale 2.4 kW wind turbine modelled in Ashes software is direct drive wind turbine without pitch control system. Turbulent wind profile and aerodynamic loads analysis of the turbine is done in multi body analysis software package Ashes. Spatial distribution of a wind field is defined together with time dependent wind in certain number of grid points of a wind field. Turbulent wind time history loading is generated by TurboSim module integrated in Ashes software for 9, 12 and 15 m/s average wind speed. Turbulent wind time history loading generated for 9 m/s average wind speed is shown in Figure 2a.

The result of small-scale wind turbine in Ashes are loads arising from operation of the turbine in form of time-histories of forces and bending moments calculated using spatial wind profile as loading having the average wind speed of 9, 12 and 15 m/s. Time-histories of forces and bending moments calculated in time-history analysis in Ashes show significant increase during the first second of time history analysis, as shown in Figure 2b. Increase of forces (up to four times greater axial force) and moments at the beginning of time-history analysis are the consequence of the immediate start of analysis with rated wind speed and do not represent real conditions in urban built environments, as shown in Figure 2b. In real environmental conditions start-up wind speed for the wind turbine is lower than rated wind speed which gives rated power production. In order to exclude unrealistically high influence of wind turbine on the building structure, first two seconds of time-histories of turbine forces and bending moments is excluded from the analysis of floor vibrations (Figure 2b).

Time-histories of axial forces, shear forces and bending moments for strong and weak wind turbine axis for 9, 12 and 15 m/s average wind speed, applied on the building roof are shown in Figure 3. Upper and lower peak amplitudes of axial forces for three average wind speeds are shown in Figure 3. Average axial force for three wind speeds, 9, 12 and 15 m/s, is 5.64 kN, 5.70 kN and 5.74 kN, respectively, which shows close agreement to the total mass of the small-scale wind turbine.

2.2 Numerical model of steel building

The time-history response of the steel building to the dynamic load excitation by the wind action is analysed in Sofistik FE software, using DYNA module for dynamic analysis which is incorporated in this software (Sofistik AG, 2011). Typical steel building presented in this paper is chosen for numerical study. It is appeared that the results gained in this framework will be validated also in the case of other layouts of steel building structures. Dimensions of the building's base are 24x40 m and the total height of the building is 18 m, as shown in Figure 4a. Steel-concrete decks are composed by 330 mm high steel I beams, 8 m span, 4 m distance, connected by shear connectors to the 160 mm full-depth concrete slab. Horizontal stability of the building in longitudinal and transversal direction is achieved by moment resisting frames and vertical bracing, respectively, as shown in Figure 4a. Design of the case study building is performed according to requirements given in EN1994-1-1 (2009) and EN1993-1-1 (2009) in order to provide a real case design and mass vs. stiffness properties of the structure. Installation of wind turbine by clamping it's tower at the roof is analysed in the positions shown in Figure 4b: 1) in the mid-span of a floor beam; 2) immediately above an internal column.

Wind action on the building is analysed through external and internal pressure coefficients for building's walls and roof, adopted according to the recommendations given in EN1991-1-4 (2010). The wind action on the building in two orthogonal directions is applied as a time-history loads at floor levels, obtained using time-history wind speed obtained in Ashes, see Figure 2a and pressure coefficients.

Dynamic loads induced by human activities can be classified as continuous dynamic loading and is known as most usual internal source of floor vertical vibrations (Gluhović *et al.*, 2016). Numerical model of a walking pedestrian is developed in Sofistik FE software in order to compare the accelerations of building floor caused by mounting of small-scale wind turbine with accelerations induced by a walking pedestrian.

3. Current design recommendations for floor vibrations

Increase of floor vibrations is compared with current design requirements for floor vibrations, given in EN1990 (2010), EN1991-1-4 (2010), ISO 10137 (2007) and BS 6472-1 (2008). EN1990 (2010) gives basic requirements for structures exposed to the dynamic loading. According to EN 1990 Annex A2 (2010) pedestrian comfort criteria should be defined by National Annex, but recommended maximum values of acceleration are given for vertical (0.7 m/s^2) and horizontal (0.2 m/s^2) vibrations. According to EN 1990 A1.4.4 (2010), considering serviceability limit state of a structure or a structural member, it is recommended that the natural frequency of vibrations of the structure or structural member should be kept above appropriate values. The standard refers to EN 1991-1-4 (2010) and to ISO 10137 (2007).

