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On the structural response of a tall hybrid onshore wind turbine tower

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Abstract

Given the increasing demand for taller structures in wind energy applications and the accompanying need for a better understanding of their structural response, the present study performs aeroelastic analysis on a novel wind turbine structure and discusses the obtained results. The response of a hybrid onshore wind turbine tower consisting of a 60 m lattice structure and a 60 m tapered tubular structure, with a 5 MW class AII turbine, is investigated. From the Design Load Cases (DLC) established in IEC64100-1 standard, focus is set on DLC 1.1 and DLC 1.3 which correspond to power production conditions and embody the requirements for loads resulting from atmospheric turbulence during normal and extreme operating conditions respectively. DLC 6.1 which refers to standstill or idling conditions under extreme wind model is also studied. In order to account for the interaction between elastic, viscous and inertial forces of the structure and the external aerodynamic forces, ashes, an integrated analysis software, is used. After developing the wind turbine tower model and generating the turbulence models, 600 seconds simulations are performed. The wind flow is assumed to be parallel to the hub axis. For DLC 1.1 and DLC 1.3, parametric studies with the wind speed ranging from 3 to 25 m/s, with an incremental step of 1 m/s, are executed. In DLC 6.1, the blades are feathered and the wind speed is rapidly increased to 42.5 m/s. Time histories of the elemental forces and the nodal displacements are extracted in critical positions of both the lattice and the tubular part. The mean values of the output data are evaluated and plotted against the wind speed. Conclusions regarding the influence of the wind speed on the induced tower behaviour are drawn.

Keywords: Wind turbine tower; hybrid tower; aeroelasticity; DLC; time history

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1. Introduction

Growing demand for clean and renewable energy has emerged owing to the increased amount of greenhouse emission gases. Wind farms consisting of lattice or tubular wind turbine towers have considerably contributed to an increase in the renewable energy production across the world. Demands for higher wind turbines with larger capacities, aimed to be installed at high altitudes or at places with high wind velocities, have recently appeared. In order to fulfil the required safety and durability verifications, whilst keeping the solution economically and environmentally sustainable, hybrid structures, efficiently combining tubular and lattice parts, could be applied. Towards this direction, the present study performs numerical analysis on a tall hybrid structure. Emphasis is placed upon three design load cases from those established in IEC64100-1 standard [1].

Nomenclature

CHS	Circular Hollow Section
DLC	Design Load Case
NTM	Normal Turbulence Model
ETM	Extreme Turbulence Model

2. Methodology

The present paper focuses on the structural response of a 120 m hybrid onshore wind turbine tower. The current section presents the adopted methodology for the evaluation of its response. Subsection 2.1 describes the geometry of the considered hybrid tower and the employed cross-sections. Having established the wind turbine tower, a brief description of the aeroelastic analysis is given in Subsection 2.2.

2.1. Wind turbine tower

As a first step, a series of parameters, including the height of the tubular and the lattice part, the number of legs, the arrangements and the angle of bracings in the lattice part, need to be defined. An initial study should be carried out in order to find the most efficient structure, ensuring compromise between the lowest structural weight and the fabrication and assembly costs which commonly come as a function of the number of connections.

For the present study, a hybrid tower consisting of 60 m tube at the upper part and 60 m lattice structure at the lower part, as shown in Fig. 1, has been selected. In order to increase the load distribution, six columns (legs) have been chosen for the lattice structure. The employed cross-sections were based on a preliminary study [2]. Cold-formed built-up polygonal cross-sections in steel grade S355 were employed for both the tubular and the lattice part. For the simulation of the employed cross-sections of the hybrid tower herein, it was deemed adequate to model the polygonal cross-sections with circular hollow sections (CHS). The tubular part was tapered ranging from 5500 mm in the base to 4000 mm in the top, with constant plate thickness equal to 40 mm. The transition part was conservatively designed with bracings of large cross-sections. Note that the transition piece is a critical component, aiming to transfer all the dynamic and self-weight loads to the lattice, and needs separate in-depth investigation, out of the scope of the present paper. Various cross-sections, as can be seen in Fig. 1, were chosen for the lattice structure.

