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Design of wind turbine tower:

Analysis and Optimization approach.

(Project Report)

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***Abstract*— Throughout this course, many examples in real life are stated. However, wind turbines remain an integral part of the real-life application of the theoretical concepts of the course. In addition, A renewed commitment in world, especially after the Paris summit to electricity from renewable resources, such as wind, along with the recent deployment of very large turbines that rise to newer heights, makes obtaining the most efficient and safe designs of the structures that support them ever more important. Towards this goal, the present report of the project seeks to understand how optimization concepts and ANSYS's analysis capabilities can be used in the design of wind turbine towers and foundations. This report presents various angles for dealing with the subject matter. For this project, A Cad model of a real wind turbine is constructed and then imported into ANSYS for extensive analysis and then to be compared to the actual values of the real-life turbine. These analyses include calculating the applied loads on the wind turbine tower in case of a survival wind speed of 50 m/s, so that an insight onto the response of the wind turbine corresponding to theses loads can be reached. After that, extensive vibrational analysis on the tower is performed in order to find the maximum stresses the structure endures. Visual models will be generated. Based on the last steps. Also, the model is then subjected to modal analysis to determine its natural frequencies that will cause the tower structure failure. The calculated values for natural frequencies and loads will then be optimized to implement in future designs.

Keywords— Vibration; Tower structures; Wind turbine; Dynamics; Optimization

I. Introduction & Literature Review:

A recent Harvard University study, published in the Proceedings of the National Academy of Sciences of the United States 2009, estimated world wind power potential to be 40 times greater than total current power consumption [Lu 2009]. This large increase over previous studies, which found this multiple to be closer to 7 times, is in large part due to the increasingly common deployment of very large turbines that rise to heights not considered by previous studies. As turbines rise to new heights, in order to tap into the greater wind speeds available at these heights, obtaining the most efficient and safe or optimal design of the structures that support them will become of increasing importance to the successful proliferation of wind power in the United States and abroad.

Over the past 20 years, a significant amount of research has been conducted to formulate the design of various pole and tower structures as optimization problems. This project aims at providing us many valuable insights into the optimal design of such structures as well as into the characterization of various optimization approaches.

Each paper in the review of literature developed results base on certain assumptions convenient to its generated results. The same applies for the optimization criterion, mainly there are six different strategies for finding the optimal design of a wind turbine: 1) minimization of tower's mass 2) maximization of tower's stiffness 3) maximization of tower's stiffness to mass ratio 4) minimization of vibration 5) minimization of performance index that measures the separation between the structure's natural frequency and the turbine's exciting frequency 6) maximization of the system natural frequency [1]. In this work the sixth strategy was chosen. it has been proven that maximization of a weighted-sum of the system natural frequencies is the most representative objective function which directly reflects the major design goals and ensure a balanced improvement in both mass and stiffness [1]. In 2005, a study made by Murtagh, Basu and Broderick proved that incorporating the soil damping effect to the tower base would reflect a significant amount of damping to the system. Therefore, in this research both cases were tested. The first includes having the tower fixed into the soil and the second includes the soil having a damping factor of 1000 MN in order to get more realistic results.

II. *OPTIMIZATION PROBLEM FORMULATION*

a) *Assumptions:*

The work is based on these assumptions: 1) the tower is cantilevered to the ground. 2) the soil damping effect is taken into consideration as explained in the introduction. 3) modulus of elasticity and other material properties are constant throughout the project. 4) The nacelle is assumed to be a uniform aluminum mass rigidly attached to the tower top. 5) the tower structure is analyzed as a circular shell. 6) aerodynamic forces acting on the tower and nacelle are considered; where the survival wind speed is assumed to be 50 m/s during the static structural analysis. 7) Deflection is calculated using CFD Methods integrated into ANSYS. 8) Deflection happens in the direction perpendicular to the rotary plane is considered, in other directions deflection is ignored [1][2].

b) *Design requirements:*

In each case of the strategies mentioned in the introduction, constraint must be imposed. The constraints used in this project are: allowable stress, maximum deflection, resonance, tower mass limitation, maximum allowable tower diameter, maximum wall thickness. This work emphasizes the limit on the natural frequency.

