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Numerical modal analysis of a 850 KW wind turbine steel tower

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ABSTRACT

The study deals with the numerical analysis aspects that are necessary for identifying of modal parameters of the tower structure as the most important part of the horizontal axis wind turbine, which are basic for the dynamic response analysis. In the present study, the modal behavior of an actual 55-m-high steel tower of 850 KW wind turbine (GAMESA G52/850 model) is investigated by using three-dimensional (3D) Finite Element (FE) method. The model was used to identify natural frequencies, their corresponding mode shapes and mass participation ratios, and the suggestions to avoid resonance for tower structure under the action wind. The results indicate that there is a very good agreement with the fundamental vibration theory of Euler-Bernoulli beam with lumped masse in bending vibration modes. When the rotor of the wind turbine runs at the speed of less than or equal to 25.9 rpm it will not have resonant problems (stiff-stiff tower design). Furthermore, in case the rotor runs at the speed of between 25.9 and 30.8 rpm, the adequate controller is necessary in order to avoid the corresponding resonant susceptible area of the tower structure (soft-stiff tower design).

KEYWORDS

wind turbine tower, modal analysis, natural frequencies, mode shapes, finite element method, mass participation ratio

1. INTRODUCTION

In the world today, wind energy sector has been the fastest growing phenomenon in the sphere of renewable energy. Wind power can definitely play a significant role for guaranteeing a sustainable future, with the addition of 52 GW in 2017, an annual growth rate of approximately 11% [1, 2]. According to the Algerian government, the new and renewable energy strategy in Algeria (since 2011) aims to install 22,000 MW of generated energy from renewable sources by 2030 (37 % out of the total generated energy). Wind energy constitutes the second axis of development after solar energy with an electricity production of about 5010 MW (approximately 23%) [3, 4]. Algeria ranks at the lowest in the global installed wind energy capacity table in the Africa. The first and only one wind farm with generating capacity of 10.2 MW (consists 12 GAMESA G52-850 kW wind turbine) was installed in June 2014 by the national company Sonelgaz at Kabertene in Adrar province, which is situated in the southwestern part of the country (Fig. 1). This site is the most convenient place for wind farm installation because it is the windiest zone in Algeria with the annual average wind speed of about 6.3 m/s [5, 6].

Wind turbines are continuously subjected to varying dynamic (wind, sand, temperature variations, etc.) and gravitational loads [7]. As a result of these loads the wind turbine undergoes deformations and rigid body motions. The first can be divided into two types, a dynamic response and a quasi-static. The dynamic response of a wind turbine may be characterized by its modal parameters (natural frequencies, damping characteristics and mode shapes) [8, 9]. Modal analysis has the ability to determine these parameters allowing the tracking of small changes in

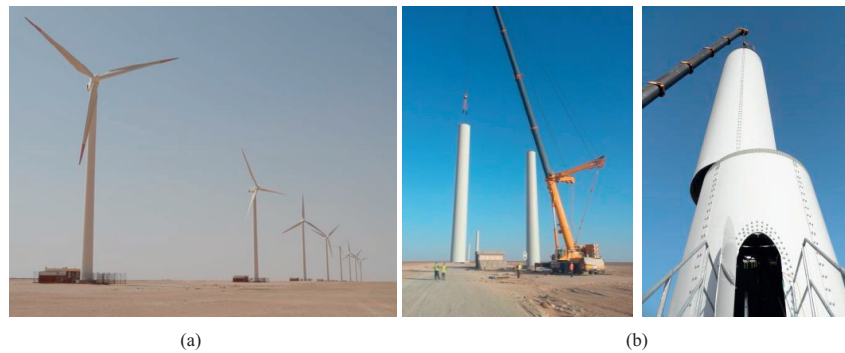


Fig. 1. (a) Gamesa G52/850 wind turbine towers at the Kabertene wind farm; (b) Gamesa G52 tower during construction [13]

these parameters over time. These changes may originate from characteristics of the loads, changes in mass distribution or damage to the structure [9–12].