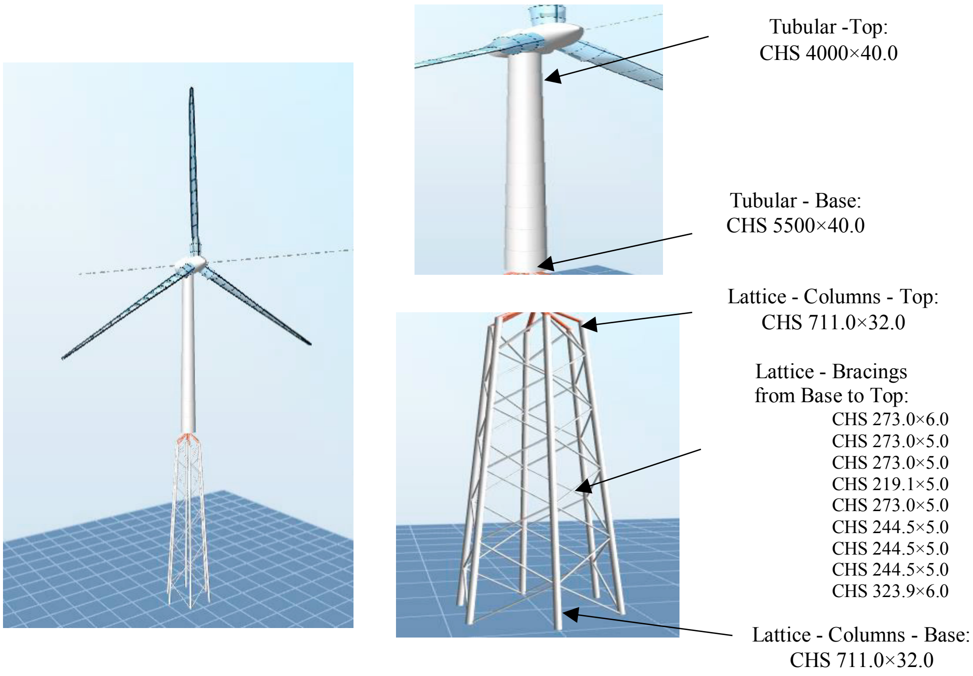


Fig. 1. Wind turbine tower (60 m lattice & 60 m tubular).

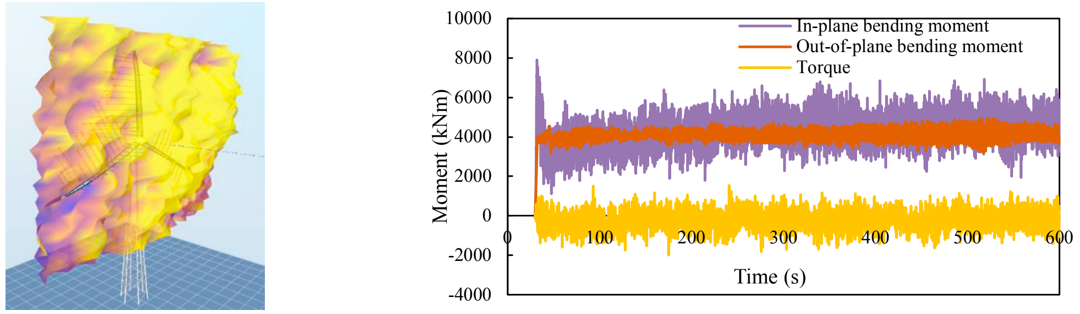
2.2. Aeroelastic analysis

In order to account for the interaction between elastic, viscous, and inertial forces of the structure and the external aerodynamic force, ashes [3], an integrated analysis software, has been used for the numerical analysis. Ashes uses blade element momentum (BEM) algorithm for aerodynamics and combines it with finite element (FE) solver for the evaluation of the induced structural behaviour. Wind turbulence can be simulated with Turbsim tool [4], a stochastic, full-field, turbulence simulator, and imported into ashes. For the considered hybrid structure, an NREL 5 MW Class AII turbine, thoroughly described in [5], is assumed.