c) *Natural frequency limitation:*

The rated rotor speed for the NREL 5-MW baseline wind turbine is 12.1 rpm, which means the operating frequency is 12.1/60 = 0.202 Hz [3]. Operating intervals typically range from 14 to 31.4 rpm for the smaller turbines and from 6.2 to 17.7 rpm for the larger turbines. These correspond to operating frequencies between 0.23 and 0.52 Hz for smaller turbines and 0.10 and 0.30 Hz for larger turbines.
In order to avoid resonance, the natural frequency of the wind turbine structure must be above the largest operating frequency by a typical factor that varies from 1.1 as a minimum and 2 as a maximum [1].

d) *Cross sectional dimension Limitation:*

The outer diameter of a tower should not exceed 4.5 meter for a practical logistic reason: transportation Additionally, due to limitations on the thickness of steel that can be rolled using standard equipment, the maximum tower wall thickness is 40 mm. [1].

e) *Tower deflection:*

The typical allowed deflection at the tower top ranges from 0.25% to 1% of the tower height [1].

f) *Formulation:*

Optimization Variables: Variables used in the optimization problem formulation include design variables, independent parameters, dependent variables. Design Variables: Cross-sectional dimensions of the tower are treated as design variables in the optimization problem formulation, mainly (t) the thickness of the wall.

Independent Parameters The following parameters are independent of the design variables and require specification before the optimization process can begin including V_{ref}=Reference wind velocity. H=height of the tower. E_S=Modulus of Elasticity and other constants.

The dependent Variables will be: I= Cross-sectional moment of inertia, m_t=mass of the tower, w_n=natural frequency, r_i=radius of gyration.

Objective:

The primary goal of this approach of design is to increase efficiency and safety measures by separating the operational frequency of the rotor from the natural frequency of the tower. In non-direct Mean this methodology reduces cost as well.

Mathematical Configuration:

Consider the simplest case of a uniform one-segment cantilever beam with non-dimensional height H_1 and radius of gyration r_1. The associated transcendental equation of bending frequencies can be shown to have the form:

$$\cos\left(\frac{\Gamma_b H_1}{\sqrt{r_1}}\right)\cosh\left(\frac{\Gamma_b H_1}{\sqrt{r_1}}\right) = -1$$

In **Figure(1):** variation of the fundamental frequency parameter Γ_{b1}=$\sqrt{w_1}$, with r_1=D_1 radius of gyration.

Where The radius of gyration $r_1 = \sqrt{\frac{I}{A}}$, I is the moment of inertia assumed above as cross-sectional moment of inertia, A is the cross section area, in this project the change in A is almost negligible compared to the change in the moment of inertia. H_1=The tower height which in this case is assumed constant for the round thin-walled tubular configuration. The mass-to-thickness ratio, M=t1, is also shown in the Figure. It is seen that both of the frequency and mass functions are well behaved and continuous in the variable D_1. Based on That, varying the thickness will vary the radius of gyration and so will vary the natural frequency. Extensive computer analysis for numerical frequency solutions has proved the validity of such a mathematical concept.

III. MECHANICAL DESIGN:

The mechanical design is inspired by a real-life wind turbine from the national renewable energy laboratory (NREL), NREL/TP-500-38060, The Cad model is constructed accordingly **Figure (2).**

