NUMERICAL INVESTIGATION ON STATIC AND BUCKLING BEHAVIOURS OF A MAST SUPPORT FOR H-ROTOR DARRIEUS TURBINE UNDER EXTERNAL LOADING

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The mast support for small vertical axis wind turbine is considered an important parameter during the design process of wind turbine structure. It has been receiving a great attention by researchers and academics. This study presents a numerical investigation on the static and buckling strength behaviors of whole wind turbine mast structure by means Finite Element Analysis (FEA) technique. The FEA simulations are performed in order to evaluate the reliability and the strength of the mast structure under the extreme wind conditions (IEC 61400-2 and Eurocode 1991-1-4 standards) and gravity loads. The simulation results show that the mast structure will not undergo structural failure because the maximum stress induced is less than the yield strength of the material and the maximum displacement is within material allowable deformation limit. In addition, the buckling strength of the structure meets requirement of design.

Keywords: buckling, H-rotor Darrieus, numerical simulation, static, wind turbine mast.

1. Introduction

In recent years, due to the increasing conscience for the necessity of a renewable energy source, wind power is important player in the global energy market. According to the BP Statistical Review of World Energy report from 2019, wind power is second fastest growing source with the global installed capacity more than 591 GW at the end of 2018 (an increase of 9% to 2017) [1]. The complexity of the wind turbine structure and the effect of the environment have caused of a number of serious accidents that have collapsed or damaged wind turbine [2]. Most wind turbine collapses is often caused by blade failure or steel tower (structural failure) [3]. The literature contains many research papers available on blade failures containing experimental tests or numerical simulations [4–9].

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Wind turbine tower or mast structures is essential structural element in wind turbine systems which represent about 20-30% of the total cost of the typical wind turbine project and it transfers wind loading from rotor (thrust force) and self-weight load of whole turbine structure to the foundation. Therefore, the mast structure has been receiving a great attention by researchers and academics [10].

Wind turbine towers can be constructed in several structural versions tubular (cylindrical cross section) or conic steel structures, lattice (or truss) masts, concrete masts, and guyed masts. The use of steel tubular tower (free standing) in wind turbine structures provides many benefits relating to economical, mechanical behavior, constructability (simple field assembly) and low maintenance [11,12]. Tubular mast structure adopts cylindrical shell structure, this type of structure is apt to be collapsed or damaged by high wind, steel fatigue due to vibration and partial or whole buckling (instability). Therefore, the analysis for safety design in particular buckling behavior is important information for preventing the collapse of the mast [2, 13].

The buckling behavior for towers has investigated by few research papers. Dimopoulos and Gantes [14] investigated a numerical analysis and experimental of buckling response of the tower structure with stiffening rings and a door opening under bending. Adhikari et al. [15] presented a design procedure for tubular lattice towers (tripods or quadrapods) for small wind turbines, by means of analytic approximations. Alonso-Martinez et al. [2] analyzed the col-lapse of a whole wind turbine tower due to flange failure, by means numerical simulations and design of experiments analysis. According to a review existing works (experimental and analytical), there are several fields worthy of further research on the buckling behavior of wind turbine towers [11].

The purpose of this research paper is to evaluate the static and buckling strength behaviors of the whole mast support for vertical axis wind turbine, subjected to the extreme wind conditions (IEC 61400-2 and Eurocode 1991-1-4 standards) and gravity loadings by using the commercially available finite element code SOLIDWORKS Simulation [16]. Results from the finite element analyses are presented. This paper is organized as follows: the description of the mast support structure is presented in Section 2. In Section 3, we define the external loads characteristics, which are used in the finite element analysis, the finite element development model; in Section 4, the numerical simulation results (static and buckling behaviors) are dis-cussed. Finally, the main concluding remarks are summarized in the last section.