After developing the wind turbine tower model, the turbulence models are generated. The assigned turbulence depends on the considered design load cases. In order to ensure the engineering integrity of onshore wind structures, IEC6400-1 [1] outlines the minimum requirements for wind turbines by providing 15 and 7 design load cases (DLC) for the ultimate and the fatigue limit state respectively. Hereafter focus is placed on DLC 1.1 and DLC 1.3 which embody the requirements for loads resulting from atmospheric turbulence during normal (NTM) and extreme operating conditions (ETM) respectively. The generated extreme turbulence model applied in DLC 1.3 is depicted in Fig. 2(a).

Once the NTM and ETM models have been developed, 600 seconds simulations are executed. For both DLC 1.1 and DLC 1.3, parametric studies with the wind speed ranging from 3 to 25 m/s, with an incremental step of 1 m/s, are performed. The wind flow is assumed to be parallel to the hub axis. In order to eliminate initial impact effects, the first 30s of each simulation, during which the simulated flow was not fully developed yet, are disregarded. A typical example of the recorded moment time histories at the top of the tubular part is shown in Fig. 2(b), for wind speed 12 m/s.

Adopting the aforementioned assumptions, DLC 6.1 corresponding to standstill or idling conditions under extreme wind model is also examined. The blades are feathered (i.e. pitch angle equal to 90°) and the RPM (rotations per minute) is set equal to zero. The wind speed is rapidly increased to 42.5 m/s and the induced response is recorded.



a) Extreme Turbulence Model (ETM)

b) Moment time histories - Tubular - Top - Wind speed 12 m/s - DLC 1.3

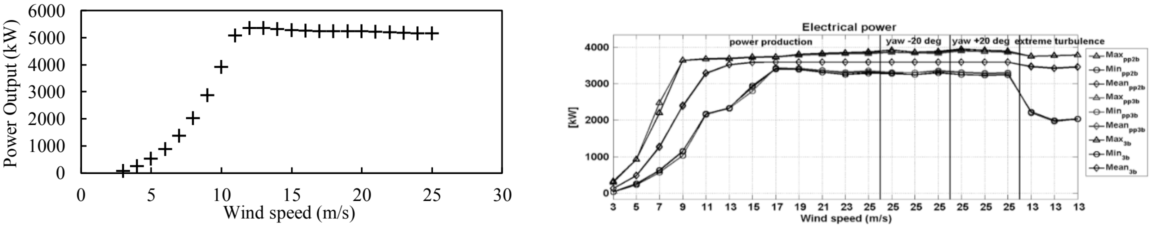
Fig. 2. Aeroelastic analysis in ashes [3].

3. Results

Upon execution of the aeroelastic analyses, the obtained results are visualised separately for DLC 1.1, DLC 1.3 and DLC 6.1 in Subsection 3.1, 3.2 and 3.3 respectively.

3.1. Design Load Case 1.1

Before examining the structural performance of the hybrid tower, the mean values of the power output is plotted against the wind speed in Fig. 3(a). An increasing trend can be observed for wind speeds up to 11 m/s; for higher wind speeds, the power output remains relatively stable. Similar is the trend found in literature [6], as shown in Fig. 3(b).

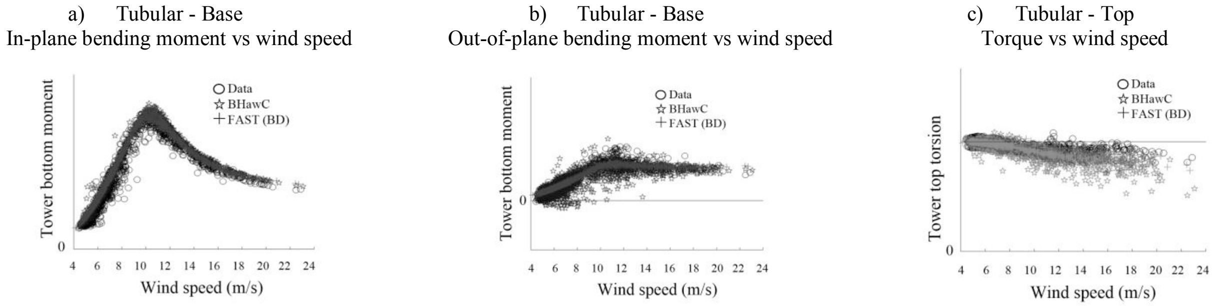


a) Hybrid wind turbine tower (mean values)

