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ORIGINAL RESEARCH ARTICLE

NUMERICAL ANALYSIS OF A MICRO HORIZONTAL AXIS WIND TURBINE TOWER UNDER EXTREME LOADS

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ABSTRACT

One of the major challenges in the development of horizontal axis wind turbine is the selection of appropriate and cost effective tower that will elevate the rotor meters above the ground for wind energy harvest. In this work a tubular structural steel material having an external diameter of 0.1 m, internal diameter of 0.092 m and height of 10 m was selected based on cost, mechanical properties and market availability for the tower. Response of this tower material due to simultaneously applied extreme static, dynamic and aerodynamic loading conditions was analyzed in terms of frequency of vibration, deformation and stress using the numerical code COMSOL Multi-physics 5.2. Three dimensional model of the structural steel tower was developed and boundary conditions defined in the numerical code's model wizard interface. The tower was considered as a cantilever and a static load of 2128.77 N was applied at 10 m height in the y plane. Dynamic load of 413.96 N was applied on the tower in the x,y,z planes and an aerodynamic load of 4967.58 N was applied as uniformly distributed loads in the x plane. Extra fine regular quadrilateral mesh was generated for the computation. Frequency response result of the transfer function at 110 GHz excitation shown in terms of electric field norm was uniformly distributed at the outer boundary layer of the tower with a minimum value of 3.7×10^{-79} V/m. The result of the deformation analysis under the predefined extreme loading conditions shows a maximum deflection value of 197 mm at 10 m height and 0 mm at 0 m height of the tower. Additionally, the stress analysis result shows a predicted maximum value 3.28×10^{6} N/m^2 between 0 m and 1.98 m height of the tower in the wind direction. The deformation was within the elastic limit of the tower material, because the total exerted extreme loads without the self-weight of the tower (2,397.54 N) was less than the determined safe load of the tower (7,107.96 N). The study has established that the selected horizontal axis wind turbine (HAWT) tower material was reliable under the predefined simultaneously applied extreme loads, thus the structural steel tower can function in areas this or similar loading conditions.