2. Mast structure description

This paper describes the 3D modelling of a mast structure that supports a 10-kW H-rotor Darrieus turbine [17]. The mast structure is a freestanding tube steel structure and is fully fixed at the bottom (joined to a soil-foundation). It is manufactured in one hollow section (cylindrical). Its height (H), outer diameter (constant) and thickness (uniform along the mast height) are 14m, 1m and 14mm respectively. The full-scale CAD model of the mast was performed by means of the SOLIDWORKS software, as seen in Fig. 1.

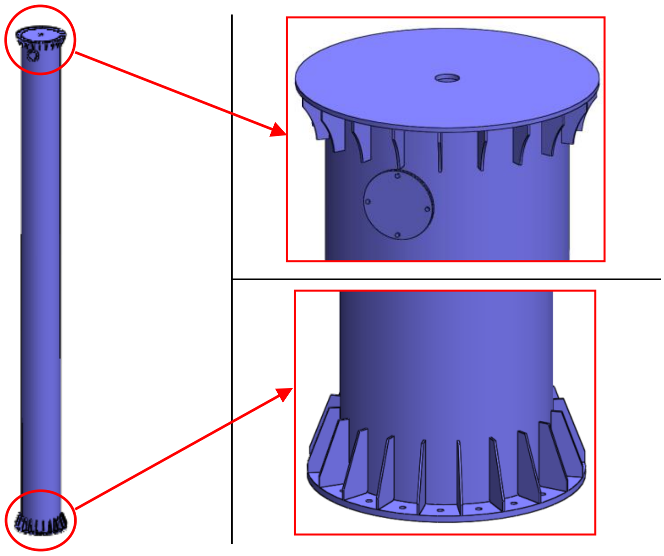


Fig. 1. CAD model of mast support

3. Computer-aided simulation

This study focuses on the static (stress) and buckling analysis of the mast structure. The SOLIDWORKS Simulation software is used since finite element solutions of this software are very effective. The FEA is a key, indispensable technology in various engineering fields. For ensuring the fiability and reliability of the finished product and cost effectiveness, design engineers go through a sophisticated procedure of modelling, simulation, visualization, analysis, design, prototyping, testing, and finally, manufacture [18,19]. The procedure of FEA consists of the following four steps: modeling of the model (geometry), meshing, specification of material properties and specification of boundary conditions [20].

3.1. Loadings

During different phases of wind turbine operation, three main types of static loads acting on a mast structure: the first is load acting on the top of the mast, which mainly created from the aerodynamic rotor thrust. The second is wind load acting on the mast body and the third load is the forces due to the weight (gravity) of the mast head (rotor and generator) and own weight of the mast. Our wind turbine will install at Melouka site in Adrar city located in the south-west of Algeria. The reference wind velocity (10-min average of extreme wind speed with a 50-year return period) equals to 28 m/s (Wind Zone II) [21]. According to the Eurocode 1991-1-4 [22] and IEC 61400-2 [23], the extreme wind velocity $V_{e50}(z)$, the static wind load pressure $P_{W,j}$ are distributed along the mast structure and the thrust load (F_{thrust}) [24] are defined by the formats (1), (2) and (3), respectively:

$$V_{e50}(z) = 1.4\,.\,V_{ref}\left(\frac{z}{z_{hub}}\right)^{0.11} \tag{1}$$

$$P_{W,j} = \frac{1}{2}C_e(z_j).\,C_{f,j}.\,C_s C_d.\,\rho_{air}.\,[V_{e50}(z)]^2 \quad j = 1, \ldots 14. \tag{2}$$

$$F_{thrust} = \frac{1}{2}C_T.\,\rho_{air}.\,A_{rotor}.\,V_{e50}^2 \tag{3}$$

Where z is the height above ground level and z_{hub} is the hub height, ρ_{air} is the density of air (1.225 kg/m³), $C_s\,C_d = 1$ is the structural coefficient, $C_{f,j}$ is the force coefficient for the segment j, $C_e(z_j)$ is the exposure factor at height z, A is the swept area by the rotor (68 m²) and C_T is the thrust coefficient of the rotor equals to 0.75. After the calculation, the values of the extreme wind pressure and velocity acting on each segment (FE model is divided into 14 segments) are presented in Table 1. The thrust load equal to $F_{thrust} = 51.693\,kN$ and the gravity load of rotor with generator is $F_{rotor+generator} = 18\,kN$ (the weight of generator and rotor are equal to 0.8 and 1t, respectively) and self-weight of the mast is 51.712 kN.