b) Wind turbine towers studied in [6]

Fig. 3. 10-min values of power output vs the wind speed.

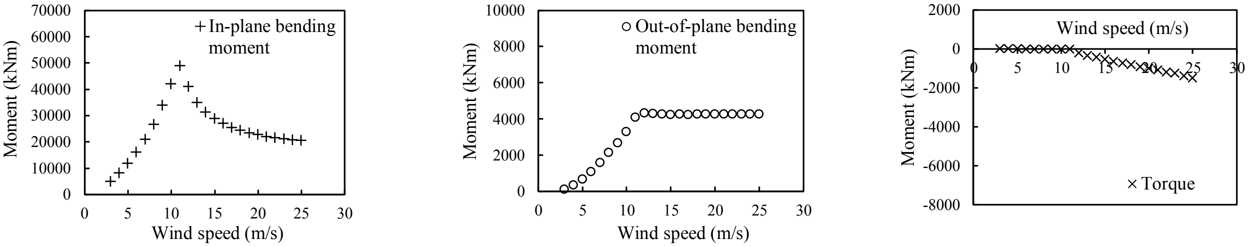
In order to evaluate the structural response, the mean values of the elemental forces and the nodal displacements are calculated and plotted against the wind speed. The observed response is shown in Figs. 4-6. In particular, Fig. 4 presents the mean values of the induced moments on the tubular structure for increasing wind speed. In order to verify the results, the data from measurements on a tubular structure [7] are shown for comparison purposes. Even though the measurements refer to a different, still comparable, support structure, the similarity on the observed response is evident. For in-plane bending moments, peak values are achieved for wind speed 11 m/s. This is related with the pitch controller that decreases the angle of attack in order to mitigate the excitation load on the blade structure and keep the RPM and the power output constant. The influence of the aforementioned effect is less significant on the out-of-plane and torsional moments, which remain relatively stable for wind speeds higher than 11 m/s. The axial forces of the columns and the bracings of the lattice structure for increasing wind speed are depicted in Fig. 5. An ascending curve for wind speed 3-11 m/s and a descending curve for wind speed 11-25 m/s are again noticeable. The axial forces are similar in the lower and the upper part of the lattice columns, justifying the selection of the same cross-section. In addition to the elemental forces, the mean values of the attained displacements at the top of the tubular and the lattice structure are shown in Fig. 6. Peak values of 0.07 m and 0.37 m have been found for the in-plane deflections at the top of the lattice and the tubular structure respectively. The attained values can be utilised for serviceability limit state verifications.


a) Tubular - Base
In-plane bending moment vs wind speed

b) Tubular - Base
Out-of-plane bending moment vs wind speed

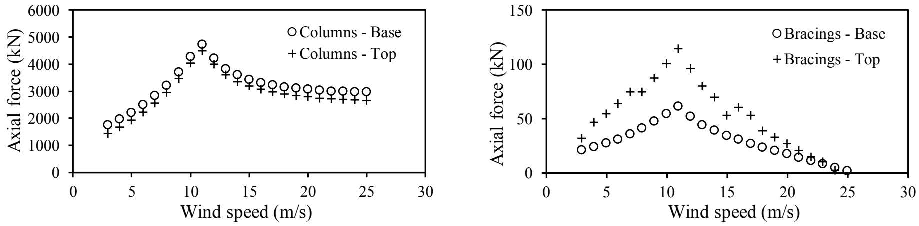
c) Tubular - Top
Torque vs wind speed

Measurements on wind turbine towers [7]



