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Modal Analysis of a Wind Turbine Tower: A Case Study of University of Benin Energy Research Centre wind Turbine Tower

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Abstract: *In this research work, the modal analysis of a wind turbine tower, located at University of Benin Energy Research Centre, was carried out in order to determine the structural integrity of the tower. Finite element analysis was carried out using ANSYS 16.0 Modal Module Ten. Wind log data from the month of January to the month of May, 2018 was collected from Nigerian Institute for Oil Palm Research (NIFOR) and the theoretical modal analysis was computed. The results obtained show that the frequency of the first mode shape from the simulation was 6.9039 Hz and the highest natural frequency computed from the wind speed log data was 5.9958 Hz. With these results, it can be concluded that the tower is not expected to resonate due to the impact of the wind speed on the blade of the wind turbine.*

Keywords: Modal analysis, Finite element analysis, Wind turbine tower, Wind log data, ANSYS

Nomenclature

C	Damping matrix
F	External load matrix
fn	Frequency
h_1	First height
h_2	Second height
K	Stiffness matrix
M	Mass matrix
n	Ground surface friction coefficient
R	Maximum displacement of the windmill tower during vibration
u	Node displacement matrix
V_1	Wind velocity at first height
V_2	Wind velocity at second height
$\emptyset_i$	Modes of vibration
$\dot{u}$	Velocity matrix
$\ddot{u}$	Acceleration matrix
ω_i	Natural frequencies

INTRODUCTION

Free vibration is a demonstration of the oscillatory behaviour in mechanical systems, as a result of continuous interchange of kinetic and potential energies between components in the system (Michael and Sebastian 2014). Before designing an engineering system for good vibratory performance, it is important to understand the mode shape, and analyse the vibratory characteristic of the system (Hongzhu and Zhenhua, 2015). An engineering system, when given an initial disturbance and allowed to execute free vibrations without a subsequent forcing excitation will tends to do so at a particular preferred frequency and maintaining a particular preferred geometric shape (Yan *et al.,* 2008). This frequency is called natural frequency of the system and the corresponding shape of the moving parts of the system is referred to as mode shape. Any arbitrary motion of a vibrating system can be represented in terms of its natural frequencies and mode shape (Ion *et al.,* 2012). The subject of modal analysis is concerns with the determination of natural frequencies and mode shapes of a dynamic system. Once the modes are determined, they can be used to understand the dynamic nature of the systems, and also in design and control. Over the past two decades, several research studies have examined the dynamics of wind turbines to optimize their performance (Emilio *et al.,* 2013).

Kessentini *et al.* (2010) developed a mathematical model of a horizontal axis wind turbine (HAWT) with flexible tower and blades. The equations of motion were derived using the extended Hamilton's principle. The eigenvalue problem was solved in closed form and numerically using the Differential Quadrature Method (DQM). They performed a set of numerical simulations to examine the dynamics of the wind turbine subjected to initially-distributed energy and insistent excitations applied to the blades. Their findings showed that dynamic tower blade coupling cannot be considered insignificant. Also, Zhao (2010) developed a modified version of the mathematical model in which he took into consideration the fluid-solid interaction via wind loads that induce the rotation of the hub and flapping vibrations of tower and blades. The HAWT aerodynamics was modelled using the Blade Element Momentum (BEM) theory in Quilligan. Wang and Tao (1995) proposed a mixed flexible rigid multi-body analytical model that employed the thin-walled beam theory that was superior to the traditional 1D beam finite element when applied to compute the dynamic behaviour of wind turbines. The mathematical model developed was applied to predict the dynamic performance of a wind turbine system. The kinetic and potential energy terms of each flexible body and rigid body were derived for use in the Lagrange approach to formulate the wind turbine system's governing equation. The mode shapes were then obtained from the free vibration solution while the distributions of dynamic stress and displacement of the tower and rotor were computed from the forced vibration response analysis. Ping *et al.* (2012) used numerical finite element modelling in order to compute the frequencies and mode shapes of wind turbine blades. In addition, dynamic stresses were calculated for the root zone of the blades using the finite element method. This region was a highly loaded and structurally complex area. The resulting dynamic stresses were used to estimate the blade fatigue, in order to make an optimal design of the blades that resist fatigue and being energetically efficient. Peeters and Van der (2005) used finite element model of wind turbines using an assembly of beam elements in ANSYS. They validated their ANSYS model on a real wind turbine and relevant dynamic analysis of in-situ-measured responses. The modal analysis of the structure subjected to operational conditions was called Operational Modal Analysis (OMA). They also stated that for a wind turbine, the excitation (wind loading) was impossible to be measure during operation. Manzato *et al.* (2012) used modal monitoring of wind turbine blades, which was primarily based on the evaluation of Eigen frequencies. Modal monitoring was combined with FEM simulation (Huaming, 2004) and with the comparison of results obtained from measurement and simulation. In addition, they combined the global modal methods with locally sensitive monitoring methods, based on guided elastic waves. Hongzhu and Zhenhua (2015) established a finite element model for modal analysis of a 55 kW direct-drive permanent-magnet generator to confirm its inherent frequency and vibration mode.

