MECH511-Fall23 Report:
Vibration Analysis of a Wind Turbine Blade

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Abstract

There is a growing demand for clean energy sources and among the best viable sources is wind energy, which is harvested using wind turbines. Optimizing the wind turbine is thus highly important and this project aims to conduct a focused vibration modal and harmonic analysis of a horizontal axis (HAWT) wind turbine blade. The primary objective is to understand the blade's vibration behavior, tip deflection under different loads, and differences in response according to material change.

1 Introduction

The are multiple types of wind turbines including horizontal axis wind turbine (HAWT), vertical axis wind turbine (VAWT), Savonius, Darrieus, Hybrid, etc. The main blade shape this project aims to study is the common HAWT type. There are a lot of factors that go into making an optimal wind turbine, such as structural analysis, aerodynamic analysis, modal and harmonic analysis, material choice, cost, durability, etc. Optimizing all of the mentioned above is the main job of numerous industrial companies and would be too large for this course project. Thus, we will constrain our analysis on the vibration analysis and use a performance criterion to differentiate between turbine blade designs. Stability is a highly important factor, so modal analysis and minimizing the natural frequency are important. Another important factor for the blades is the amount of tip displacement (deflection). Thus, we will compare frequency response for modal and harmonic analysis and the tip deflection for various geometrical and material properties. We will first start with a brief literature review of important papers, then discuss the CAD design and then the FEA results.

2 Litereture review

Numerous studies were conducted to understand wind turbine vibration behavior. [1] investigated the dynamic behavior of the S809 wind turbine blade by analyzing its modal characteristics under varying geometrical and material parameters. They specifically focused on natural frequencies and mode shapes, which are crucial for understanding the blade's vibration response to wind loads. They used 4 different materials with variable density and modulus of elasticity as is shown in Table 2. Another valuable study was performed by [3] and they discussed FEA analysis for HAWT blade using composite materials and a variable airfoil cross-section along the blade. The program used was ABAQUS and different pressure loads were applied and tip displacement was compared. They also did a time-based (transient) displacement analysis. [4] did an FEA analysis on 5MW 48m composite wind turbine blade and investigated materials savings. They considered numerous shear webs (inside support) and compared their effects on load and vibration. Another similar study was performed by [2] and they also considered the optimization of wind turbine blades. The blade alone is 15-20% of the cost of the turbine [2], so a significant cost reduction can be made if we optimize the blade. They used a NACA 63–212 airfoil and tried numerous materials (same used with [1] and are provided in appendix Table 2. Another study focused on HAWT modal analysis was done by [7]. The blade considered is much smaller (600 kW) and their reported natural frequencies (first 5) where ranging from 19.4 up to 230. This is much larger than the other papers, but there is a considerable difference in both material and geometry.

3 Methodology

3.1 Generating CAD

Making a good CAD model is the first step towards analyzing the blade. Each turbine blade has certain key characteristics, such as, blade length, airfoil shape, and material. Following a reference is the best way for this project so it can be compared with the results of the literature. For the first blade design, we followed Appn.Table 1.

The blade shape includes multiple airfoil shapes: NREL airfoil types S818 at the 9.648-m span location, S825 at 32.667-m, and S826 at 41.873-m and 44.175-m [3]. The airfoil describes the overall shape of the blade section along with its thickness and chord length as is shown appendix in Figure 7

To get the best results from the CAD design, each airfoil section was generated separately and imported. Then a sweep surface was performed to connect all of them together App.Fig 8

(a) Blade CAD result

(b) reference from paper [3]

Figure 1: Blade shape comparison with literature [3]

(b) Second blade [1]

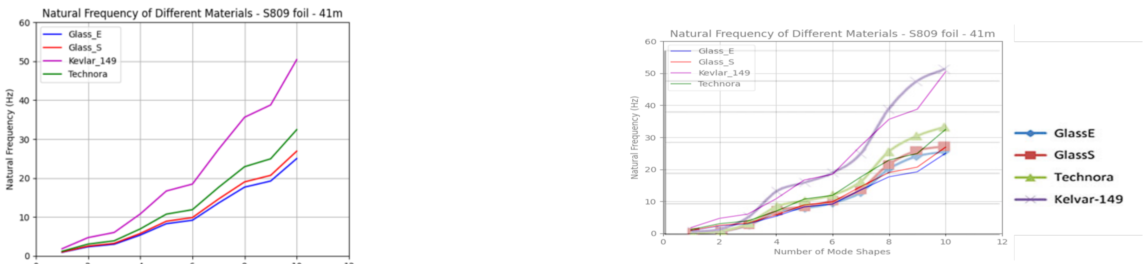
(a) First blade [3]