EN 1991-1-4 (2010) provides two methods for calculation of peak accelerations of a structure induced by wind, but this standard does not define design limits for peak acceleration. ISO 10137 (2007) deals with serviceability of structures against vibrations. ISO 10137 Annex D (2007) provides guidance for human response to wind-induced motions in buildings with accelerations limits for residential areas and offices. Accelerations limits are provided in form of peak acceleration - first natural frequency diagrams, and for residential buildings and hotels maximum peak acceleration is 0.04 m/s^2. According to ISO 10137 Annex D (2007), frequencies between 1 and 2 Hz are least favourable. While ISO 10137 (2007) gives diagrams with peak acceleration and represent hand-on calculation for horizontal *x* and *y* vibrations, BS 6472-1 (2008) gives acceleration limits in function of RMS (root mean square) accelerations. This standard covers many vibration environments in buildings and limits of satisfactory vibrations are given in relation to a frequency weighted base curve and multiplying factors. In this paper, horizontal peak floor accelerations induced by wind turbine mounted on the building roof is compared with recommendations given in ISO 10137 (2007) and vertical RMS accelerations with recommendations given in BS 6472-1 (2008), considering lack of design recommendations for serviceability limit state of existing buildings due to mounting of small-scale wind turbines.

4. Results of numerical analysis

Considered positions of small-scale wind turbine on the building roof are shown in Figure 4b. Both positions of wind turbine on the building roof are analysed for wind in two orthogonal directions, *x* and *y* shown in Figure 4b, considering different orientation of wind turbine in order to achieve that turbine horizontal axis is always in the direction of wind action. Different positions of wind turbine are analysed in order to compare accelerations increase for mounting of wind turbine on different building elements. Possible increase of the vibrations is analysed only for one wind turbine at a time. Horizontal and vertical accelerations are obtained at the roof nodes 1 and 2 for wind turbine position 1 and nodes 3 and 4 for wind turbine position 2 (Figure 4b) at the building roof. Accelerations are obtained also for the same vertical position of nodes at the fourth floor, denoted as node 5 and 6 for position 1 and node 7 and 8 for position 2. Nodes for accelerations obtaining are selected in order to analyse the increase of floor vibrations at the position of wind turbine and spreading of floor vibrations in the surrounding zone, four meters from the wind turbine. Horizontal and vertical accelerations are obtained for three analysed average wind speeds.

For both considered positions of wind turbine on the building roof, up to 2 times higher horizontal peak accelerations are obtained for wind action in direction of global *x* axis, in comparison to the wind action in direction of global *y* axis. In all considered situations horizontal axis of wind turbine corresponds to the wind direction. Results presented in this paper correspond to the wind action in global *x* direction of building, see Figure 4. Roof horizontal and vertical vibrations for both positions of wind turbine in the middle of the time history analysis are shown in Figure 5. Figure 5a and 5b represent accelerations in *x* and *z* global direction for wind turbine position 1 and Figure 5c and 5d acceleration for wind turbine position 2, respectively. Significant influence of wind turbine on the node accelerations are obtained on the building roof for both wind turbine positions. Higher horizontal and vertical peak accelerations are obtained for higher average wind speed, as shown in Figure 6 and Figure 7.

As shown in Figure 6, higher vertical peak accelerations are obtained for wind turbine position 1 (node 1) in comparison to the wind turbine position 2 (node 3), which is caused by positioning of wind turbine at the intersection of roof beams in comparison to the mounting of small-scale wind turbine at the top of the column. In the surrounding zone of the wind turbine, four meters from the wind turbine, vertical peak accelerations are more than 50 % lower at the building roof, for both positions of wind turbine. Mounting of small-scale wind turbines on the building roof has negligible influence on peak accelerations at the fourth floor (nodes 5 and 6), for wind turbine position 1. Significant amount of vertical peak accelerations is transferred through column from the building roof to the fourth floor, which can be seen on Figure 6b. Vertical peak accelerations in node 7 (position 2) are even four times higher in comparison to the node 5 (position 1) for 15 m/s average wind speed.