Moreover, the wind turbine tower is an important component of wind turbine. The weight of the wind turbine is very big, sometimes is even bigger than the lower tower. In order to get more wind, the tower is generally very high. So it is very easy to produce resonance phenomenon, which can cause horizontal amplitude (Yan *et al.,* 2008). In designing a tower, resonance phenomenon is design out or avoided.

However, in the process of the use of wind turbine, some manufacturers change the model of wind turbine in pursuit of economic efficiency, thus, resulting in a resonance phenomenon which causes the destruction of the tower (Ion *et al.,* 2012). As the support structure of the wind turbine, the tower bears alternating loads of wind when the wind turbine runs (Hongzhu and Zhenhua 2015). Wind turbines are found in many places where wind resource is rich. Though wind turbines supply energy using the kinetic energy of the wind and save non-renewable energy. The tower is the support structure of the wind turbine and the alternating loads that the tower bears are complex. There have been many accidents caused by tower faults in different wind farms during the past years (Hongzhu and Zhenhua, 2015). To make sure the tower is suitable for the wind turbine, structural analysis of the tower is essential. Natural frequency of the wind turbine tower which should be different from the frequency of the rated speed, can be given by modal analysis, and this will help to avoid resonance (Hongzhu and Zhenhua, 2015). To ensure the reliability of the wind turbine, it is necessary to carry out modal analysis on the tower, and this would prevent the natural frequency of the tower close to the rated speed of wind turbine. In this research work, modal analysis of a wind turbine tower of University of Benin Energy Research Centre was carried out using ANSYS to study the natural frequencies and mode shapes of different geometries for the construction of a wind turbine tower.

MATERIALS AND METHODS

PHYSICAL MODEL

The physical model is lattice wind turbine tower geometry. The design consists of three slant pipes with five different sections of variable diameters joined together with bolts. The first and second sections were constructed with three inches diameter steel pipe, third section was constructed with a two and half inches diameter steel pipe, while the forth section was constructed with a two inch diameter steel pipe and the fifth section was constructed with a one and half inches diameter steel pipe. The tower material is a galvanised steel type with elasticity modulus of 206 GPa, Poisson ratio of 0.3 and density of 7850 kg/m^3. The support constraint is rigid connection and the tower is 80ft high. The distance between the pipes is 5ft at the bottom and 2ft at the top. The blade has a radius of 3m.

THEORETICAL ANALYSIS

The differential equation of vibration system with multiple degrees of freedom according to Chi *et al.* (2013), Hongzhu and Zhenhua (2015) was used.

$$M\ddot{u} + C\dot{u} + Ku = F \tag{1}$$

Without regard to the structure damping and external force, Equation (1) becomes the control equation of the modal analysis as shown in Equation (2).

$$M\ddot{u} + Ku = 0 \tag{2}$$

Assuming the general expression of the solution as:

$$u = \emptyset_i \cos \omega_i t \tag{3}$$

$$\dot{u} = -\emptyset_i \omega_i \sin \omega_i t \tag{4}$$

$$\ddot{u} = -\emptyset_i \omega_i{}^2 \cos \omega_i t \tag{5}$$

The following equation can be obtained by plugging Equation (4) and Equation (5) into Equation (2).

$$(K - \omega_i M)\emptyset_i = 0 \tag{6}$$

ANSYS MODELLING

ANSYS offers a comprehensive range of engineering simulation solution sets providing access to virtually any field of engineering simulation that a design process requires. The module to be employed for this analysis is the modal module for the mode shape and natural frequency analysis.

In setting up the various analyses, the following steps were carried out;

i. Import the model from the AutoCAD inventor into the Design Modeller
ii. Generate mesh for the model
iii. Do the setup in the analysis section
iv. Run the solution till it converges
v. Extract the result at the post processing

GEOMETRY

The geometry was modelled using AutoCAD inventor and imported into design modeller of ANSYS MODAL. Fig.1 shows the geometry of the wind turbine tower.

SURFACE MESH

The mesh was carried out in ANSYS modal using the default settings and then refined to improve the mesh quality. The surface mesh for the geometry is shown in Fig.2.