Figure 2: Blade shape comparison

Another blade was made following another airfoil design S809 [1]. Its shape overall is similar, but the main difference is its phase angle. A comparison between the 2 blades from the tip view is provided below Figure 2

3.2 FEA

The modal analysis is performed for both blades using different materials. The focus here will be on the blade with the phase angle difference and a comparison with its paper results is shown in fig



(a) Comsol results

(b) Comparison with the literature(overlayed image)[1]

Figure 3: Natural frequency comparison with literature [1]

We see in Figure 3 the results of the modal analysis. fig shows the difference in natural frequencies according to material change [1] and the specifications of the materials are shown in the appendix Table 2. When we look at Figure 3 b), it shows a good results in comparison with literature results [1] (the 2 graphs are overlayed for better visualisation of the results). There is some deviation which as shown for some frequencies and it can be attributed to differences in the model shape (airfoil simplification near sharp edges was made), or other different factors may be the cause. Still, the range of values is close enough.

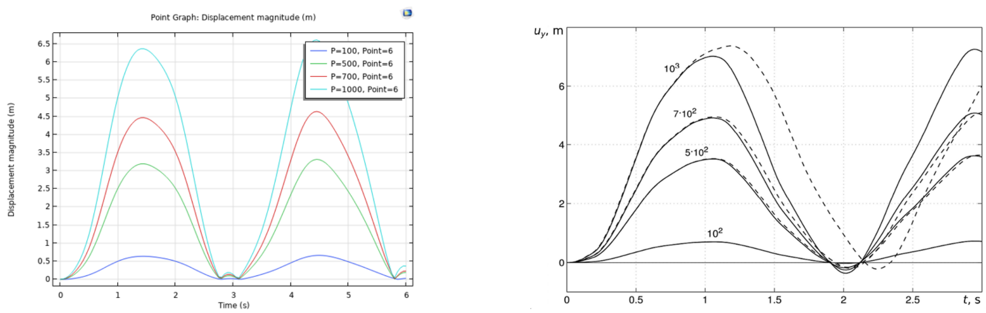
Another comparison was made between the 2 blades Figure 4. We see a considerable difference between the 2 results. This is mainly due to 2 factors: 1) difference on total length (blade 1 = 41m , blade 2= 44m) and airfoil difference (blade 1 = S809 and phase angle=16 degrees, blade 2= S818-826). The Airfoil affects thickness and phase angle so we expect a variability in results.

(a) Comsol Result for blade 1 [3]

(b) Comsol results blade 2 [1]

Figure 4: Natural frequency comparison for blade 1 and 2

A comparison between tip deflection under variable pressure load (applied on the whole wing) is shown for blade 1 and compared with the results of [3] Figure 5. The amplitude of the deflection (checked at the tip of the beam) matches almost perfectly under the 5 different loads. However, there is some deviation in the cycle time response of the beam. This is probably due to simplification done in the analysis as [3] used a longleaf pine support for the blade and we did not add it in the calculations for simplicity. The material used for this part is following [3] values Appn.Table 2.



(a) Comsol results blade 1

(b) Reference results blade 1 [3]

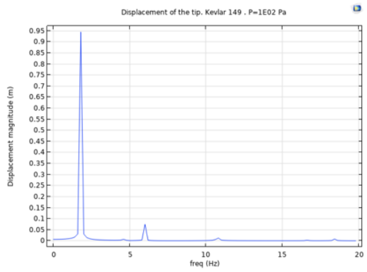
Figure 5: Transient blade deflection comparison with [3]

Finally, a comparison between the tip deflection for variable materials under the same pressure load (1E02 Pa applied on the whole wing) is shown for blade 2 Figure 6. We see a variability in the deflection according to material and we see the largest near modal frequencies (shown first 10 for each material in Figure 3

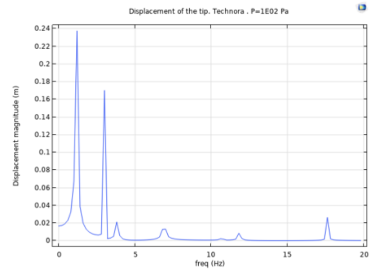
We see that the deflection is the largest for Kevlar149 and lowest for Glass E. Thus, higher density showed more deflection here. However, more elastic modulus results in lower deflection. These results show that if we want the minimum deflection, we should select Glass E composite material as it results in lower tip deflection under the same load and geometrical properties.