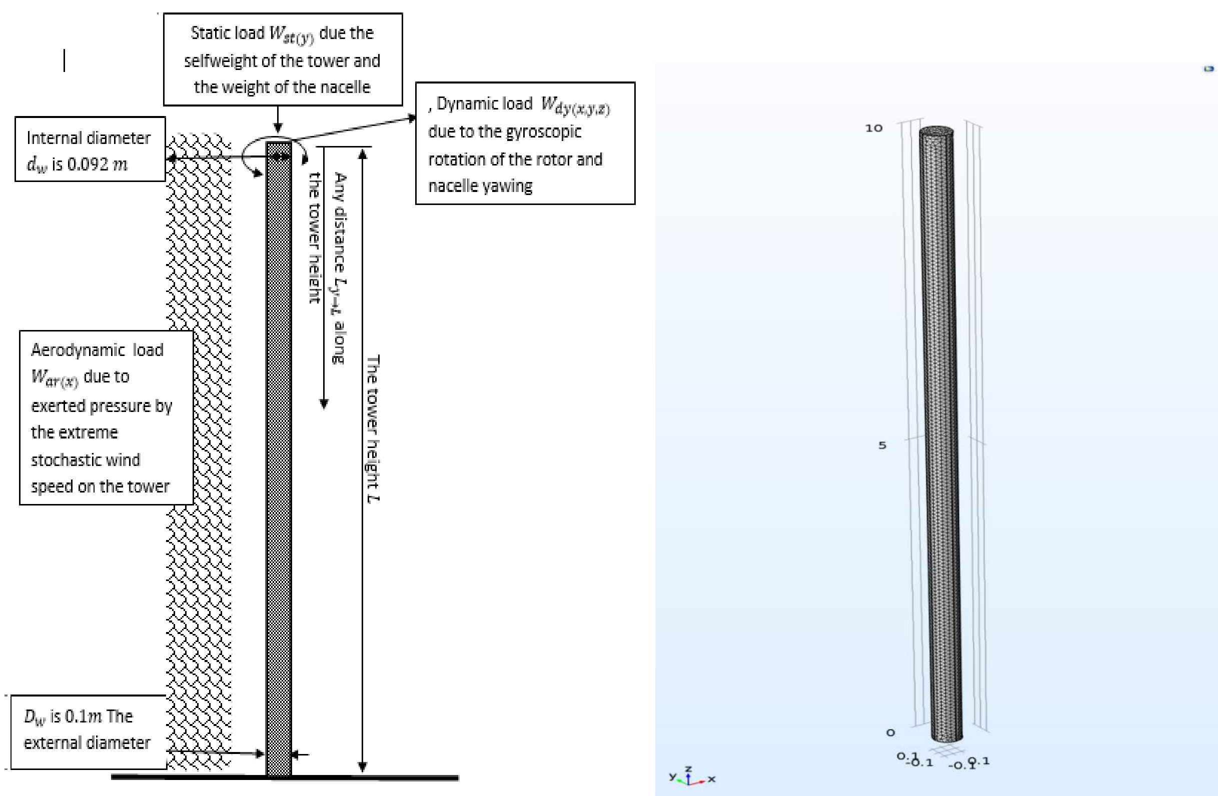
1.0 Introduction

Horizontal Axis Wind Turbine (HAWT) is the most common type of wind turbines used for harvesting some of the kinetic energy possessed by wind and it is a type of wind turbine that has wind flowing along the axis of rotation of its rotor (Ngala et al., 2015). The main components of HAWT (examples are rotor, drive train components, control and yawing mechanism) are supported by a tower. The HAWT tower also elevates the rotating blades at a certain elevation to obtain desirable wind characteristics. There are three types of tower commonly used for micro horizontal axis wind turbines; Free-standing lattice (truss), Cantilevered pipe (tubular tower) and Guyed lattice or pole. Generally micro HAWT towers are produce from reinforced concrete, steel or composites material, the steel material is the most popular choice because of its strength and low cost (Shuwa et al, 2016; Da Silva and Oliveira, 2018). The height of a HAWT tower is very important in assessing turbine performance since wind speed increases with height and performance of the turbine depends on wind speed magnitude. In performing this task erected towers are subjected to loads that are transferred from rotor operations, wind pressure, the weight of the nacelle and that of the tower itself (Biswajit, 2010; Gizachew and Belete, 2019). However, wind loads are dominant in most cases and if not properly addressed may result in excessive deformations which, in turn can cause significant damage, or even collapse of the wind turbine. For optimal tower design that will withstand these loads, a numerical optimization model is inevitable, because it deals with simulation of the design variables, searches for optimal solutions and less expensive than experimental analysis (Adhikari and Bhattacharya, 2012; Umesh, 2016). A numerical model is defined by a mesh network, which is made up of the geometric arrangement of elements and nodes. Nodes represent points at which features such as displacements, stress are calculated. The numerical packages use node numbers to serve as an identification tool in viewing solutions in structures such as deformation or deflection, stress and strain caused by applied structural and aerodynamic loads (Strivridou et al., 2015; Ferroudji, 2021).

Literatures on the study of dynamic interaction of wind turbine components with regard to the structural design of the tower with the interaction of the mechanical rotor system is ongoing (Karpat, 2013; Wagner and Mathur, 2018; Gizachew and Belete, 2019). The motion of a HAWT tower is strongly connected to the motion of the blades, as the blades transfer an axial force onto the low speed drive shaft which is ultimately transferred into the nacelle base plate at the top of the tower (Wagner and Mathur, 2018). The free vibration properties of a tower carrying a rigid nacelle mass at the top may be evaluated by techniques such as the discrete parameter method, the finite element method or by using closed form solutions (Kandil et al., 2016; Da Silva and Oliveira, 2018). The discrete parameter method was used to study the behavior of transmission towers under the action of stochastic wind loading. Researchers have used this technique to assess the accuracy and reliability of more computationally expensive finite element analyses of wind turbine tower (Da Silva and Oliveira, 2018; Ferroudji et al., 2020). Recent studies using the finite element (numerical) technique for free vibration analyses of structures in wind engineering have derived expressions in closed form to yield the eigenvalues and eigenvectors of a tower-nacelle system comprising of a prismatic cantilever beam with a rigid mass at its free end (Guoyang and Song, 2016; Saihi and Roummani, 2020; Ferroudji, 2021). In this work a tubular structural steel tower was selected based on cost, mechanical properties and local availability. The resistance and stability of the selected tower to extreme operational loading conditions was analyzed. The aim was to identify if the selected micro HAWT tower structure will function optimally with minimal or no risk of failure in regions associated with stochastic high wind speeds like the semi-arid region of Nigeria.