Tower that carries the nacelle and the rotor is one of the key components and it represents beyond 20% of the total wind turbine cost. It is also the most critical component according to structural safety under aerodynamic loadings. Taking into consideration all this, optimal design of the tower structures (structural behavior) is of great importance related to the final cost of energy [14–16].

In a survey of technical literature, we see a great number of studies on wind turbine technology (horizontal-axis or vertical-axis) are focused on the aerodynamics and performance of wind turbines by using the experimental testing [17–19] and Computational Fluid Dynamics (CFD) numerical simulation [20–24]. In the recent years there has been increasing interest by the scientific community in the structural design behavior of wind turbines. Most of these studies focused on the structural design behavior (static and dynamic) either of the rotor blades [25–27] or of the single blades, which are independent of the rest of the structure [28–30]. On the other hand, many researchers in the wind energy have been interested in the response of the tower structure subjected to several dynamic loadings [31–36].

The objective of this paper is to investigate the dynamic behavior of an actual 55-m-high steel tower of 850 KW wind turbine (model G52/850 KW manufactured by Gamesa Company) when subjected to wind excitation by numerical modal analysis using three-dimensional (3D) Finite Element (FE) method. The analysis was conducted in order to evaluate natural frequencies, their corresponding mode shapes and mass participation ratios, and the suggestions to avoid resonance for tower structure. The material presented here is organized as follows: In Section 2, a description of the tower structure is presented. In Section 3, the Finite Element Method FEM-simulations of the model are described. The numerical results of the study are discussed in Section 4. Finally, in Section 5 the main concluding remarks are drawn.

2. WIND TURBINE TOWER DESCRIPTION

The wind turbine GAMESA G52/850 KW is 3-bladed, horizontal-axis wind turbine with a 52 m rotor diameter

(Fig. 1a). The tower is a free standing tube steel structure varying its diameter (conical) and thickness along the height. It is manufactured in three hollow sections (total height of 55 m) with circular flanges at either end, and bolted together in order to enable transportation and assembling on the site, as shown in Fig. 1b. The structure also includes an opening of the door at the base. The tower is conical to increase its strength, durability and to save material. The shell thickness of structure varies between 18 mm at the base and 10 mm at the top. Computer Aided Design (CAD) software, namely, SolidWorks (version 2016) was used in order to create a 3D full-scale model for the tower structure as seen in Fig. 2. The main parameters of the wind turbine are tabulated in Table 1.

3. FEM-SIMULATIONS

Numerical modeling and simulation for engineering systems has grown rapidly as a result of the advent and the development of computer technologies. The wind turbines are complex structures in design and dynamic behavior, demand detailed FEs modeling [39–41]. There are many software commercial packages based on FE method available on the market that meet the simulation requirements, SolidWorks, Ansys and Abaqus. The detailed 3D FE model of the tower structure is modeled by using SolidWorks Simulation software [42].

Since the tower has many complex parts, it is necessary to simplify its structure for establishment of the 3D FE model and for reducing calculation time. The simplified principles cover ignoring the bolts, ladder, power cable, and other small parts. The whole tower structure is made from Steel (AINS 1020 Steel, cold rolled) with the following material properties: $E = 2.05 \times 10^{11} \text{ N/m}^2$ yield stress, $\nu = 0.29$ Poisson's ratio, $\rho = 7870 \text{ kg/m}^3$ mass density and $S_y = 350 \times 10^6 \text{ N/m}^2$ limit stress. These properties are given as input to the SolidWorks. Boundary conditions of the tower model, all degree of freedoms (DoFs) are constrained (fixed) at its bottom, bolted connections between the flanges and the friction between the circular flanges were replaced by suitable connections (bolt connector and Bonded Contact respectively) and no others loads are