Increase of fourth floor vertical accelerations for wind turbine position 2 are also negligible in the surrounding zone, as shown in Figure 6b.

Increase of horizontal roof and fourth floor accelerations are also obtained for higher average wind speeds, as shown in Figure 7. Horizontal peak accelerations have the same values for node 1 and 2 at the building roof, and nodes 5 and 6 on the fourth floor (wind turbine position 1), for three analysed average wind speeds (Figure 7a). Mounting of small-scale wind turbine on the top of the column incorporated in the internal vertical bracing (wind turbine position 2) causes higher horizontal peak accelerations at the position of mounting (node 3 in comparison to the node 1, Figure 7). Horizontal peak accelerations four meters from wind turbine mounted in this position have the same value as horizontal accelerations for position 1 (node 4 in comparison to the node 2, Figure 7).

Comparison of vertical and horizontal peak accelerations of analysed nodes on building roof and fourth floor after mounting of small-scale wind turbine with same accelerations without wind turbine and vertical accelerations induced by pedestrian walking is shown in Figure 8.

Comparison is made only for 9 m/s average wind speed, which can represent usual wind conditions in urban built environments. Vertical peak accelerations in node 1 and node 3 (Figure 8) are 0.01 and 0.02 m/s^2, respectively, without wind turbine mounted on the building roof, for 9 m/s average wind speed. For the same average wind speed, peak accelerations in nodes 1 and 3 after mounting of wind turbine is 0.120 and 0.080 m/s^2, as shown in Figure 8. Vertical node accelerations on the fourth floor are significantly lower. Vertical peak accelerations in nodes 5 and 7 (same vertical position as nodes 1 and 3 respectively, but on the fourth floor) is 0.02 and 0.04 m/s^2 (Figure 8). Vertical peak accelerations for nodes on the fourth floor influenced by mounting of small-scale wind turbine are in the range of vertical accelerations caused by pedestrian walking (Figure 8). Relatively similar horizontal and vertical accelerations arrangement on the fourth floor can be obtained for both wind turbine positions and also for the wind action on the building without small-scale wind turbine mounted on the building roof as shown in Figure 8. Therefore, influence of wind turbine mounting on the fourth floor vibrations is very small which is very favourable considering human comfort and people’s quality of life at the top floor of considered building.

For analysis of floor vibrations and human comfort accelerations of fourth floor are analysed, considering that fourth floor of the analysed building can be occupied with certain purpose, such as residencies, offices, hospitals, or schools. First natural frequency of the floor is calculated according to the simply calculation methods (Feldmann *et al.,* 2009). Mean value of the first natural frequency of the considered steel-concrete composite floor is 4.94 Hz.

Horizontal peak accelerations for nodes at top floor are compared to the design recommendations given in ISO 10137 (2007), as shown in Figure 9a. Considering high wind speeds (15 m/s) horizontal accelerations of nodes at top floor obtained from time history analysis can not satisfy demands for building with offices and residential buildings. For 12 m/s wind speed horizontal accelerations do not satisfy acceleration demands for residential buildings. Vertical RMS accelerations for nodes at fourth floor presented in Table 1 are compared to the design recommendations given in BS 6472-1 (2008), as shown in Figure 9b.

Figure 9b represents base curve which in comparison with multiplying factors given in BS 6472-1 (2008) presents design recommendations for different building functions. Multiplying factor for residential buildings is 2 and for building with offices 4. Therefore, minimal value for RMS accelerations is 0.01 m/s^{2}for residential buildings and 0.02 m/s^2 for offices. Vertical RMS accelerations at analysed nodes of fourth floor obtained from time history analysis satisfy these acceleration demands. RMS vertical accelerations of node 7 at fourth floor (Table 1) are accelerations of node at column and are significantly higher than other accelerations because of vibration transfer through column. Taking into account that these values are not accelerations of floor structure, they are compared with design recommendations presented in Figure 9.