3.2. Element type, mesh size and boundary conditions

The mast structure model is simulated in SOLIDWORKS Simulation using 125.106 three-dimensional solid elements, 247.507 nodes and roughly 739.299 degrees of freedom (DoF). The element is a second-order (high quality) tetrahedral element, which is defined by ten nodes. The global size of the selected mesh (with an element size of Min-55.296 mm and Max-279.483 mm) is also enough to satisfy the precision needed in the analysis. Due to the large number of DOF's, the FFEPlus solver (iterative) is used for the numerical FEA solution [25, 26]. As for the boundary conditions on the mast model were applied as follows: The bottom section of the mast is specified as fixed all translation (zero displacements) and rotation and the top is specified as free to move. The applied boundary conditions and the mesh of FE mast model is shown in Fig. 2.

3.3. Material properties

The material chosen for the FEA model used in this study is steel (AINS 1020 Steel, cold rolled). Its nominal properties are as follows: Young's modulus (E) equal to 205, 000 MPa, yield stress (f_y) equal to 350 MPa, density (ρ) equal to 7870 kg/m^3 and Poisson's ratio (ν) equal to 0.29.

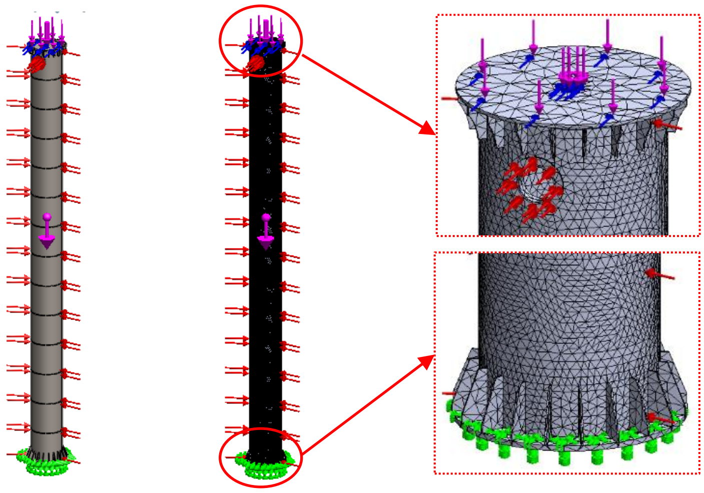


Fig. 2. Loads, boundary condition and the mesh for mast structure. Red, blue, pink and green areas represent the wind load pressure, thrust, gravity loadings and respectively and green area fixed restraint.

Table 1

Extreme wind velocity and pressure along mast height

H (m)	$V_{e50}(m/s)$	$P\ (N/m^2)$
1	30.43	1614
2	32.84	2716
3	34.34	3378
4	35.44	3935
5	36.22	4443
6	37.06	4892
7	37.69	5325
8	38.25	5729
9	38.75	6111
10	39.20	6489
11	39.61	6857
12	39.99	7218
13	40.35	7559
14	40.68	7908

4. Results and Discussion

4.1. Static analysis

The main objective of the static analysis is to ensure that the mast structure can withstand the external static loads encountered during the operation of the wind turbine without excessive deformation. Static FEA simulation is carried out in order to determine the locations of the maximum stresses (von-Mises yield criterion) and displacements of the mast structure [27]. The contour plots of von-Mises stresses (N/m²), displacements (mm), strains and factor of safety (FoS) are shown in Fig. 3.