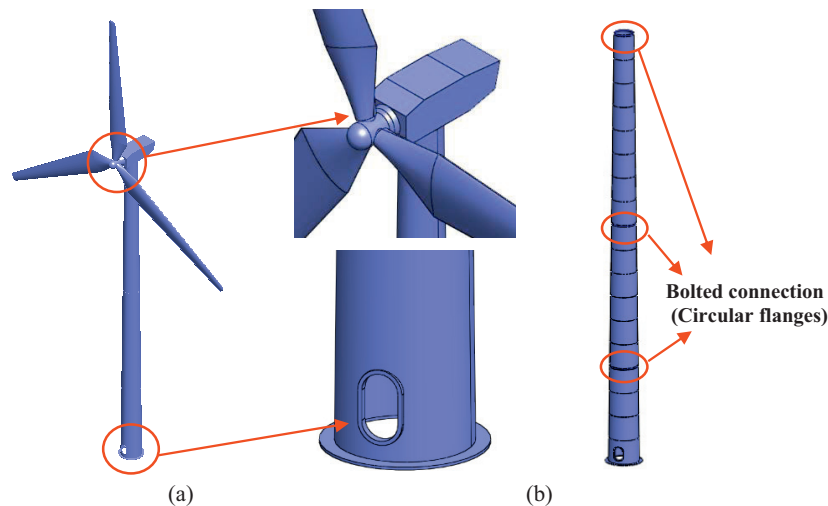


Fig. 2. (a) SolidWorks-generated full model of wind turbine Gamesa G52/850 KW; (b) steel tower structure

Table 1. Main parameters of the Gamesa G52/850 reference model [37, 38]

Item	Sub item	Value	Unit
Tower	Height	55	m
	Base wall thickness	18	mm
	Top wall thickness	10	mm
Rotor (blades + hub)	Number of blades	3	
	Rotor diameter	52	m
	Rotor speed	14.6–30.8	rpm
	Swept area	2,124	m ²
	Blade length	25.3	m
Wind speeds	Cut-in wind speed	4	m/s
	Rated wind speed	16	m/s
	Cut-off wind speed	25	m/s
	Survival static wind speed	70	m/s
Weights	Nacelle	23	ton
	Tower	62	ton
	Rotor + hub	10	ton
	Total	80	ton

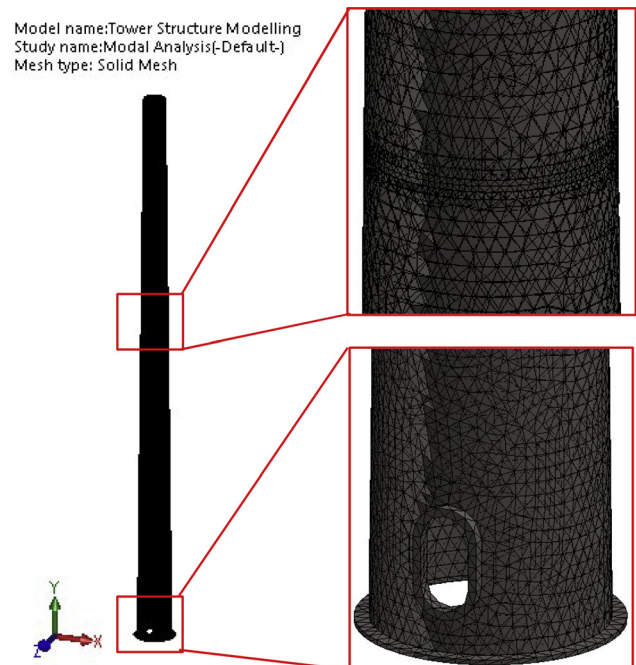


Fig. 3. FEM mesh for tower model

applied except for the structure's own weight because it can cause significant effects on the modal properties. Modal analysis assumes that the structure vibrates in the absence of any damping and excitation [42]. For the best balanced accuracy and efficiency in numerical simulations, generating a high-quality mesh is has very important implications in design analysis. The model was meshed with tetrahedral solid elements (with 10-DoFs per element) because it is suitable for complex and bulky models [31]. The resultant mesh of the tower model after the sweep and different localized refinements made in areas of interest are shown in Fig. 3, which consisted of 189,612 physical nodes and 95,320 elements for a total 566,706 DoFs. As the tower model has a large number of DoFs, an iterative solver, namely, FFEPlus (Fourier Finite-Element Plus) was used for the numerical solution. A workstation (using 12 processor (INTEL (R);