5. Conclusions

Increase of vibrations in a typical five storey steel framed building by mounting a small-scale HAWT on the rooftop is analysed in this study by numerical analysis. Numerical model of a small-scale HAWT is developed in Ashes, similar to the commercially available direct drive small-scale wind turbines, with 5 m diameter and 2.4 kW rated power. Time dependent wind histories used in analysis are generated at wind speeds in range from 9 m/s to 15 m/s. Numerical analysis is performed combining time-history FEA of the building with results obtained for the turbine in Ashes software based on BEM (blade element momentum) theory. The following conclusions are obtained:

1. For both wind turbine positions current limitations of horizontal floor vibrations in design code ISO 10137 (2007), as the criterion of human comfort for offices and residential buildings, are fulfilled for 9 m/s and 12 m/s average wind speed and does not satisfy design recommendations for 15 m/s average wind speed.

2. Up to four times higher peak accelerations are obtained at certain “singularity” points of the roof top after small-scale HAWT installation.

3. In both cases, with and without the wind turbine, current limitations of vertical floor vibrations of fourth floor in design code BS 6472-1 (2008), as the criterion of human comfort, are fulfilled.

4. Mounting of small-scale HAWT on a rooftop of typical steel building in urban environments, results in increased vibrations only in near surrounding zone of the wind turbine position at the roof. Influence of a small-scale wind turbine on horizontal and vertical vibrations of the fourth floor is negligible.

Further analysis of the implementation of small-scale wind turbine on the building roof in urban environments should include more detailed assessment of different building layouts, wind conditions on a rooftop and further study of optimal position and layout of the turbine tubular tower. Also, the use of dumpers in the supporting structure of the turbine as possible solution for reduction of floor vibrations should be implemented in further analysis.

Acknowledgements

This investigation is supported by the Serbian Ministry of Education, Science and Technological Development through the TR-36048 project.

List of notation

HAWT	horizontal axis wind turbine
FEA	finite element analysis
BEM	blade element momentum theory
RNA	rotor-nacelle assembly
NREL	National Renewable Energy Laboratory
RMS	root mean square

References

BSI (2008) BS 6472-1. Guide to evaluation of human exposure to vibration in buildings. Part 1: Vibration sources other than blasting. BSI, London, UK.

Gluhović N, Spremić M, Marković Z et al. (2016) Vibrations of composite steel-concrete floors induced by human activities. Journal for research of materials and structures Building Materials and Structures vol. 59 (4): 17-29, doi:10.5937/grmk1604017G.

Cace J, Horst ter Emil, Syngellakis K et al. (2007) Urban wind turbines – Guidelines for small wind turbines in the built environment, Wineur (Wind energy integration in the urban environment). Supported by Intelligent Energy – Europe.

CEN (2010) EN1990. Eurocode - Basis of structural design. European Committee for Standardization, Brussels, Belgium.

CEN (2010) EN1991-1-4. Eurocode 1 – Actions on structures. Part 1-4: General actions – Wind actions. European Committee for Standardization, Brussels, Belgium.

CEN (2009) EN1993-1-1. Eurocode 3 – Design of steel structures. Part 1-1: General rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.

CEN (2009) EN1994-1-1. Eurocode 4 – Design of composite steel and concrete structures. Part 1-1: General rules and rules for buildings. European Committee for Standardization, Brussels, Belgium.

Encraft (2009) Warwick Wind Trials Project: Final Report. Encraft, UK.

Feldmann M, Heinemeyer Ch, Butz Chr et al. (2009) Design of floor structures for human induced vibrations. Background document in support to the implementation, harmonization and further development of the Eurocodes. JRC – ECCS cooperation agreement for the evolution of Eurocode 3 (Sedlacek G, Heinemeyer Ch and Butz Chr (eds.)). ECCS, Italy.

Fingersh L, Hand M, Laxson A (2006) Wind Turbine Design Cost and Scaling Model. NREL National Renewable Energy Laboratory Denver West Parkway Golden, Colorado, USA, Technical Report NREL/TP-500-40566.

ISO (2007) ISO 10137. Basis for design of structures. Serviceability of buildings and walkways against vibrations. International Standard Organization, Switzerland.

Simis as Org.no.912019128 – Superpowers to engineers (2013).Leonardveien 3, NO-7790 Malm, Norway. See http://www.simis.io (accessed 08/02/2016).