4 Conclusion

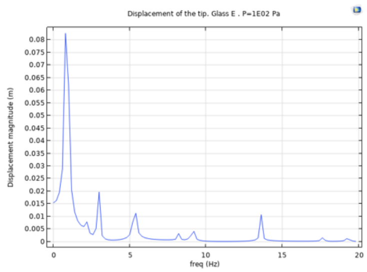
Overall, the project discussed the vibration response of horizontal axis wind turbines (HAWT). We started by replicating CAD models found in the literature. Then, we performed various FEA studies including modal analysis and harmonic analysis. Our performance criteria were modal frequency and tip deflection. The results showed that for lower modal frequencies we may choose the blade 1 design. However, since there is a difference in wattage output (1.5MW vs 3MW) we also need other parameters to decide. For the S809 Airfoil model, we saw differences in frequency and tip deflection, and the lowest frequencies and tip deflections were observed for Glass E. This is reasonable since the density is the highest in Glass E and S and their frequencies are close to each other. Granted, other economic factors may come into play when building them so they are also important factors for the final design decision.



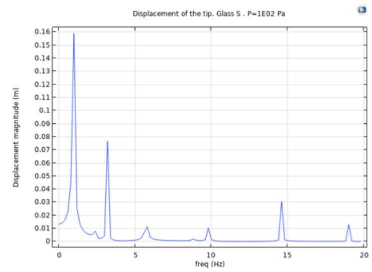
(a) Harmonic response material Kevlar



(b) Harmonic response material Technora [3]



(c) Harmonic response material Glass E



(d) Harmonic response material Glass S [3]

Figure 6: Harmonic response using applied pressure = 1E02 Pa (as used in [3])

References

[1] A. Gangele and S. Ahmed. Modal analysis of s809 wind turbine blade considering different geometrical and material parameters. *Journal of The Institution of Engineers (India): Series C*, 94, 2013.

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[3] N. Navadeh, I. Goroshko, Y. Zhuk, F. E. Moghadam, and A. S. Fallah. Finite element analysis of wind turbine blade vibrations. *Vibration*, 4, 2021.

[4] M. Tarfaoui, H. Khadimallah, A. Imad, and J. Y. Pradillon. Design and finite element modal analysis of 48m composite wind turbine blade. *Applied Mechanics and Materials*, 146, 2012.

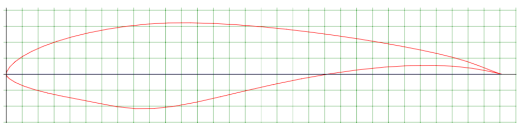
[5] Wikipedia. Airfoil, 2024.

[6] Wikipedia. Airfoil, 2024.

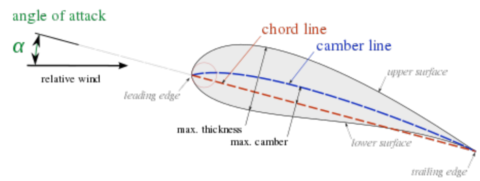
[7] Z. Ye, H. Ma, N. Bao, Y. Chen, and K. Ding. Structure dynamic analysis of a horizontal axis wind turbine system using a modal analysis method. *Wind Engineering*, 25, 2001.

5 Appendix

Figure for the Airoils and reference for airfoil characteristics image (from Wikipedia [5]



(a) Airfoil shape for NREL S825 [6]



(b) Airfoil characteristics [5]

Figure 7: Airfoils

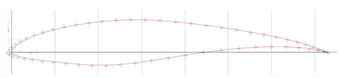
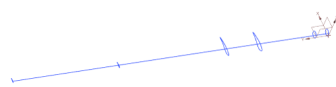
[H]   

Table 1: Section thicknesses along the beam axis (measured from the circular root) [3].

Number of Section	Distance from the Root in z-Direction (mm)	Thickness t (mm)
1	1754	96.02
2	9648	79.04
3	14,251	53.21
4	29,212	13.44
5	44,175	10.34

Table 2: Material Properties

Material	Elastic Modulus (GPa)	Density (kg/m^3)
Kevlar 149 [1]	179	1470
Technora [1]	70	1390
Glass E [1]	76	2540
Glass S [1]	88	2540
UD Composite [3]	37	1860