Core (TM) i7-4770 k; 16.0 Go; 3.5 GHz) at Renewable Energy Research Unit in Saharan Medium (URER/MS) was used for running the SolidWorks Simulation software.

Free analysis is the first step for the structure dynamic analysis to determine the natural frequencies and with them mode shapes (Eigen-modes) of a structure under evaluation, in order to determine if any of the frequencies of the several possible modes of vibration coincide with the frequency of the cyclic external (wind) loads. The matrix equations of motion associated with free vibration (in the absence of damping and external excitation) of the tower structure obtained by the FE method can be expressed in form as [43, 44]:

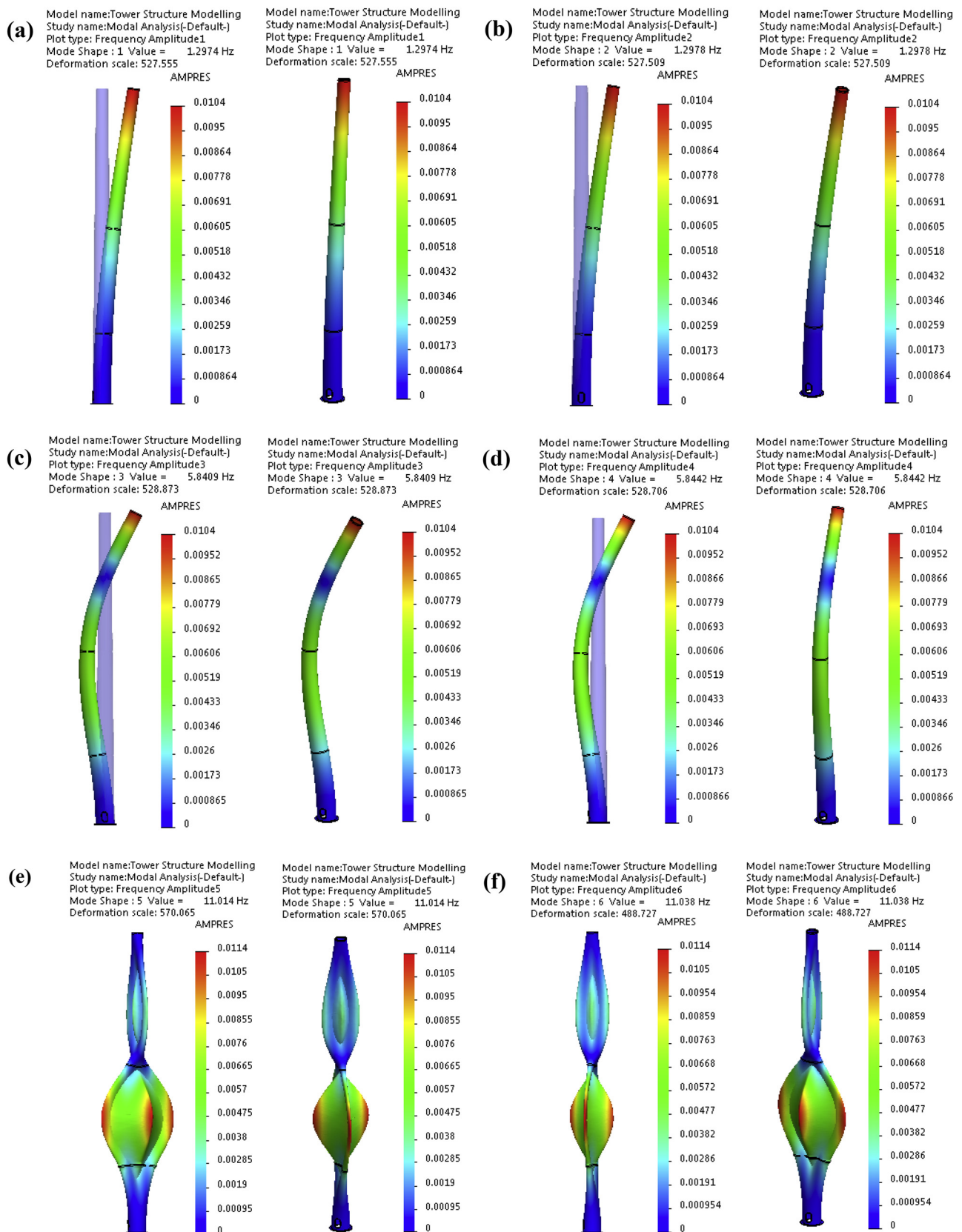


Fig. 4. Modal shapes of the wind turbine tower structure; (a) The first mode, (b) The second mode, (c) The third mode, (d) The fourth mode, (e) The fifth mode, (f) The sixth mode

Table 2. The first 10 sorted natural Frequencies and their corresponding mode shapes for tower structure

Mode number	Naturel Frequencies (Hz)	Shapes description
1	1.297	1st Bending of the tower (x-direction)
2	1.297	1st Bending of the tower (z-direction)
3	5.840	2nd Bending of the tower (Z-direction)
4	5.844	2nd Bending of the tower (X-direction)
5	11.014	1st Torsional of the tower (Y-axis)
6	11.038	2nd Torsional of the tower (Y-axis)
7	12.787	Mixed vibration (Bending and torsional)
8	12.810	Mixed vibration (Bending and torsional)
9	14.599	3rd Bending of the tower (Z-direction)
10	14.636	3rd Bending of the tower (X-direction)

$$M\ddot{u} + Ku = 0 \quad (1)$$