Pavlović M, Marković Z, Spremić M et al (2011) Usage of polyurethane foam acoustic insulation in cinemaplex steel structure, In *Proceedings of a EUROSTEEL 2011 6th European Conference on Steel and Composite Structures* (Dunai L (ed.)). ECCS European Convention for Constructional Steelwork, Brussels, Belgium, vol. C, pp. 2511-2516.

Sofistik AG. Bruckmannring 38, 85764 Oberschleißheim, Munich, Germany. See https://www.sofistik.com.

Sofistik AG (2011) DYNA Dynamic Analysis Version 13.01, Oberschleißheim, Munich, Germany.

Smith J, Forsyth T, Sinclair K et al. (2012) Built-Environment Wind Turbine Roadmap. NREL National Renewable Energy Laboratory Denver West Parkway Golden, Colorado, USA, Technical Report NREL/TP-5000-50499.

Wineur (Wind energy integration in the urban environment) (2005) Technology inventory report. Supported by the European Commission under the Intelligent Energy – Europe Programme, EIE/04/130/SO7.38591.

Table 1. Vertical RMS accelerations of building fourth floor

Average wind speed	9 m/s		12 m/s		15 m/s		Pedestrian
Nodes of fourth floor	Node 5	Node 6	Node 5	Node 6	Node 5	Node 6	Node 5
RMS accelerations for wind turbine position 1	0.002	0.003	0.005	0.006	0.006	0.008	0.0053
	Node 7	Node 8	Node 7	Node 8	Node 7	Node 8	
RMS accelerations for wind turbine position 2	0.180	0.002	0.016	0.005	0.028	0.007	

Figure 1. Blade mass scaling relationship (adapted from Fingersh *et al.*, 2006)

Figure 2. Development of small-scale wind turbine in Ashes software package
a) turbulent wind time history generated by Ashes for 9 m/s average wind speed
b) time-history of axial forces from wind turbine
Figure 3. Time-history of forces and bending moments applied on the building roof for 9, 12 and 15 m/s average wind speed
Figure 4. Numerical model of analysed steel building developed in Sofistik FE software
a) steel building layout b) position of wind turbines
Figure 5. Roof vibrations for wind turbine position 1 and position 2 a) roof horizontal acc. in *x* direction – position 1 b) roof vertical acc. in *z* direction – position 1 c) roof horizontal acc. in *x* direction – position 2 d) roof vertical acc. in *z* direction – position 2
Figure 6. Peak vertical accelerations – positions at roof and fourth floor a) wind turbine position 1 b) wind turbine position 2
Figure 7. Peak horizontal accelerations - roof and fourth floor a) wind turbine position 1 b) wind turbine position 2
Figure 8. Comparison of roof and fourth floor peak accelerations with and without wind turbine for 9 m/s average wind speed a) wind turbine position 1 b) wind turbine position 2
Figure 9. Comparison of results of numerical analysis with design recommendations a) wind induced vibrations in horizontal direction – ISO 10137 (2007) b) vibrations in vertical direction – turbine position 1 – BS 6472-1 (2008) c) vibrations in vertical direction – turbine position 2 – BS 6472-1 (2008)