The maximum von-Mises stress value (Fig 3a) equals 271.8 MPa and appears in the vicinity of the mast bottom (base). This value is less than yield strength of mast material (350MPa). The maximum displacement (Fig. 3b) is 74.4 mm and occurs at the mast top. This value ($0.5\% << H/100$) is acceptable according to Code for Design of high-rising structures, the maximum displacement is limited to $H/100$ [15, 28].The maximum strain (Fig. 3c) is 7.58e-04, which is quite small (negligible) and indicates that the mast structure did not suffer permanent plastic deformation ($\varepsilon << 1$).

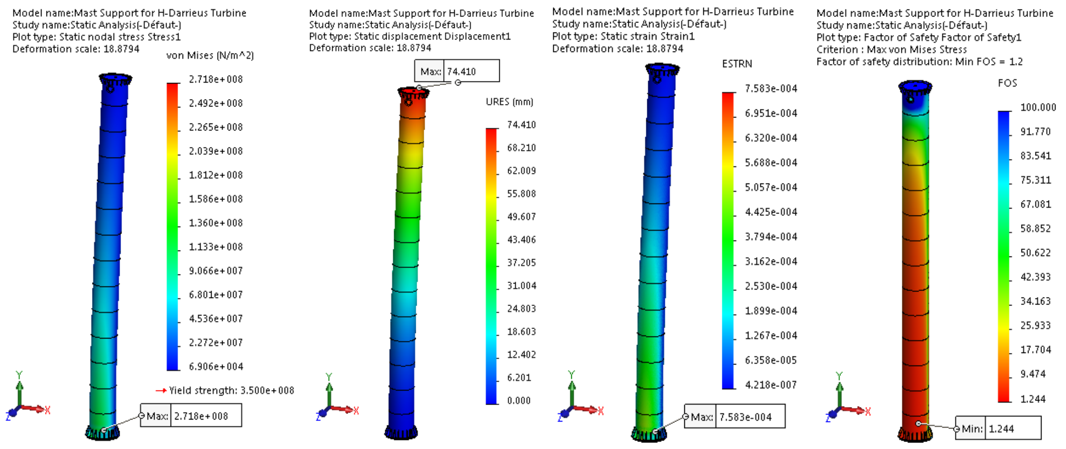
Based on simulation results, it can be concluded that the mast structure will not undergo structural failure (safe) during wind turbine operation because the minimum value factor of safety (formula 4) is 1.2 (Fig. 3d), which to mean that the mast material is always below yield strength value.

$$FoS_{yield} = \frac{yield\ strength}{max\ vonMises\ stress} \tag{4}$$

As is always the case with elastic structure, the FoS related to yield strength of the material may not be sufficient to describe the safety of the mast support. This is because of the phenomenon of buckling (instability) may possible occur and thus, it requires to perform a buckling analysis for calculating the FoS related to buckling.

4.2. Buckling analysis

Linear buckling (instability) or Eigenvalue buckling analysis of the structural system (without accounting for nonlinearities) subjected to static load is generally carried out to estimate the critical bifurcation load of stiff structures [29, 30]. The buckling analysis by using FEM is an eigenvalue (buckling load factor) problem with many solutions for eigenvalues and corresponding eigenvectors (buckling mode or mode shape), so the eigenvalue equation can be formulated by the following equation [31, 32]:



(a) (b) (c) (d)

Fig. 3. Static simulation results of the mast structure; (a) von Mises stress, (b) displacements, (c) strains and (d) factor of safety