Numerical anlysis on a hybrid structure

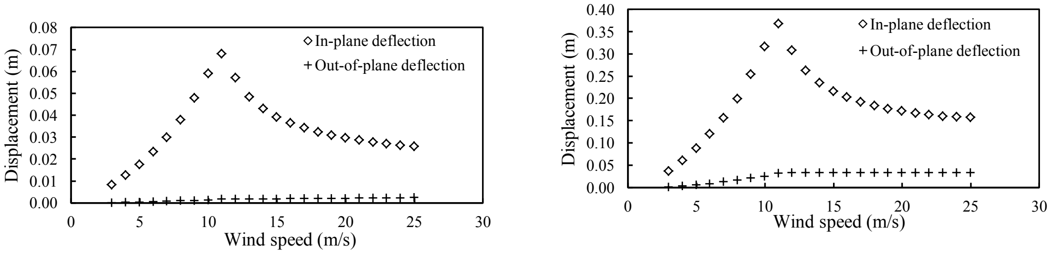
Fig. 4. 10-min mean values of moments vs the wind speed - tubular structure.



a) Lattice - Columns

b) Lattice - Bracings

Fig. 5. 10-min mean values of axial forces vs the wind speed - lattice structure.



a) Lattice - Top

b) Tubular - Top

Fig. 6. 10-min mean values of displacements vs the wind speed.

3.2. Design Load Case 1.3

The overall structural behaviour of DLC 1.3 was similar to that of DLC 1.1, with DLC 1.3 presenting slightly higher mean values compared to those of DLC 1.1. In particular, 0.57% higher mean values for the axial forces of the lattice part and 2.45% higher mean values for the in-plane bending moments of the tubular part were achieved for DLC 1.3.

3.3. Design Load Case 6.1

For DLC 6.1, the feathered blade condition together with typical instant aerodynamic forces is illustrated in Fig. 7(a). In Fig. 7(b) a representative load table referring to the top of the tubular part is depicted, with the coordinate system as defined in [3]. The diagonal of the table corresponds to the maximum recorded values during the 600s simulations; vertically the rest elemental forces at the same increment are included. Note that similar load matrices with maxima and minima have been formed for all the parts of the hybrid structure and for all the considered load cases. These can be subsequently used for the extreme load assessment for a certain cross-section at different heights.

a) Feathered blades

	Tubular - Top					
	F_x (kN)	F_y (kN)	F_z (kN)	M_x (kNm)	M_y (kNm)	M_z (kNm)
F_x (kN)	228.36	49.35	-95.74	49.35	-98.57	97.31
F_y (kN)	-59.02	501.74	113.89	501.74	-195.63	207.75
F_z (kN)	-3388.22	-3437.99	3218.97	-3437.99	3348.86	-3445.68
M_x (kNm)	-427.43	4153.54	829.04	4153.54	-1403.80	1987.25
M_y (kNm)	1326.86	-1584.73	-710.55	-1584.73	-2026.49	350.47
M_z (kNm)	337.74	2125.31	-649.82	2125.31	1498.64	3862.22

b) Typical load table (maxima)

Fig. 7. Design load case 6.1.

4. Conclusions

A numerical study on a hybrid wind turbine tower has been carried out. The extracted power output for increasing wind speed was compared with findings in [6], presenting similar response. The observed structural behavior of the hybrid tower was studied in line with measurements on a tubular wind turbine tower [7], finding comparable trend with respect to the wind speed. For the in-plane bending moments of the tubular part, the axial forces of the lattice part and the in-plane deflections of the whole structure, mean peak values were achieved for wind speed 11 m/s. The obtained results of the three considered load cases and the generated load tables with maxima and minima of the elemental forces can be used for further assessment of the wind structure's behaviour, including components' checks and limit state verifications. Further research could be realised to investigate optimal configurations of hybrid structures, compare them with conventional wind turbine towers and assess the possibility of applying higher steel grades in highly stressed regions.

Acknowledgements

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