Figure 1

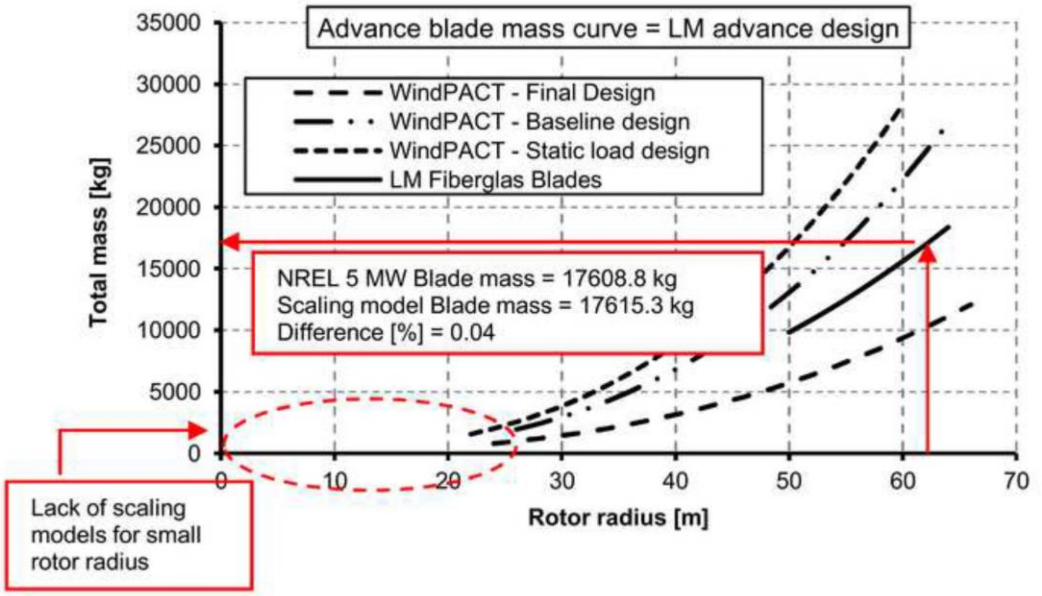
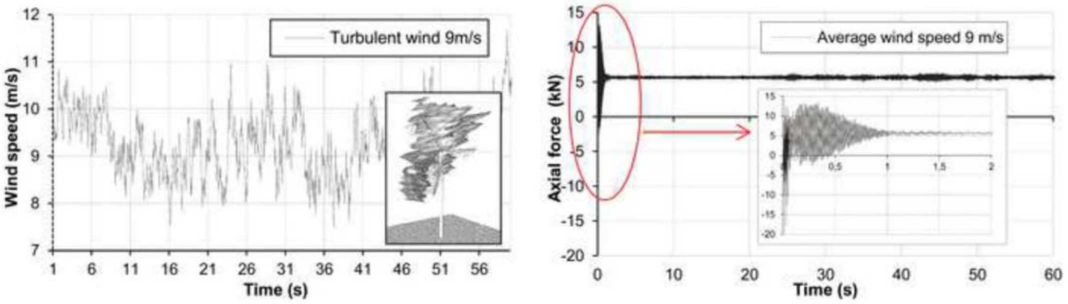

Advance blade mass curve = LM advance design
WindPACT - Final Design
WindPACT - Baseline design
WindPACT - Static load design
LM Fiberglas Blades
NREL 5 MW Blade mass = 17608.8 kg
Scaling model Blade mass = 17615.3 kg
Difference [%] = 0.04
Lack of scaling models for small rotor radius
Total mass [kg]
35000
30000
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
60
70
Rotor radius [m]