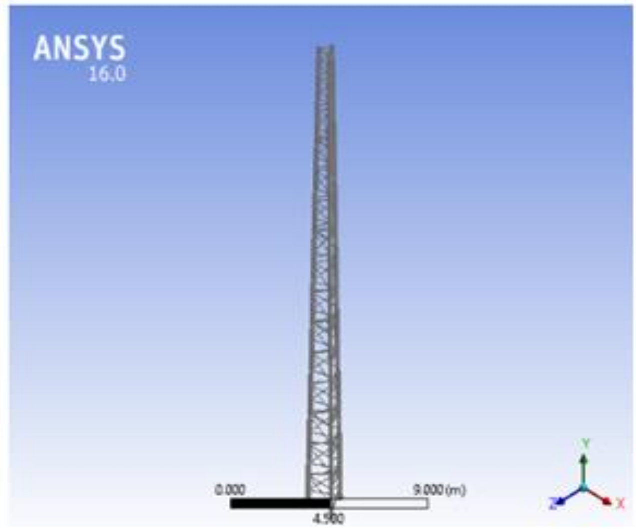

Fig. 1 Wind Turbine Tower Geometry

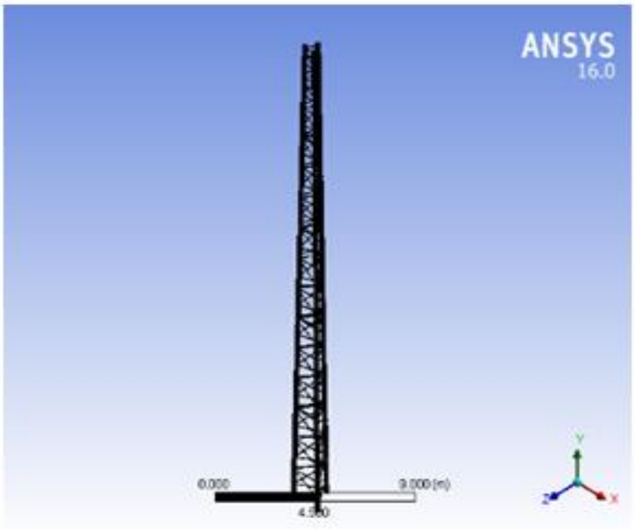

Fig.2 Surface Mesh

SETUP

The set up was done in ANSYS modal after mesh generation. Ten (10) mode shapes and total deformation were selected. Fixed boundary condition was imposed for the top and bottom boundaries and the solution was run until it converged.

GRID INDEPENDENT TEST

Grid independent test was carried out in order to ensure that the results of the simulation do not depend on grid size. The simulation was run three (3) times. Grid refinement was carried out in each case in order to generate different number of elements. Table 1 shows the natural frequency and the corresponding maximum total deformation of the first mode shapes for the three different numbers of elements.

THEORETICAL NATURAL FREQUENCY

To calculate the wind speed at one height, if it is known at another height, Wizelius and Tore (2007) Equation was used.

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^n \tag{7}$$

Where "n" can be any different values according to the nature of the terrain. For instance;

i. Water or smooth flat ground, n=0.1
ii. Tall crops, n = 0.2
iii. City downtown, n = 0.4

The angular velocity is given by Equation (8),

$$\omega = \frac{V_2}{R} \tag{8}$$

The frequency is given by Equation (9),

$$fn = \frac{\omega}{2\pi} \tag{9}$$

RESULTS AND DISCUSSION

From the grid independent test carried out as presented in Table 1, at any grid size, the result of the first modal frequency gave a very close result. Thus, it can be concluded from the test that the results are not grid dependent.

Table 1 Grid Independent Test Result of the Natural Frequency and Maximum Deformation of the First Mode Shape of the Turbine Tower

Number of element	Frequency	Maximum Deformation
47328	6.9039	0.016573
68900	6.9038	0.016571
96750	6.9039	0.016569

Ten(10) mode shapes were studied for the geometry. The results are shown in Fig 3-Fig. 10.