where the matrices M and K are the global mass and the structural stiffness matrices, respectively. By searching the solutions $u(x, t)$ in the form $u(u, t) = \phi(u) \cdot e^{i\omega t}$, then, Eq. (1) may be expressed as:

$$(-\omega^2 M + K)\phi = 0 \quad (2)$$

where $\phi(u)$ ω is the circular frequency (rad/s) and ϕ is the mode shape. The characteristic Equation (2) is:

$$|K - \omega^2 M| = 0 \quad (3)$$

Solutions of the determinant (3) are called the normal modes (n positive real roots). For each normal mode there is an associated frequency f (corresponding to the eigenvalue ω) given by $\omega = 2\pi f$.

4. RESULTS AND DISCUSSION

Natural frequencies are important results and always of concern when designing tower structure, as well as other high structures. The tower structure has several various modes of natural vibration frequencies, but for the case of a typical modern wind turbine the interest mode is the first since it should not be completely within the excitation frequency range of the turbine (to avoid resonance), with a safety distance of -15% and $+10\%$ [45, 46]. The frequency range from the rotational frequency of the rotor corresponds to 1P (operating frequency; the lower limit) plus 10% and blade passing corresponds to 3P (the upper limit) for three bladed rotor reduced 15% [32, 47]. For the performance dynamic, there are three different tower structure designs: (i) a soft-stiff (economical design) means that the natural frequency is below the 3P and above the 1P, (ii) a soft-soft (very flexible) refers to that the natural frequency of the tower being lower than the 1P, and (iii) a stiff-stiff (uneconomical design) represents where the natural frequency lies higher than 3P [48, 49].