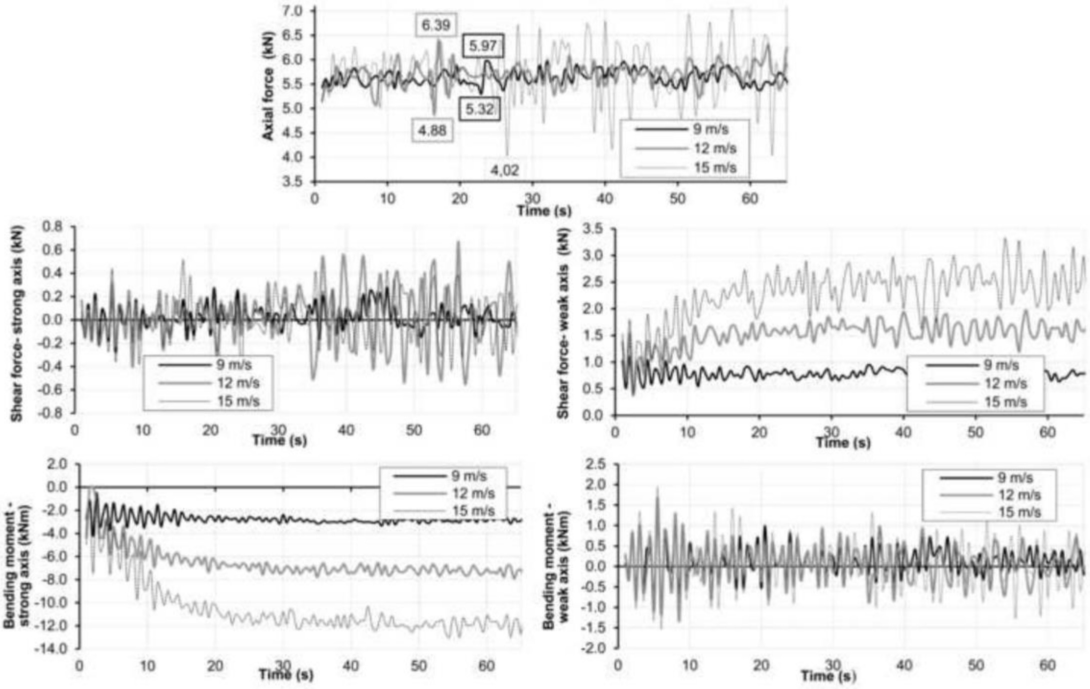
Figure 2



a) turbulent wind time history generated by Ashes for 9 m/s average wind speed

b) time-history of axial forces from wind turbine

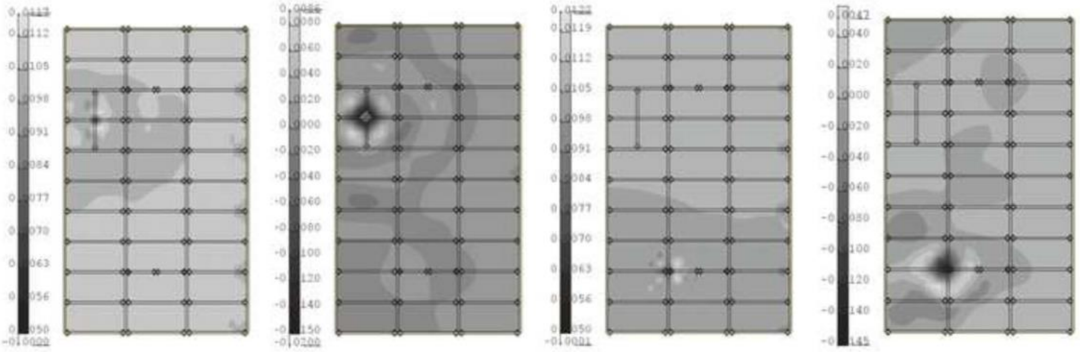
Figure 3


Axial force (kN)
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
6.39
5.97
5.32
4.88
4,02
9 m/s
12 m/s
15 m/s
0
10
20
30
40
50
60
Time (s)
Shear force- strong axis (kN)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Shear force- weak axis (kN)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Bending moment - strong axis (kNm)
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
Bending moment - weak axis (kNm)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0

Click here to download Figure Figure 4.jpg

a) steel building layout   b) position of wind turbines

Figure 5



a) roof horizontal acc. in *x* direction – position 1

b) roof vertical acc. in *z* direction – position 1

c) roof horizontal acc. in *x* direction – position 2

d) roof vertical acc. in *z* direction – position 2

Figure 6

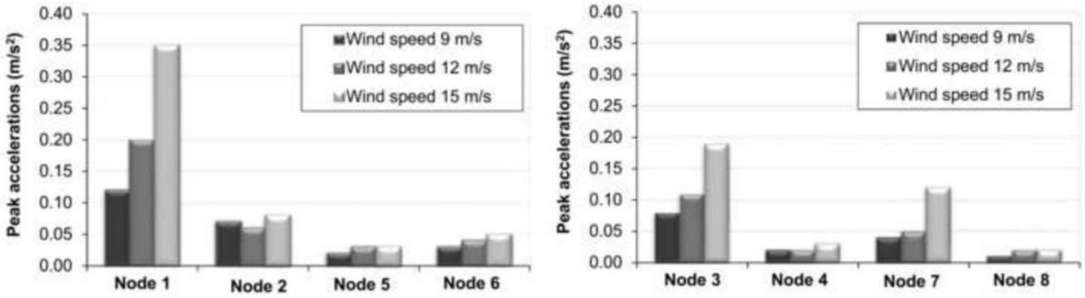

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Peak accelerations (m/s²)
Wind speed 9 m/s
Wind speed 12 m/s
Wind speed 15 m/s
Node 1
Node 2
Node 5
Node 6
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Peak accelerations (m/s²)
Wind speed 9 m/s
Wind speed 12 m/s
Wind speed 15 m/s
Node 3
Node 4
Node 7
Node 8