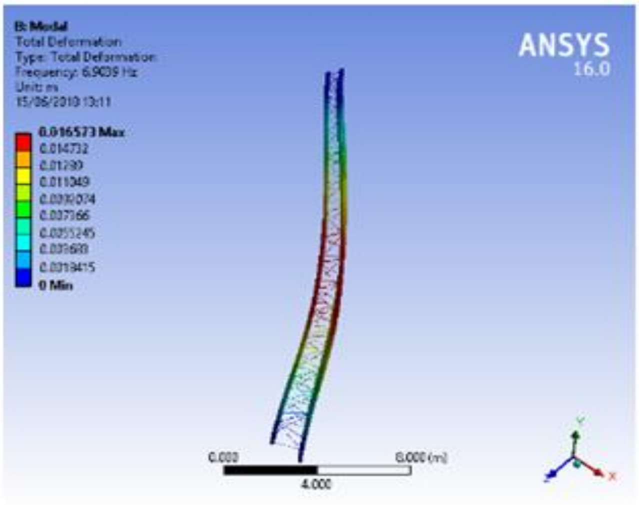

Fig. 3 First Mode Shape

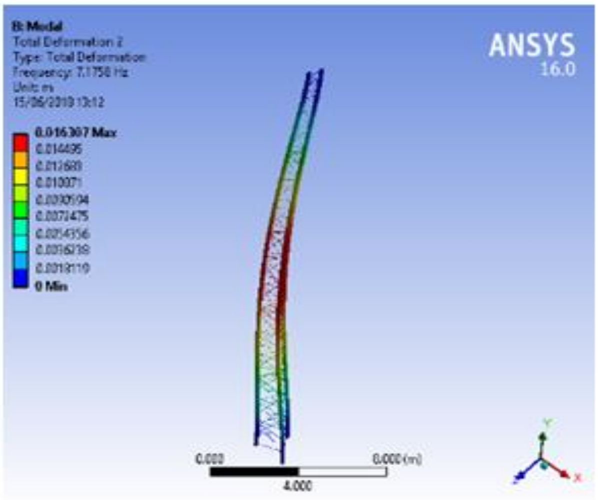

Fig. 4 Second Mode Shape

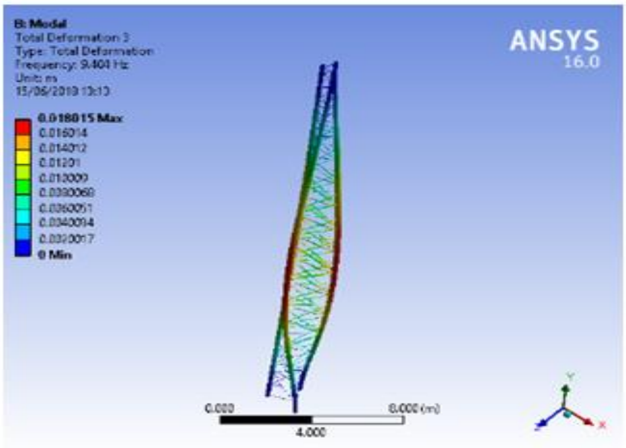

Fig. 5 Third Mode Shape

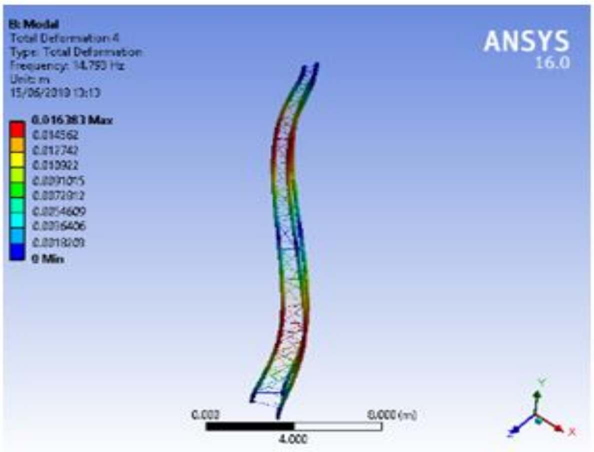

Fig. 6 Forth Mode Shape

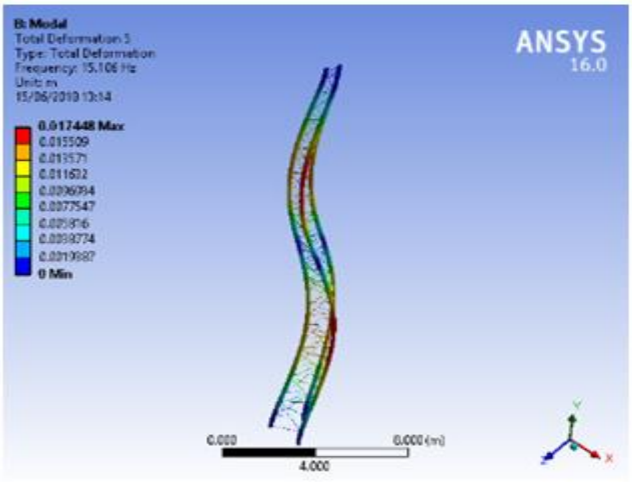

Fig.7 Fifth Mode Shape

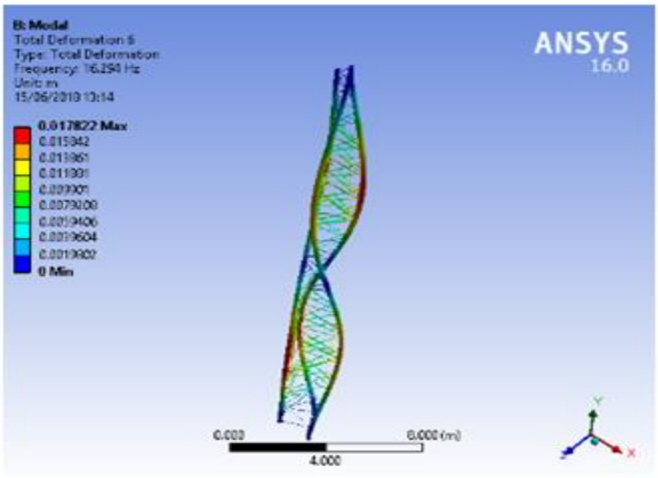

Fig.8 Sixth Mode Shape

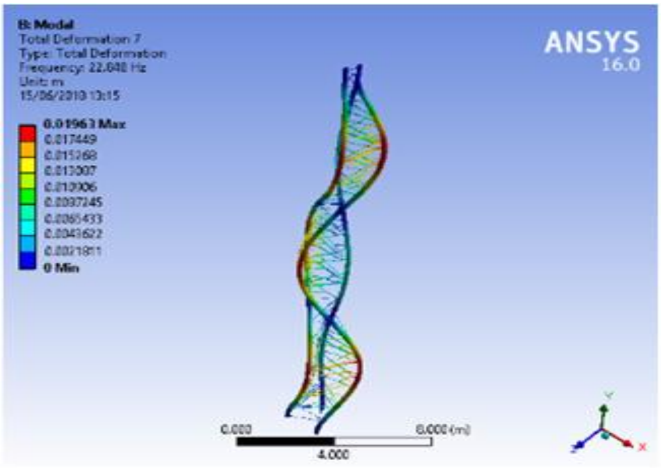