$$([K] + \lambda_m [S])\{\psi\}_m = \{0\} \tag{5}$$

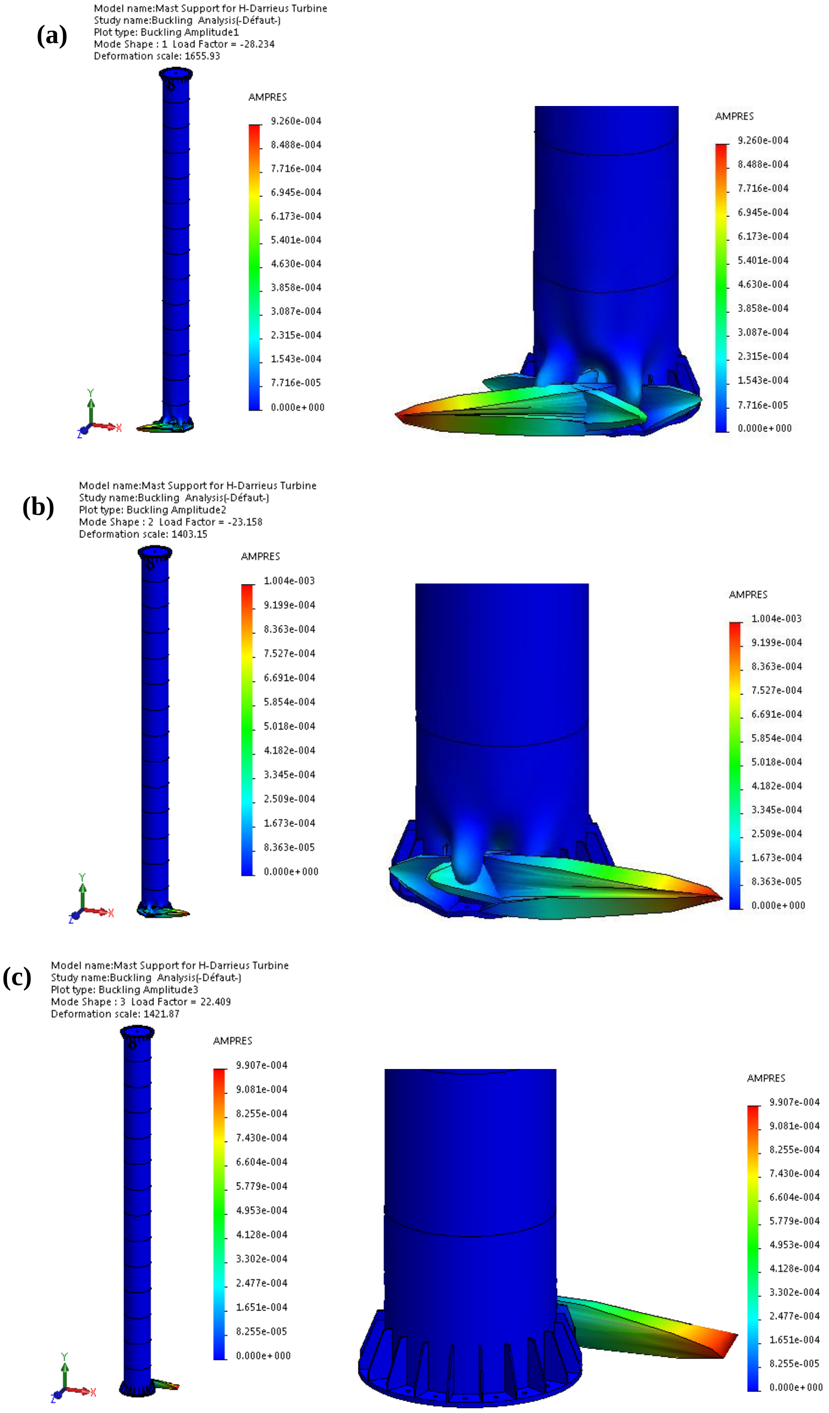
where $[K]$ is stiffness matrix, λ_m is the buckling load factor (BLF) for the m-th for buckling mode, $[S]$ is stress stiffness matrix and $\{\psi\}_m$ is the m-th eigenvector of displacement shape.

In elastic buckling, only the lowest (first) mode is usually useful by the designers because, which is associated with the lowest critical load and there is not any practical importance about the higher modes [33]. SOLIDWORKS Simulation software calculates the BLF for each buckling mode, which is an indicator of the FoS against buckling or ratio of the critical buckling loads to the currently applied loads [34, 11].

$$BLF = \frac{Buckling\ Load}{Applied\ Load} \tag{6}$$

The BLF can have negative or positive value. The load direction must be reversed if its value negative. Due to the buckling of the mast often cause to bad results (significant economical and physical loss) if it occurs, it must utilize a high BLF (at least >2) for critical buckling loads.