Figure 2

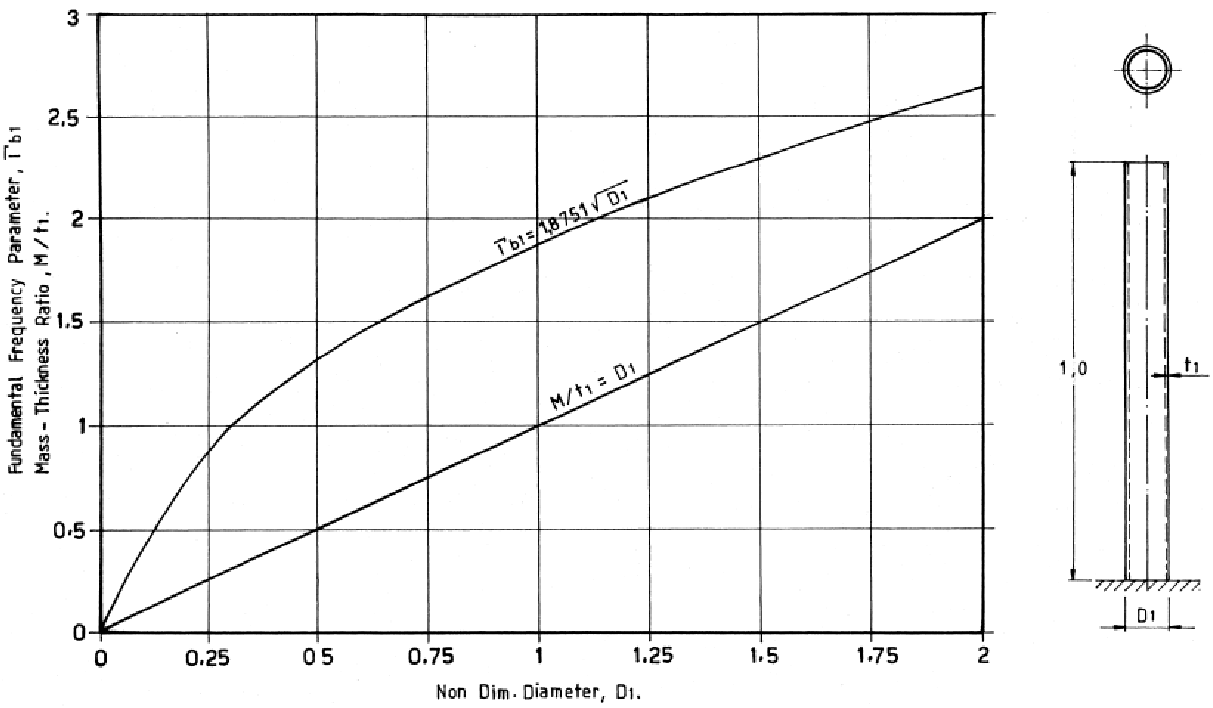

Figure 1

The key features of the design are listed below with a tower height of 87.6 m

Tower constrains	Diameter	Thickness
Base-link	4.5 m	27 mm
Nacelle-Link	3.6 m	19 mm

OBJECT	WEIGHT
NACELLE	240,000 KG
HUB	57,000 KG

BLADE.	LENGTH
CYLINDER CHORD	3.542 M
NACA64_A17 AIRFOIL CHORD	1.419 M

IV. *RESULTS AND DISCUSSION:*

All what was needed was to calculate the natural frequency of the structure which in that case may be considered the tower and nacelle of the wind turbine. To do that a survey lead to using ANSYS modal Analysis as one of the easiest methods to calculate the natural frequency. In which the CAD model is imported and the boundary conditions are stated to calculate the modes of that model. A cad model of the wind turbine was made using SOLIDWORKS as mentioned above.

a) Meshing:

Due to the geometric conditions of the model, Certain complications happened, therefore the mesh had to be simplified as much as possible. All sharp edges were eliminated and connections were approximated between bodies. The following mesh was then produced.

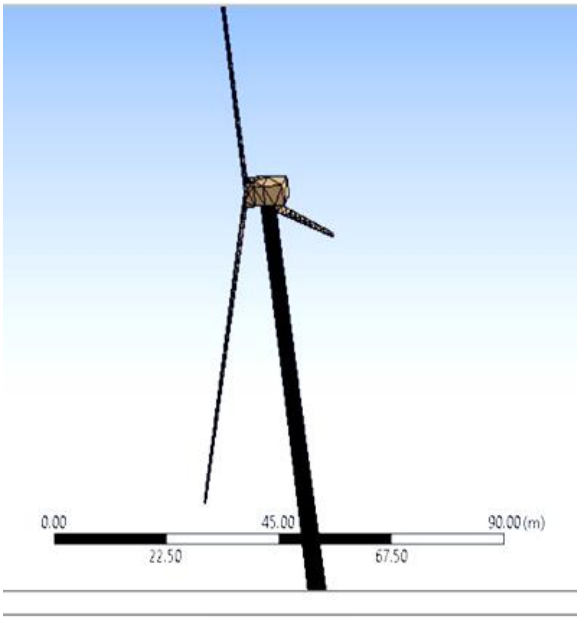

Figure 3

After that, applying modal analysis resulted in the natural frequencies of initial guess of the thickness at the base which was assumed as the maximum 40 mm, varying upwards until it reaches 19 mm at the top. The results are present in **(Figure 4).**