Fig. 9 Seventh Mode Shape

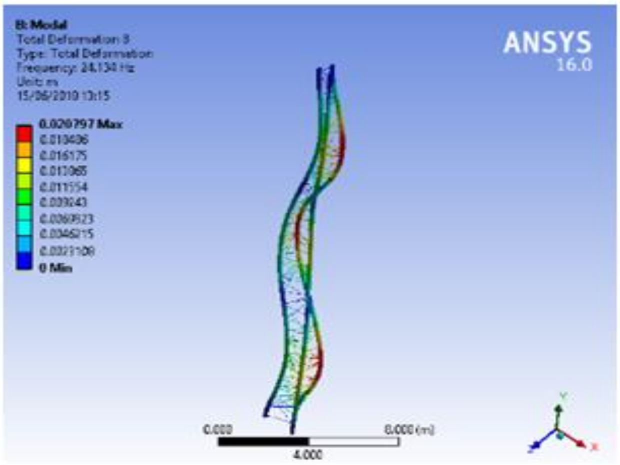

Fig.10 Eight Mode Shape

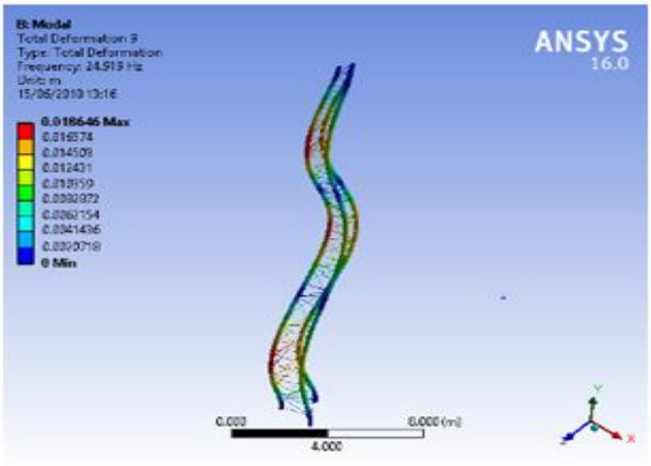

Fig. 11 Ninth Mode Shape

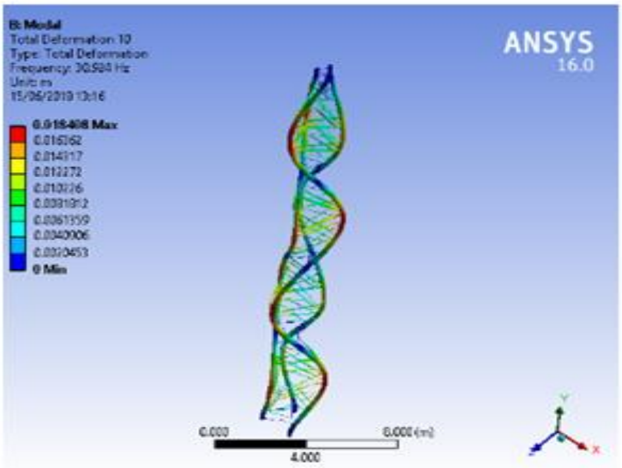

Fig. 12 Tenth Mode Shape

The wind speed log data taken from a strategic position at a height of 6ft near the site of the project located within University of Benin obtained from January to May for the year 2018 is presented in Table 2.