2. Materials and Methods

A tubular structural steel pipe of uniform cross-section with an external diameter *D* of 0.1 m, internal diameter *d* of 0.092 m, wall thickness *t* of 0.008 m and height $L_{y\text{-}L}$ from 0 m to 10 m was selected for analysis. The selection was based on local availability, strength and cost of the material. The material has Young's Modulus E_{tw} of 2 x 10^{11} N/m^2, Poisson's ratio *n* of 0.33 and density ρ_{tw} of 7850 kg/m^3 (David, 2005). COMSOL Multi-physics 5.5 numerical code was used to predict the behavior of the HAWT tower model under defined loading conditions based on the assumptions of Euler-Bernoulli's beam theory, geometry and material of the tower. Electromagnetic wave interface was used to solve for time harmonic electromagnetic field distribution of the tower model under load. Frequency response of the tower structure with respect to static, dynamic and aerodynamic loadings were predicted using the frequency domain interface at an excitation frequency of 110 GHz. Solid mechanics in COMSOL Multi-physics numerical code was also used to compute and analyze deflection or displacement and stress distribution on the tower due to simultaneously applied static, dynamic and aerodynamic loads. The selected structural steel tower geometry was created using the 3D model wizard of COMSOL Multi-physics numerical code 5.5. The predefined geometrical parameters such as internal diameter, external diameter and height were defined to build the tower in the numerical code's graphical window. Tower material properties were also selected and defined from the numerical code's material data base as structural steel. The tower is modeled and analyzed as a vertical cantilever beam under static, dynamic and uniformly distributed aerodynamic loads. Boundary conditions were applied on load application condition, with top of the tower considered as a free end and the bottom as fixed. A static load (David, 2005) due to self-weight of the tower and weight of the nacelle was applied at the top of tower in the *y* plane. Dynamic load (David, 2005) due to gyroscopic rotation of the rotor was applied at the top of the tower in the *x, y, z* planes and aerodynamic load due extreme stochastic wind speed pressure was applied as uniformly distributed loads in the x plane along the height of the tower as shown in Figure 1a. A regular quadrilateral mesh generation method was used as in Figure 1b to generate extra fine mesh for the computation.



(a) (b)

Figure 1: (a) Loads on the HAWT tower and (b) the generated grid.

The generated mesh has 29,725 quadrilateral elements and 1036 nodes with each node having 4 degrees of freedom. Using these nodes as identification tool solutions to the tower deflection, stress distribution, stiffness, natural modes of vibration in terms of corresponding frequencies due to the predefined loading conditions were obtained. In this analysis three defined loading condition are considered acting on the tower simultaneously. Static load $W_{st(y,)}$ due to the self-weight of the tower and the weight of the nacelle given by Equation 1, dynamic load $W_{dy(x,y,z)}$ due to the gyroscopic rotation of the rotor and nacelle yawing given by Equation 2 and aerodynamic load $W_{ar(x)}$ due to extreme stochastic wind pressure on the tower given by Equation 3 (Biswajit, 2010; Umesh, 2016).

$$W_{st(y)} = g(m_{tw} + m_{nl}) \tag{1}$$

Where m_{nl} is 42 kg the mass of the nacelle, m_{tw} is 175 kg the mass of the structural steel tower and g is 9.81 m/s^2 acceleration due to gravity.

$$W_{dy(x,y,z)} = \sqrt{[0.5\rho_a v^2 C L_b (C_L + C_D)]^2 + [F_{yw} + r_y]^2} \tag{2}$$

$$W_{ar(x)} = 0.5\rho_a \lim_{l \to L} L\left(v^2 \varphi D_r C_f\right) \tag{3}$$

Where density of air ρ_a is 1.225 kg/m^3, v is 18.75 m/s (NIMET, 2017) the stochastic wind velocity considered for this work. The maximum blade chord length C of the HAWT is 0.26 m, L_b is 1.5 m the blade span, F_{yw} is nacelle thrust, r_y is 1.8 m the nacelle radius of gyration, C_L and C_D are 1.157 and 0.0122 the lift and drag coefficient of the blade respectively. The rotor diameter D_r of the HAWT considered for this work is 3 m. While φ is the gust factor and the form factor C_f is 0.6 for steel towers (Gizachew and Belete, 2019). In defining the boundary condition maximum calculated static load of 2128.77 N due tower self-weight and weight of the nacelle was applied to free end of the tower. While determined aerodynamic load of 1655.86 N and dynamic load of 413.96 N were applied on the top upwind vertical face and along the height of the tower. These loads are applied simultaneously on the discretized elements of the tower model and are the cause of tower vibration, deformation and stresses in the tower. The tower's vibration frequency, stiffness, deformation and stress distribution are predicted from Equations 4, 5, 6 and 7 respectively (Biswajit, 2010; Kandil et al., 2016; Ferroudji, 2021).