4.1. Mode Shapes and Natural Frequencies

The first six modal shapes of the tower structure are shown in Fig. 4. The most significant dynamic properties of the

complete tower structure can be seen from this figure. It will be remarked that the elastic strain of the tower has generally appeared in the top. This is due to the structure being discontinuous in this area. The results show that the 1st and 4rd vibration modes are bending deformation along the X-direction in phase or in phase opposition in the YZ plane,

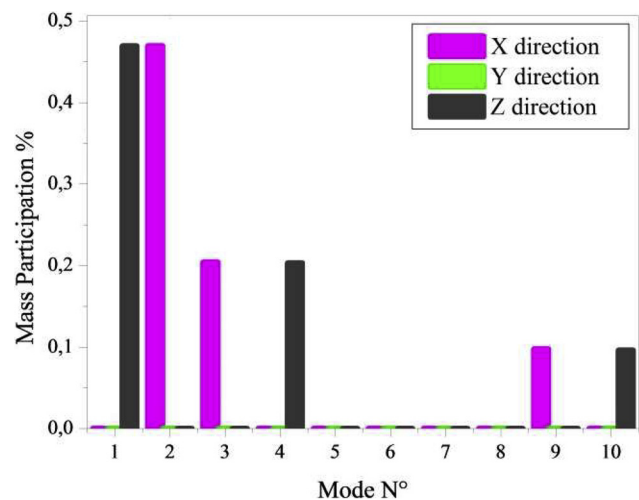


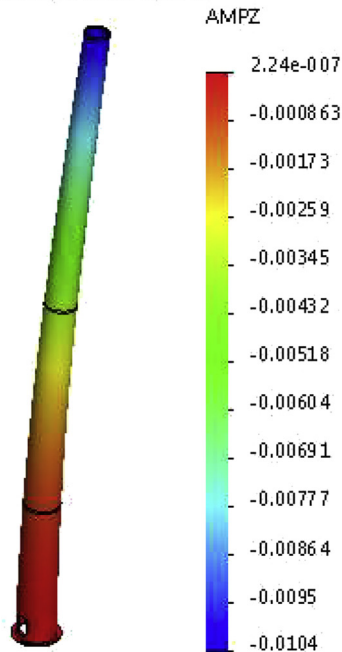
Fig. 5. Mass participation ratios

Table 3. Mass participation ratios for the first 10 modes. Highest mass participation ratio for each direction has been bolded

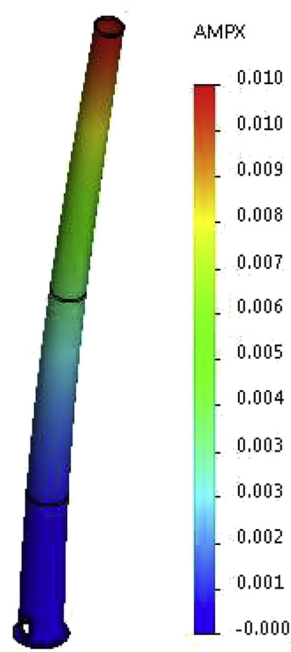
Mode number	Natural Frequencies	Mass participation ratio (Percentage)		
		X	Y	Z
1	1.297	0.000	0.000	46.925
2	1.297	46.921	0.000	0.000
3	5.840	20.406	0.000	0.000
4	5.844	0.013	0.000	20.322
5	11.014	0.000	0.000	0.000
6	11.038	0.000	0.000	0.000
7	12.787	0.000	0.000	0.000
8	12.810	0.000	0.000	0.000
9	14.599	9.777	0.000	0.000
10	14.637	0.007	0.000	9.619



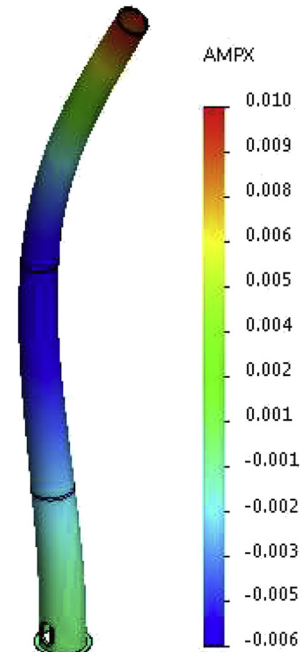
Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude21
Mode Shape : 1 Value = 1.2974 Hz
Deformation scale: 527.555