Table 2 Wind Velocity from January to May in the Year 2018 (km/hr.) (NIFOR, 2018)

Month/date	Jan	Feb	March	April	May
1	39.10	18.93	112.34	29.09	48.68
2	77.99	34.28	14.46	34.02	58.76
3	114.1	45.59	34.36	50.70	41.41
4	41.91	29.89	40.06	34.67	76.24
5	26.45	63.31	41.40	44.61	6.00
6	13.28	54.62	51.55	5.34	40.98
7	16.38	29.20	40.51	58.25	47.97
8	24.01	59.88	36.59	63.27	30.17
9	27.61	52.31	39.24	41.07	36.18
10	43.82	52.80	92.00	31.63	25.30
11	33.71	43.07	47.00	34.72	41.66
12	38.43	21.25	22.29	45.67	10.32
13	27.08	31.71	8.58	7.97	43.68
14	16.67	77.50	44.54	112.19	27.82
15	30.60	44.23	42.29	10.91	30.01
16	30.60	44.23	30.59	44.36	38.97
17	26.44	3.56	144.37	38.40	24.55
18	22.36	68.27	38.75	43.51	22.37
19	38.39	41.35	53.50	59.91	37.37
20	28.21	31.37	37.86	33.39	67.25
21	39.14	52.25	40.83	28.96	41.98
22	23.29	47.89	48.00	36.45	26.54
23	24.91	5.86	40.79	47.55	54.28
24	23.30	105.38	12.96	47.26	-63.00
25	23.94	27.21	12.61	17.29	61.68
26	20.74	34.38	10.11	47.45	26.88
27	7.11	38.06	85.72	12.84	55 29
28	38.83	9.65	46.98	25.52	53.80
29	28.18	-----	32.53	59.30	25.30
30	33.59	-----	43.03	99.38	24.41
31	28.26	-----	36.08	-----	39.23

Equation 7 was used to determine the velocities at 80ft where n is taken to be 0.4. The angular velocity was computed using equation (8) where the radius of the blade is taken to be 3m and the natural frequency was computed for the various wind speed from January to May using equation (9). MATLAB code was developed to compute the natural frequencies from January to May, 2018. The various natural frequencies from January to May, 2018 are presented in Table 3.

Table 3 Natural Frequency from January to May

Month/date	January	February	March	April	May
1	1.6238	0.7862	4.6655	1.2081	2.0217
2	3.2390	1.4237	0.6005	1.4129	2.4403
3	4.7386	1.8934	1.4270	2.1056	1.7198
4	1.7405	1.2413	1.6637	1.4399	3.1663
5	1.0985	2.6293	1.7194	1.8527	0.2492
6	0.5515	2.2684	2.1409	0.2218	1.7019
7	0.6803	1.2127	1.6824	2.4192	1.9922
8	0.9971	2.4869	1.5196	2.6276	1.2530
9	1.1467	2.1725	1.6297	1.7057	1.5026
10	1.8199	2.1928	3.8208	1.3136	1.0507
11	1.4000	1.7887	1.9519	1.4419	1.7302
12	1.5960	0.8825	0.9257	1.8967	0.4286
13	1.1246	1.3169	0.3563	0.3310	1.8141
14	0.6923	3.2186	1.8498	4.6593	1.1554
15	1.1035	1.8369	1.7817	0.4531	1.2463
16	1.2708	1.8369	1.2704	1.8423	1.6184
17	1.0981	0.1478	5.9958	1.5948	1.0196
18	1.1363	2.8353	1.6093	1.8070	0.9290
19	1.5944	1.7173	2.2219	2.4881	1.5520
20	1.1716	1.3028	1.5723	1.3867	2.7929
21	1.6255	2.1700	1.6957	1.2027	1.7435
22	0.9672	1.9889	1.9935	1.5138	1.1022
23	1.0345	0.2434	0.5382	1.9748	2.2543
24	1.0092	4.3765	0.5237	1.9627	2.6164
25	0.9942	1.1300	0.4199	0.7181	0.6927
26	0.8613	1.4278	3.5600	1.9706	1.1163
27	0.2953	1.5807	1.9511	0.4984	2.2962
28	1.6126	0.4008	1.3510	3.4886	2.2343
29	1.1703	-	1.7871	1.0599	1.0507
30	1.3950	-	1.4984	2.4628	1.0138
31	1.1737	-	1.4984	-	1.6292