Figure 7

Click here to download Figure Figure 7.jpg

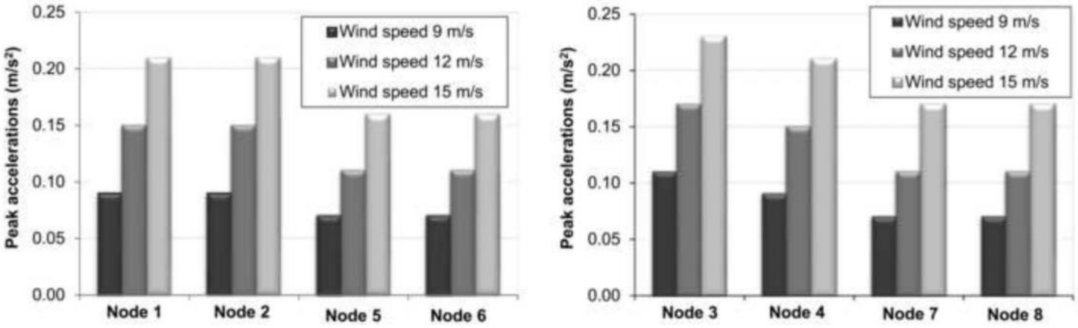


Figure 8

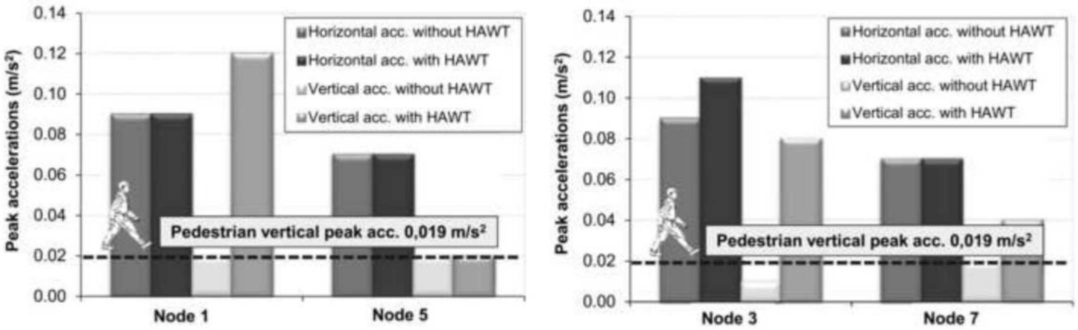
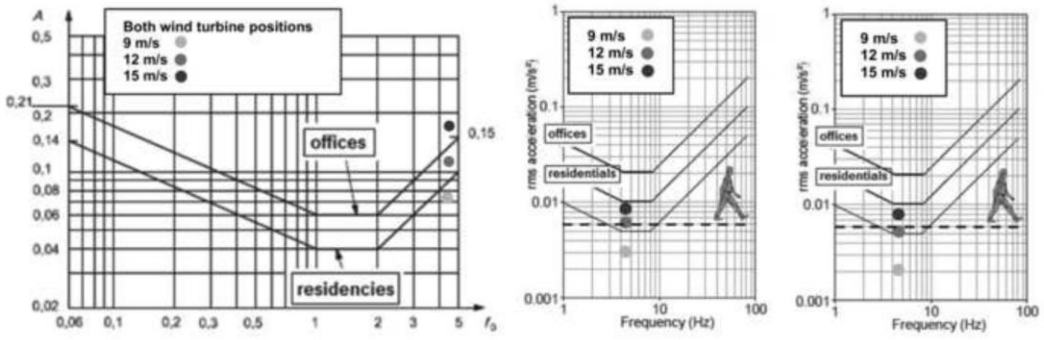

0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Peak accelerations (m/s²)
▨ Horizontal acc. without HAWT
■ Horizontal acc. with HAWT
□ Vertical acc. without HAWT
▨ Vertical acc. with HAWT
Pedestrian vertical peak acc. 0,019 m/s²
Node 1
Node 5
Node 3
Node 7

Figure 9



a) wind induced vibrations in horizontal direction – ISO 10137 (2007)

b) vibrations in vertical direction – turbine position 1 – BS 6472 (1992)

c) vibrations in vertical direction – turbine position 2 – BS 6472 (1992)