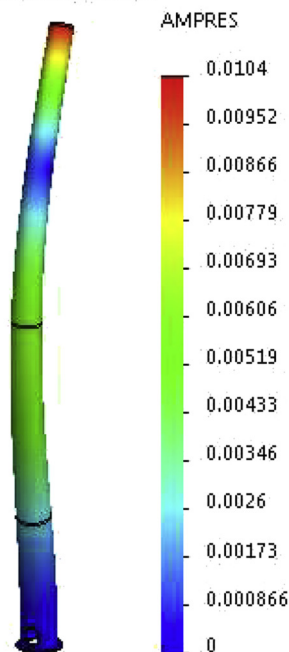
Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude22
Mode Shape : 2 Value = 1.2978 Hz
Deformation scale: 527.509



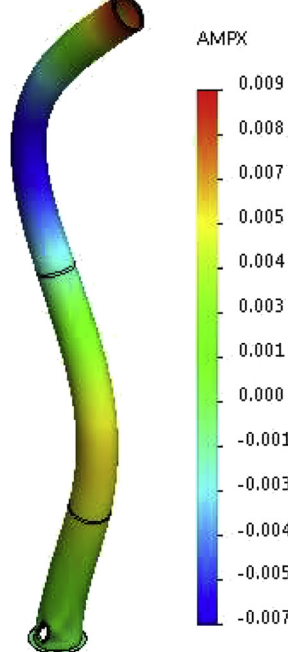
Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude23
Mode Shape : 3 Value = 5.8409 Hz
Deformation scale: 528.873



Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude4
Mode Shape : 4 Value = 5.8442 Hz
Deformation scale: 528.706



Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude24
Mode Shape : 9 Value = 14.599 Hz
Deformation scale: 584.404



Model name: Tower Structure Modelling
Study name: Modal Analysis(-Default-)
Plot type: Frequency Amplitude10
Mode Shape : 10 Value = 14.637 Hz
Deformation scale: 588.923

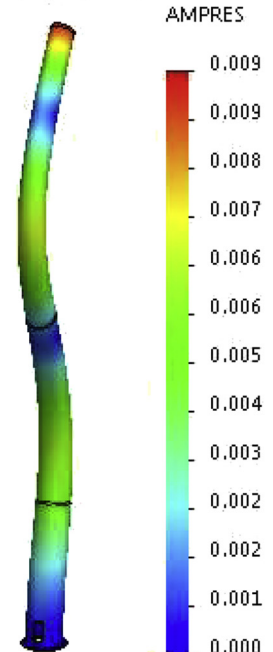


Fig. 6. The mode shapes for mode 1, 2, 3, 4, 9 and 10th respectively (from left to right). These modes have the highest mass participation ratio

the 2nd and 3rd modes are bending deformation along the Z-direction in phase or in phase opposition in the XY plane, and the 5th and 6th modes are torsional around the Y-axis.

This is in good agreement with the fundamental vibration theory of Euler-Bernoulli beam with lumped masses in bending vibration modes [50].

The first 10 sorted natural frequencies for tower structure and their corresponding mode shapes are tabulated in Table 2. As shown, the first 10th lowest natural frequencies of the tower structure are ranging from 1.297 to 14.636 Hz and it is distributed evenly on each order. The natural frequency of 1st and 2nd, 3rd and 4th, 5th and 6th, 8th and 9th are close to each other, respectively. That is because the tower structure is with the axial-symmetrical structure, so the vibration mode shape is also symmetrical, which is consistent with the mechanical structure.