As depicted in Table 3, for the month of January, the frequency of vibration of the wind turbine due to the wind speed is less than the first mode shape of the modal analysis. Therefore resonance is not expected to occur at any day in the month of January, 2018. Also, for the month of February 2018, the frequency of vibration of the wind turbine due to the wind speed is less than the first mode shape of the modal analysis. For the month of March, the frequency of vibration of the wind turbine due to the wind speed are all less than the first mode shape of the modal analysis. The highest frequency recorded occurs on 17th March, 2018 which corresponds to the day with the highest wind speed. Since the frequency is less than that of the first mode shape, the tower can rigidly withstand the vibration. For the month of April, the frequency of vibration of the wind turbine due to the wind speed is less than the first mode shape of the modal analysis. Thus, the resonance is not expected to occur at any day in this month. Lastly, the frequency of the first mode shape is seen to be more than the highest frequency due to the wind velocity for the month of May, 2018, thus, the tower is not expected to fail. The results were validated by modelling a lattice wind turbine tower in line with the design presented by Hongzhu and Zhenhua (2015). Fig. 13 shows the geometry from Hongzhu and Zhenhua (2015) used for their simulation while Fig. 14 shows the geometry used for validation of this research work.

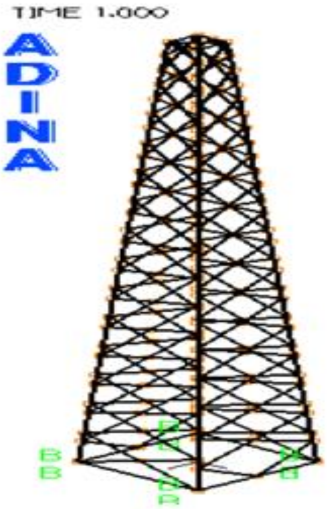

Fig. 13 The Finite Element Model of ADINA

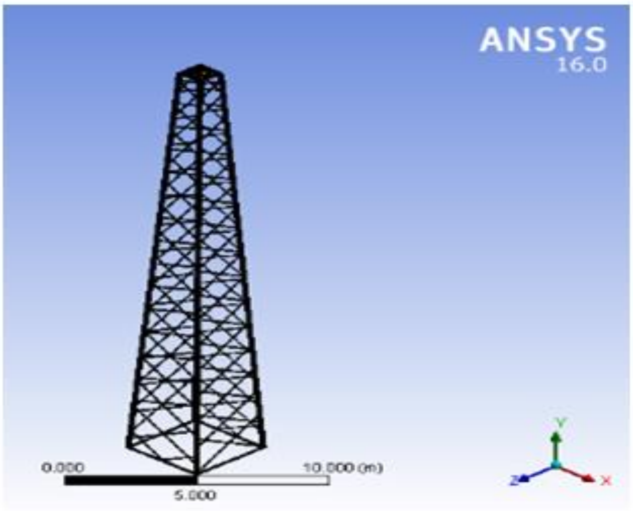

Fig. 14 The FEM Mesh of Validation Model

The simulation in Hongzhu and Zhenhua (2015) was carried out using ADINA software. Six mode shapes were studied. The frequency of their first mode shape was obtained to be 1.902Hz while that obtained in this present work validation was 2.7403 Hz. They also obtained total deformation at that frequency as 0.25m as compared to 0.24378m obtained in this research work. The little differences in the results could be due to numerical approximations of the different software. The validation simulation result obtained in this research is presented in Fig. 15.