$$f_n = \frac{\pi}{4}\left(N_n + \frac{1}{2}\right)^2 \sqrt{\frac{g E_{tw} I_{tw}}{W_{tw}\, L_{y\to L}^4}} \tag{4}$$

Where N_n is the mode number i.e. 1,2,3, 4… n, W_{tw} is the weight of the tower determined as 1716.75 N (175 kg x 9,81m/s)

$$k_{tw} = \frac{3E_{tw} I_{tw}}{L_{y\to L}^3} \tag{5}$$

$$\delta_{max} = \frac{3\left[W_{st(y)} + W_{dy(x,y,z)} + W_{ar(x)}\right] L_{y\to L}^2}{E_{tw} I_{tw}} \tag{6}$$

$$\sigma_{tw} = \frac{4\left(C_{efc} E_{tw} k_{rg} \pi\right)}{\left(D_{tw}^2 - d_{tw}^2\right) L_{y\to L}} \tag{7}$$

Where E_{tw} is 2 x 10^{11} N/m^2 Young Modulus of the tower material, I_{tw} is 6.174 x 10^{-4} m^4 the moment of inertia of the tower. The end fixity coefficient C_{efc} is 0.25 for a beam with one end fixed and the other free (Khurmi and Gupta, 2005).

The tower was considered and analyzed as a cantilever with one end fixed and the other free and the objective functions were solved using solid mechanics elasticity equations (Equation 4, 5, 6 and 7) based on Euler-Bernoulli's beam theory. These equations were solved at each of the 29,725 quadrilateral created elements to determine deformation (deflection), stiffness, vibration frequency and stress distribution along the tower geometry under the predefined loading conditions . The transfer function was predicted at 110 GHz excitation frequency (the maximum excitation frequency predicted by the numerical code) in terms of electric field norm under the loading conditions at an average rotor speed of 40 rpm. The predicted results were post processed and validated with experimental results using the F-Test statistical tool.

3. Results and Discussion

The meshed HAWT tower model was first solved in a frequency domain interface for time-harmonic electromagnetic field distributions. Figure 2 shows frequency response of the tower model under applied extreme static, dynamic and aerodynamic load distribution excited up to 110 GHz. The frequency response of the transfer function in terms of electric field norm was uniformly distributed at the out surface boundary layer of the tower with a minimum value of 3.7 x 10^{-79} V/m. However, this value increases inwards along the thickness of the tower at the transfer ports and there exist a similarity in the transfer function from port one (tower root) to port two (top of the tower). This result shows stability in the tower structure and that failure could be avoided. In an investigation carried out by Ferroudji (2021) on a 55 m high steel wind turbine tower reveal that the natural frequencies of the tower under load correspond to the mode shapes and mass participation ratio values. This shows that resonance in the tower structure was uniform and failure could be avoided under the action of high wind speeds

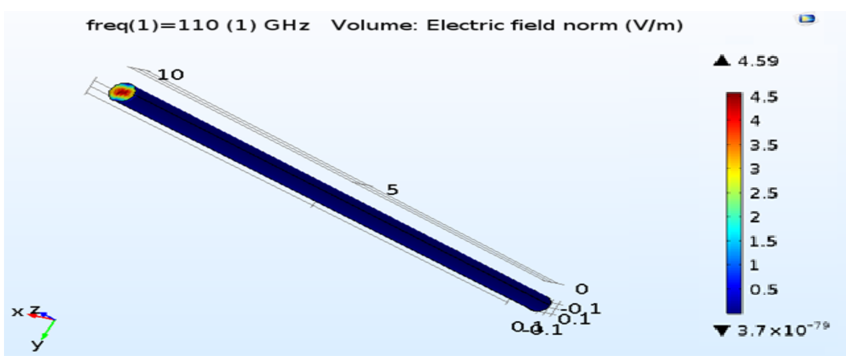


Figure 2. Frequency response of the transfer function in terms of electric field norm at 110 GHz excitation.