The problem here is that the operational frequency was about 0.202 Hz so we have to vary the thickness to raise the natural frequency of the tower above the operational frequency by a factor from 1.1 to 2 of it.

A set of simulations were done and we got the optimum thickness to be 27 mm all over the tower to have natural frequency greater than the operational and the natural frequency was calculated again **(Figure 5).**

The next step was to calculate the deflection of that tower if it was exposed to extreme wind speed so a CFD was made using survival wind speed of 50 m/s and the pressure on the turbine tower and blades were imported to static module (**Figure 6).**

After that the pressure distribution was imported **(Figure 7)** and then used to calculate the deflection as well as the stresses on the structure in the **(Figures 8,9)**

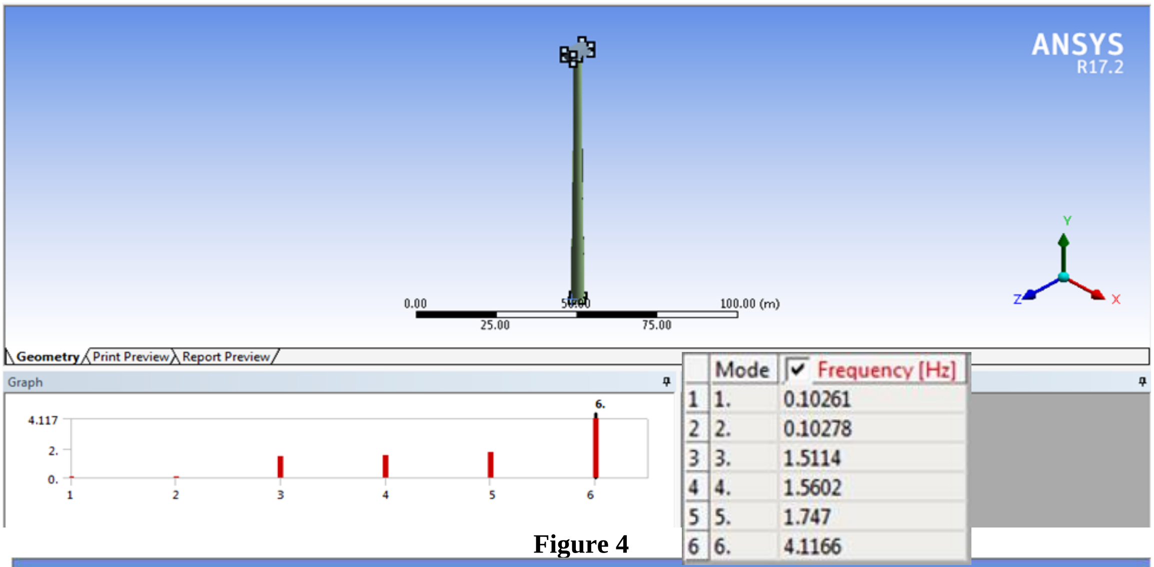

Figure 4

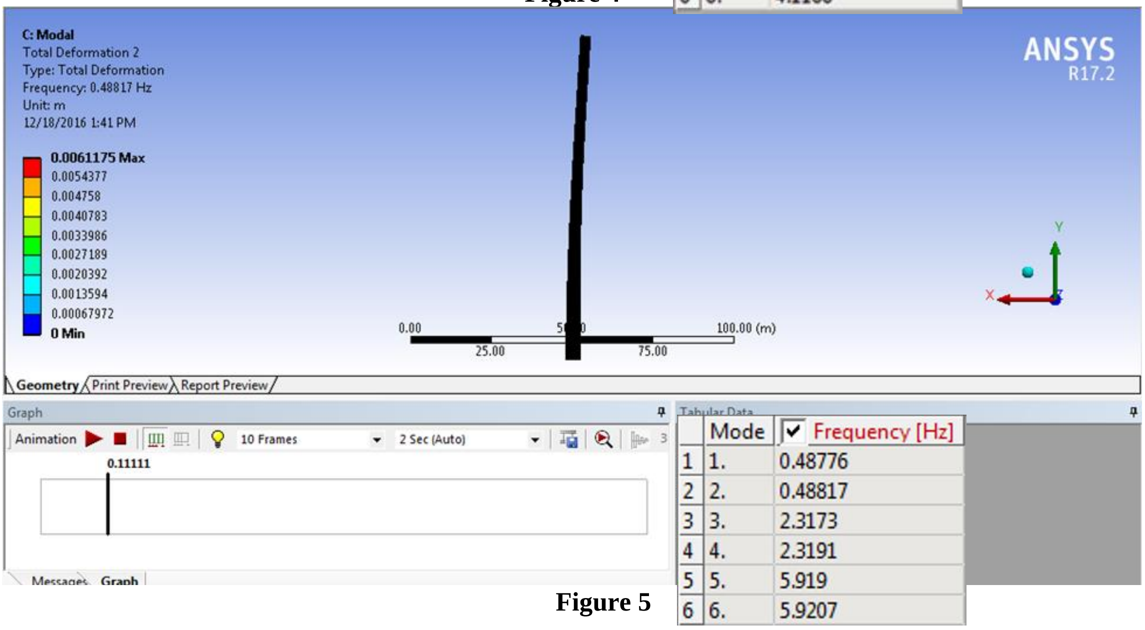

Figure 5

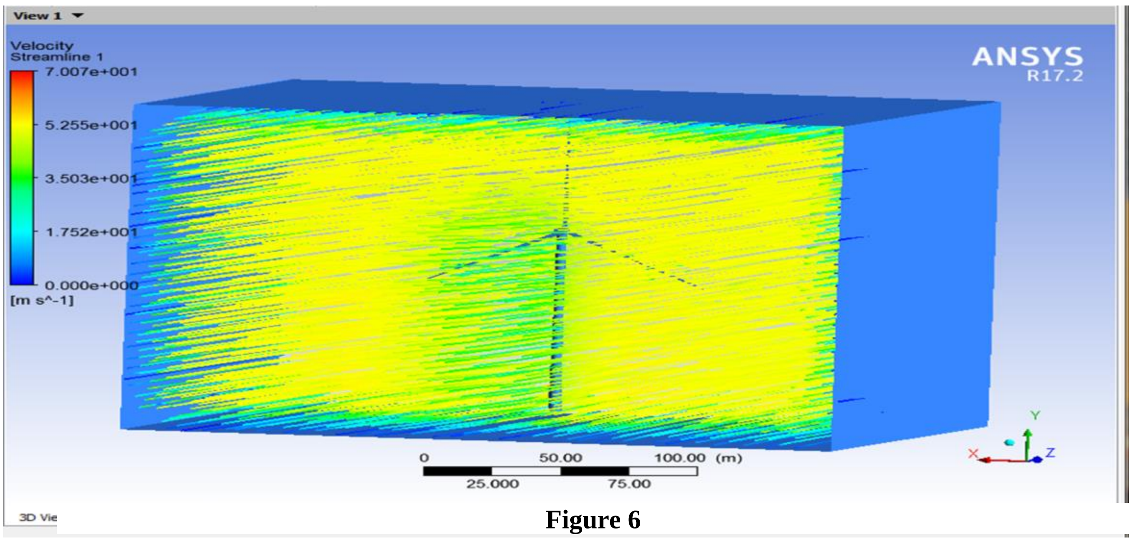

Figure 6

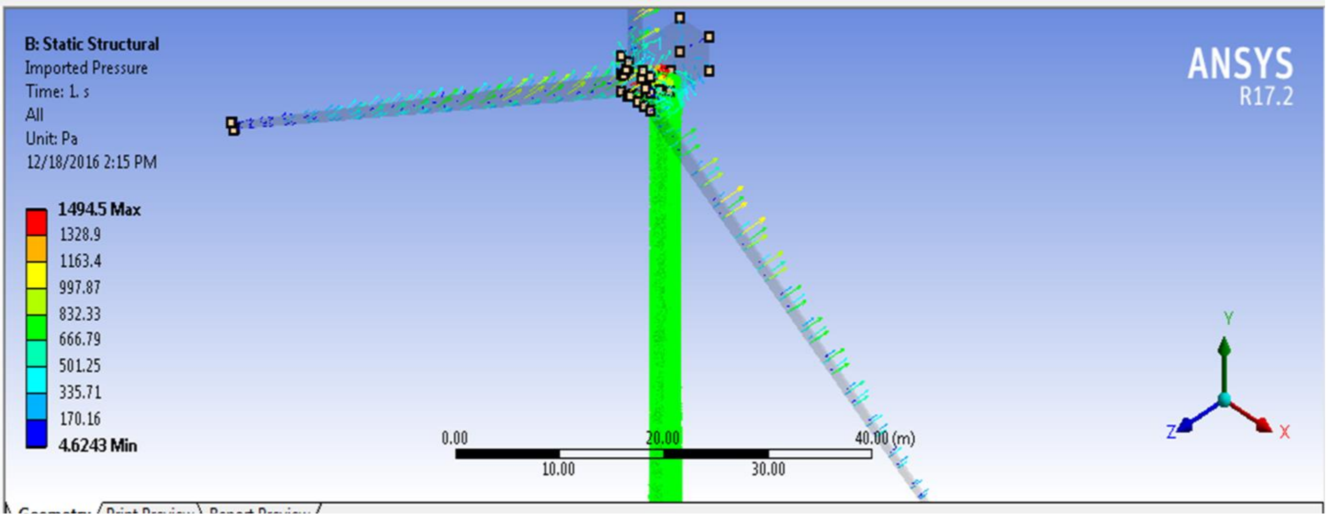

Figure 7

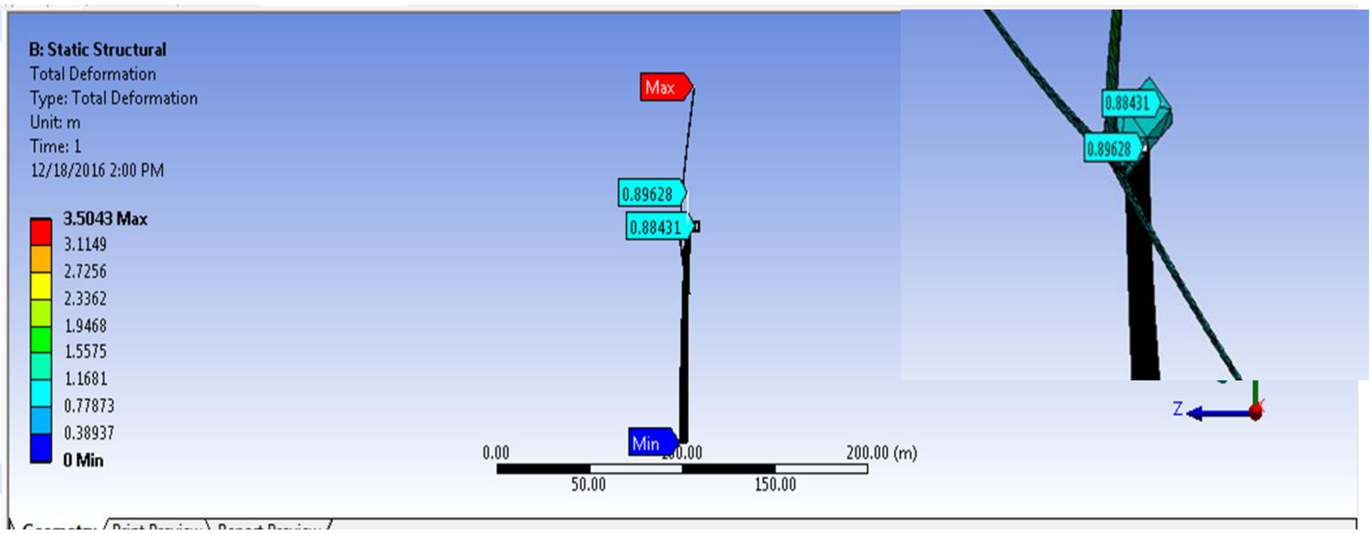

Figure 8

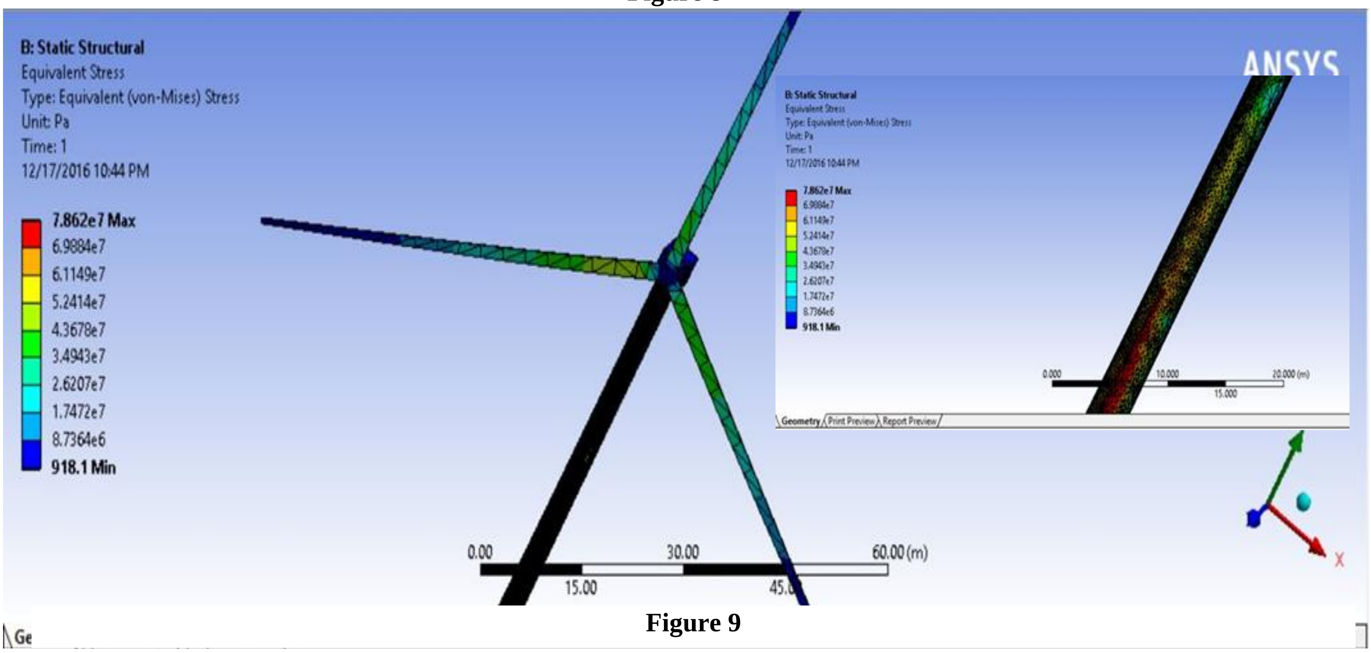

Figure 9

V. *CONCLUSION & FUTURE RESEARCH:*

This project mainly aimed at providing a simplified version of both, the static structural analysis of a wind turbine under possible wind speed conditions and use the resulting pressure distribution to calculate and understand the deflection and stress distributions. As well as, Calculating the natural frequencies for different thicknesses and using that to create an optimized design of the existing wind turbine.

The results were promising and the optimization version proved its efficiency and a newer value for the thickness were estimated.

However, there are still multiple optimization methods to analyze starting from the extensive literature review, then branching out to test newer, more efficient methods and comparing the results with the results existing in this report.

Also, the wind turbine model used here was a bit simplified, in the next research, the used models should be more complex to match reality and provide a better, more realistic results compared to the calculated values here.

VI. *REFRENCES:*

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