The first fourth buckling modes of the structure are shown in Fig. 4. It will be remarked that the buckling instability of the mast structure model is local buckling waves. They occur mainly on the down of the model, near the bottom. The mast structure has both negative and positive BLFs. The BLF for the 1st and 2nd buckling modes is -28.234 and -23.158 (Fig. 4a and Fig. 4b), respectively, and thus, it must be reversed all loads direction. Therefore, the first real BLF is 3rd buckling mode ($BLF = 22.409$), which is higher than 1, meaning that the mast structure will not buckle under the currently applied load.



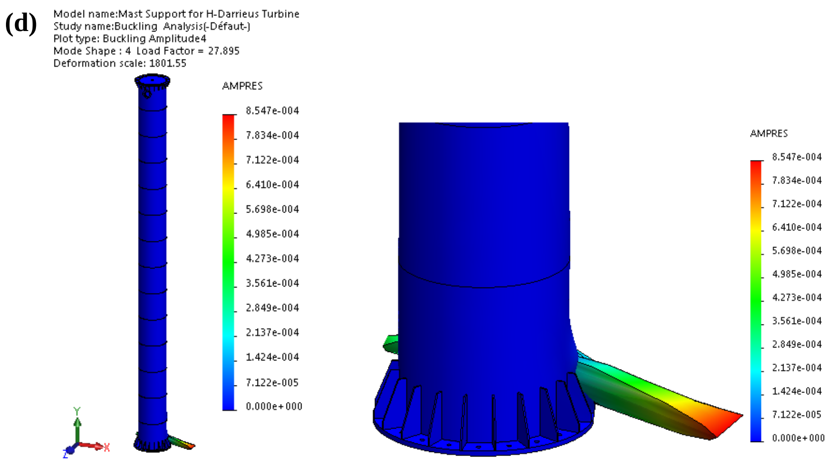


Fig. 4. The fourth buckling modes of the mast structure; (a) first mode, (b) second mode, (c) third mode

Table 2 presents the BLFs and critical buckling loads for the fourth first mode of the mast model. Through calculation (Table 2), Buckling in the 3rd mode (first real BLF) will occur if we apply: a force of 112 kN on face–top of the mast (y direction) and a pressure of 1562 kN/m² on face-along of the mast (Z direction). Therefore, results simulation show that buckling strength of mast structure meets requirement of design.

Table 2

BFS and Critical buckling loads for the fourth first mode of the mast

Mode N°	BLF	Critical buckling loads	
		Face – along the mast	Face- upper part of the mast
1	-28.234	141 kN/m²	1967 kN
2	-23.158	116 kN/m²	1614 kN
3	**22.409**	**112 kN/m²**	**1562 kN**
4	27.895	140 kN/m²	1944 kN

5. Conclusions

This study has investigated the static and buckling behaviours of the mast support for H-rotor Darrieus turbine (with 10 kW rated power). Mast structure model is performed by means of the SOLIDWORKS software. Finally, FEA simulations are conducted to analyse the strength of the mast and evaluate its buckling under the extreme wind conditions and gravity loadings (IEC 61400-2 and Eurocode 1991-1-4 standards). The following main conclusions obtained from simulation results are outlined below:

- The mast structure will not fail during wind turbine operation under external static loads. According to maximum stress, which is lower than the yield strength of the material (minimum factor of safety equals 1.2) and the maximum displacement is within materials allowable deformation limit.
- Buckling instability of the structure model is local buckling waves. They occur mainly on the down of the model which next to bottom.
- According to the first real buckling load factor ($BLF = 22.409$), the mast structure will not buckle under the currently applied load.
- The mast structure will buckled if we apply: a force of 112 kN on face–top of the mast (y direction) and a pressure of 1562 kN/m² on face-along of the mast (Z direction).

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