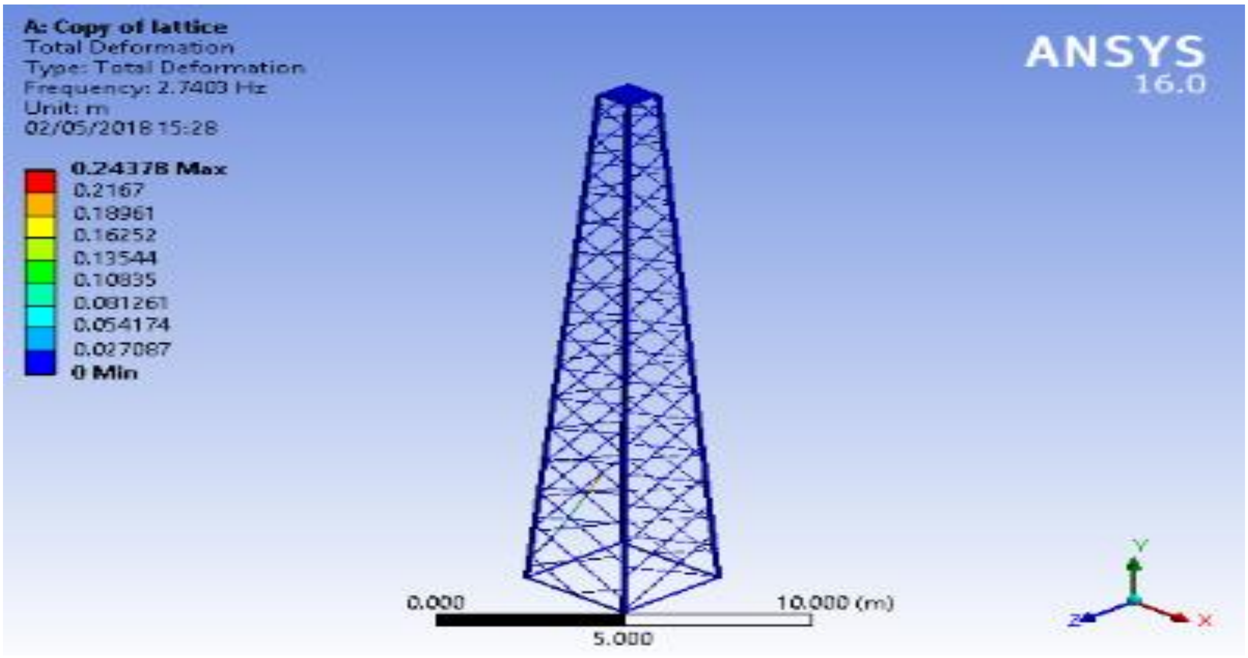

Fig. 15 First Mode Shape of Validation Model

CONCLUSION

Wind turbine towers are continuously under the periodic excitation generated by the rotation of the blades and horizontal load. The tower generates periodic vibration, and the additional stress caused by the effect of this vibration, not only influence the strength of the tower but also give rise to vibration and deformation of the tower and other components. In this research work, modal analysis of a wind turbine tower was carried out using ANSYS in order to investigate the structural integrity. The geometry was modelled using AutoCAD inventor and imported into ANSYS modal design modeller. Ten mode shapes were studied. The frequency of the first mode shape from the simulation was gotten to be 6.9039 Hz and the highest natural frequency computed from the wind speed log data was 5.9958 Hz which occurred on 17th March, 2018. From the result analysis and the natural frequency computed from January to May 2018, it can be concluded that the tower is not expected to resonate due to the impact of the wind speed on the blade of the wind turbine.

RECOMMENDATION

Further studies should be carried out to investigate modal analysis of wind turbine tower using different geometries of the wind turbine tower. This will help ascertain best geometries of wind turbine tower.

CONFLICT OF INTEREST

This research work was carried out by Erameh A.A., and Orhorhoro E.K. There is no conflict of interest associated with this research work.

REFERENCES

Emilio, D.L., Simone, M., Bart, P., Herman, V.A. (2013). Virtual Structural Monitoring of Wind Turbines Using Operational Modal Analysis Techniques. *Key Engineering Materials*: 523-530

Hongzhu, S. and Zhenhua, L. (2015). Modal analysis of a wind turbine tower based on the finite element method. *Applied Mechanics and Materials.* (744-746):179-182

Huaming, L. (2004). Optimization design and analysis of wind turbine tower based on the finite element method. Xinjiang: Xinjiang Agricultural University

Ion, N., Radu, B., Marcel, S., Daniela, B. (2012). Modal analysis of a small vertical axis wind turbine (Type DARRIEUS). *INCAS Bulletin.* 4(2):75-81

Kessentini, K., Choura, S., Najar. F., Franchek, M.A. (2010). Modeling and Dynamics of a Horizontal Axis Wind Turbine. *Journal of Vibration and Control*. 16(13):2001-2021.

Manzato, S., Moccia, D., Peeters, B., Janssens, K., White, J.R. (2012). A Review of Harmonic Removal Methods for Improved Operational Modal Analysis of Wind Turbines, Proceedings of ISMA2012, International Conference on Noise and Vibration Engineering, Leuven, Belgium: 17-19

Michael, M. and Sebastian, S. (2014). Design Optimization of Wind Turbine Support Structures—A Review. *Journal of Ocean and Wind Energy*. 1(1):12-22

Nigerian Institute for Oil Palm Research (2018). Wind log data from the month of January to the month of May, 2018

Peeters, B., Van der, A.H. (2005). A revolution in Operational Modal Analysis, Proceedings of IOMAC, 1st International Operational Modal Analysis Conference, Copenhagen, Denmark: 26-27

Ping, L., Huang, S., Zhang, J. (2012). Finite Element Analysis of Static and Dynamic Characteristics of the Cylinder Wind Turbine Tower. *Acta Energiae Solaris Sinica*: 359-363

Wang, Y., Tao, Q. (1995). Dynamic Analysis of Wind Turbine Tower. *Acta Energiae Solaris Sinica*:162-168

Zhao, R. (2010). The horizontal axis wind turbine tower vibration modal analysis. *Journal of Ianzhou University of Technology*. 495): 23-34