The rotor speed of the wind turbine studied (GAMESA G52/850KW) in this paper lies between 14.6 and 30.8 rpm [38]. This means that the corresponding rotational frequency ($n = f \times 60$) lies between 0.243 and 0.513 Hz, and the blade passing frequency between ($n = f \times 20$) 0.729 and 1.539 Hz. According to [32, 36] in the wind turbine industry, a $\pm 1\%$ safety distance should be considered to avoid resonance problem. So, the admissible range of frequencies lies between 0.267 and 1.308 Hz for the rotor speed of 14.6–30.8 rpm. Obviously, the 1st natural frequency of the tower is 1.297 (Table 2), so the corresponding rotor speed is 29.5 rpm. Which indicates when the rotor of the wind turbine runs at the speed of less than or equal to 25.9 rpm it will not have resonant problems and the tower is a stiff–stiff tower design. Furthermore, when the rotor runs at the speed above 25.9 rpm (up to 30.8 rpm), the 1st natural frequency is not close to the corresponding 1P and 3P (the resonance problem does happen in the tower structure) and the tower is a soft–stiff tower design. However, the adequate controller is necessary in order to avoid the corresponding resonant susceptible area of the tower structure.

4.2. Mass participation ratio

The mass participation ratio (MPR) represents a modal contribution for a specific mode and DoF in structures when subjected to force excitation. The MPR is the percentage of the part of structure mass in a specific direction to the total mass without considering stiffness. The MPRs are given by [51, 52]:

$$X_{\text{mass}} = \frac{\sum_{n=1}^N p_{nx}^2}{\sum m_x} \quad Y_{\text{mass}} = \frac{\sum_{n=1}^N p_{ny}^2}{\sum m_y} \quad Z_{\text{mass}} = \frac{\sum_{n=1}^N p_{nz}^2}{\sum m_z} \quad (4)$$

where X , Y and Z are the principal directions of the structure, N is the number of the modes, m_x , m_y and m_z is the mass in its direction and p is the vibration mode taken under consideration. Several FE Codes require that a minimum 90 percent of the total structure mass in the calculation of response for each principal direction of the participating mass can be considered enough to capture the dominant dynamic response of the structure [9, 53]. In this study, it would require the calculation of 50 modes to obtain the 90% mass participation.

In order to facilitate visualization, only the MPRs for the first 10 modes found in the structure are presented in Fig. 5 and Table 3, the modes with highest MPR in each direction are shown in bold face. These modes are presented in Fig. 6.

It can be seen in Table 3, that many modes have little or no mass participation. When the MPRs of 1st, 4th, and 10th modes are considered, it appears that the Z-directions are most critical, the tower structure shows total bending along Z-direction under dynamic load. In the case of 2nd, 3rd, and 9th modes, the tower structure shows total bending along X-direction and in all the modes although the Y-direction values seem zero. The dominant behavior of the tower structure is bending.

5. CONCLUSION

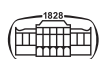
In this present work, the modal behavior of the full-scale actual 55-m-high steel tower of 850 KW wind turbine (GAMESA G52/850) was investigated under the action of wind. A 3D FE model to perform numerical analysis using SolidWorks Simulation computational program. Initially, the vibration of the tower structure was studied to calculate the natural frequencies and their corresponding modes shapes of the structure. There was a very good agreement with the fundamental vibration theory of Euler-Bernoulli beam with lumped masses in bending vibration modes. In the case when the rotor of the wind turbine runs at a speed of less than or equal to 25.9 rpm it will not have resonant problems and the tower is a stiff–stiff tower design. Furthermore, in the case when the rotor runs at the speed of between 25.9 and 30.8 rpm, the adequate controller is necessary in order to avoid the corresponding resonant susceptible area of the tower structure, as the first natural frequency is not close to the corresponding 1P and 3P and the tower is a soft–stiff tower design. Future research work and investigation will be based on the development of buckling and fatigue (service life of the system) analyses.

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