The result of the deformation of the tower under the predefined loading conditions shows a maximum deflection of 197 mm at the top and minimum of 0 mm at the root of the tower as shown in Figure 3. The result shows that the tower was stable under the predefined simultaneously applied loads, thus the structural steel tower can function under the defined loading conditions and the deformation is within the elastic limit of the tower material. This was because the total exerted load without the self-weight of the tower 2,397.54 *N* was less than the calculated safe load 7,107.96 *N* of the tower. According to Mandal et al. (2018) the stability of a wind turbine tower is a function of geometry and design and it is important to the functioning of the wind turbine. To achieve the functioning of the tower, the exerted load should always be less than the critical load of the tower material considering its geometry and a defined factor of safety.

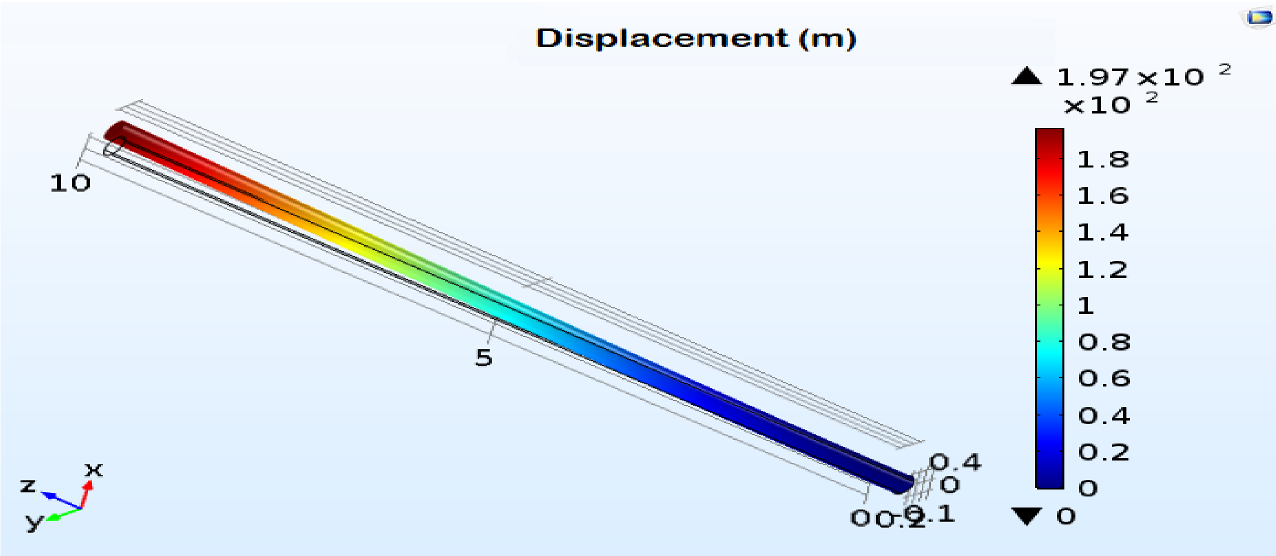


Figure 3 Deformation due applied load at an excitation frequency of 110 GHz.

The deformation of the tower along its height (from 0 m at the root to 10 m at the top) is shown in Figure 4. The result shows the gradual increases in deformation of the tower from the root (the fixed end) to the top (the free end) due simultaneously applied extreme loading conditions.

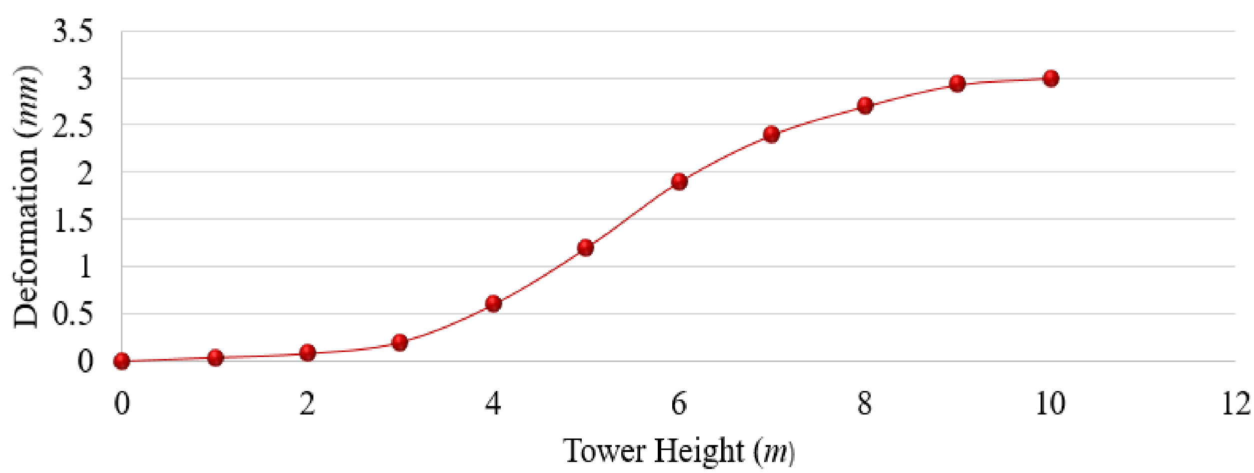


Figure 4. Deformation of the tower under the simultaneously predefined applied loads along its height.

The result of the stress distribution due to simultaneously applied static load of $28{,}245.53\ N$, aerodynamic load of $382.82\ N$ and dynamic load of $413.96\ N$ is shown in Figure 5. The response of the transfer function in terms of volume misses stress under 110 GHz excitation was 3.28 x 10^6 N/m^2 at the root of the tower in the wind direction. This value decreases with increases in tower height and drops to 0 N/m^2 at 10 m height of the tower. The predicted value was less than the axial and longitudinal stress values determined as 3.36 x 10^6 N/m^2 and 3.31 x 10^6 N/m^2

respectively. Moreover, the result also shows that the response of the tower material was due to its structural stiffness which also did not affect the frequency and dynamic response of the tower structure. Da Silva and Oliveira (2018) and Ferroudji (2021) in their works state that stable steel tower structures must offer internal resistance to externally applied load and the tower material must also have the ability to resist deformation under the resistance.

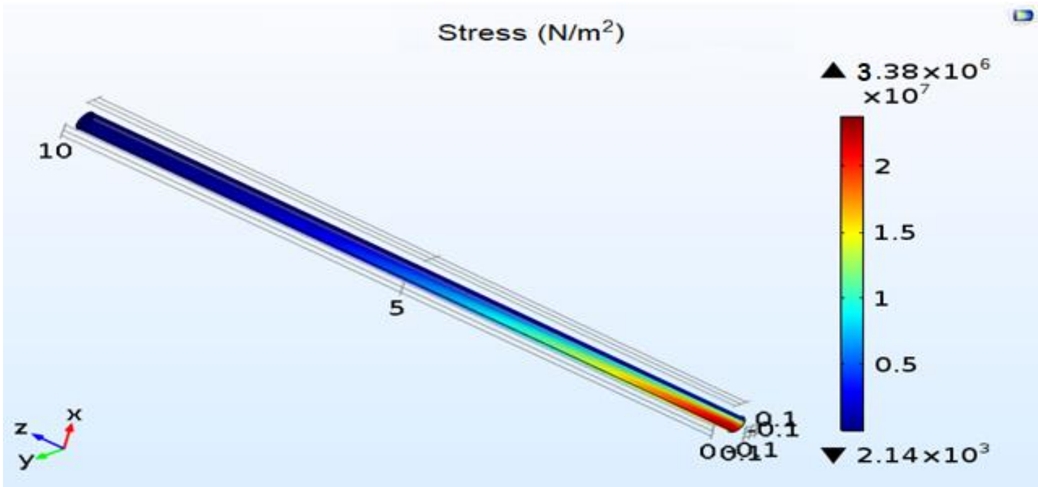


Figure 5. Stress distribution along the tower height due to simultaneously applied static, dynamic and aerodynamic loads.

The numerical results obtained in this work were validated with an experimental one and the F-test statistical tool used showed that the is no significant difference between the two results. Therefore, it has been established that the selected HAWT tower material was reliable under the predefined simultaneously applied extreme loads, thus the structural steel tower can function in areas with this or similar loading conditions.

4. Conclusion

The selected tubular structural steel tower material was numerically analyzed using the numerical code COMSOL Multi-physics 5.5. A 3D model of the tubular steel tower was developed in the numerical code's model wizard interface and analyzed based on Euler-Bernoulli's beam theory. The steel tower's response to simultaneously applied extreme predefined static, dynamic and aerodynamic design loads was examined. The result shows that the response of the selected tubular steel tower with regards to vibration, deformation and stress were within the limits of the mechanical properties of the selected tower material (structural steel). The F-Test statistical tool used to validate these results with an experimental one shows that there is no significant difference between the two results. It has also been established that the selected HAWT tower material was reliable under the predefined simultaneously applied extreme loads, thus, the structural steel tower can function in areas with this or similar loading conditions

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