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INFLUENCE OF HAWT TOWER MATERIAL ON NATURAL FREQUENCIES AND RESONANCE MITIGATION THROUGH MODAL ANALYSIS

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Abstract

Horizontal Axis Wind Turbine towers are extensively used for generating renewable energy worldwide, however due to its slenderness nature it is lacking a stable dynamic behaviour due to lateral load. The current study aims to analyse the modal frequencies produced by wind turbine towers with the help of Autodesk Fusion 360 simulation analysis tool. The modal frequencies of structures manufactured using different materials is studied. The tool analyses, how the material having a specific mass participation factors affect structural dynamics. These factors demonstrate, how much mass is participating in each mode shape. The results obtained shall give engineers valuable data for designing wind turbine towers, which helps them choose the best materials for better performance and stability. Fusion 360's simulation features are used to make a 3D model of a skyscraper that is 87.6 meters tall and has different diameters. This study examines the modal frequencies of towers made of structural steel, high-modulus CFRP, and GFRP. It shows how the qualities of the materials affect how the structure moves. When comparing the modal behavior of stainless steel (dominant frequencies: 0.867 Hz, CFRP 1.617 Hz, and GFRP 0.472 Hz buildings, we see that CFRP has a frequency range that is 86–87% greater than that of GFRP and 86% higher than that of steel. The mass participation variables related to every mode and shape show how much of the structure's mass is involved in the dynamic response. This gives us more information about how each material's structure behaves dynamically.

Keywords: evergreen; Autodesk Fusion 360, mass participation factor, Wind turbine tower, modal analysis.

1. INTRODUCTION

Wind turbine towers are very important for keeping the turbine's structure stable and getting the most energy out of it. As constant need to renewable energy and growing. It is becoming more and more necessary to design and analyze these towers [1]. One important part of designing a tower is knowing how it will behave when different loads are applied to it, especially wind alongside rotational forces. Modal analysis is a great technique to see how things like wind turbine towers move with time. Finding the tower's frequency spectrum and mode shapes might help engineers detect probable resonance problems and improve the design. This will cut down on movement and stress, which will make the structure work better and last longer. This study emphasizes to understand on how the wind turbine structure made from different materials perform over time using Fusion 360's modal analysis tool. It also aims to understand the modes along with frequencies of structures constructed of different materials [2]. This study looks at, how choosing the proper materials influence the design and performance of towers. The findings can help generate wind turbine towers work better and last longer, which would make wind power systems more efficient and better for the environment

Fig. 1. Hitachi 5 MW wind turbine tower

Fig. 1 presents Hitachi's 5 MW wind turbine generator system, the same is an example of more people choose energy sources that are good for the environment, wind turbine engineering has come a long way. It's crucial to know how they change over time in order to improve design and make sure that buildings stay sturdy. Capacity, efficiency, and reliability are still important aspects. Modal analysis is a advantageous tool in structural dynamics that helps engineers to find out the natural frequencies and mode shapes of a system. This highlights useful things concerning, how the system varies in behaviour [3]. Autodesk Fusion 360 and other simulation software and computational tools have improved recently, making it reliable to build and examine complicated structures like wind turbines. Researchers can use Fusion 360's FEA (finite element analysis) features to undertake potential modal analysis to study different materials and designs change over time. National Renewable Energy Laboratory (NREL) (HAWT) is a recognized model for studying wind turbines [4]. The goal of this study is to use Fusion 360's simulation tool to Fig. out the modal frequencies of the NREL HAWT structure, which is constructed of steel, CFRP, and GFRP. This study may assist us learn more about how these materials act when they are moving and how that can affect wind turbines.

1.1 Material Selection

Choosing the appropriate materials for wind turbine towers is a big challenge of the design process, because they determine how strong, long-lasting and well the tower works. Steel is a popular choice due to its robust and durability, it can also corrode and become weak. On the other hand, CFRP and GFRP are material composites that are very strong for their weight, don't corrode and can be moulded in different ways. But their high costs and sophisticated manufacturing processes can become a huge problems.

1.2 Research Objectives

This research aims at the modal frequencies of the NREL HAWT structure, which is constructed of steel, CFRP, and GFRP. It is aimed to add to the ongoing work in materials science and wind turbine design. This study looks at how these substances act when they are moving to find out what their advantages and disadvantages are and how well they might work for wind turbine tower purpose. The findings of this study can guide to pick the right materials and make designs better, which makes wind energy systems work better, endure longer, and be more reliable.

It is vitally crucial to be able to accurately estimate modal frequencies and mode shapes to make sure that, wind turbine towers are steady and perform well. Using modern simulation programs like Fusion 360, help to present a complete image of how wind turbine towers made of different materials act in dynamic settings. which will assist build wind energy systems that work better and are more reliable.

The purpose of this research is to find out how the standard Horizontal Axis at the National Renewable Energy Laboratory (NREL) evolved over time. We made a wind turbine (HAWT) out of stainless steel, carbon fiber reinforced polymer (CFRP), and glass fiber reinforced polymer (GFRP) using modal analysis in Autodesk Fusion 360. By observing at the modal frequencies and mode forms of different materials, the study wants to find out how well they function for wind turbine towers. This will help with choosing the right materials and improving design ideas that will make wind energy systems more efficient, dependable, and long-lasting. The results show that CFRP has the highest modal frequency of 1.615–1.617 Hz, followed by steel (0.866–0.867 Hz) and then GFRP (0.472 Hz). This suggests that CFRP may help minimize the risks of resonance and make structures perform better.

1. 3D MODELING AND MODAL ANALYSIS

1.1 Materials and Methods

Using Autodesk Fusion 360 CAD and FEA features, this study modeled and simulated how the NREL HAWT would behave in real life. Fusion 360 FEA features let you Fig. out the natural frequencies and mode shapes of complicated structures. This builds on earlier work that used different software packages, like ANSYS, ABAQUS, and Nastran, to do FEA simulations for structural evaluation of wind turbine towers. In the past, steel was used to build wind turbine towers. Recent studies have looked into using composite materials like carbon fiber-reinforced polymers (CFRP) and glass fiber reinforced polymer (GFRP) to improve the performance of the structure. Previous FEA evidence shows that these materials work to save weight while keeping the structure strong. HAWT Model shown in Fig 2

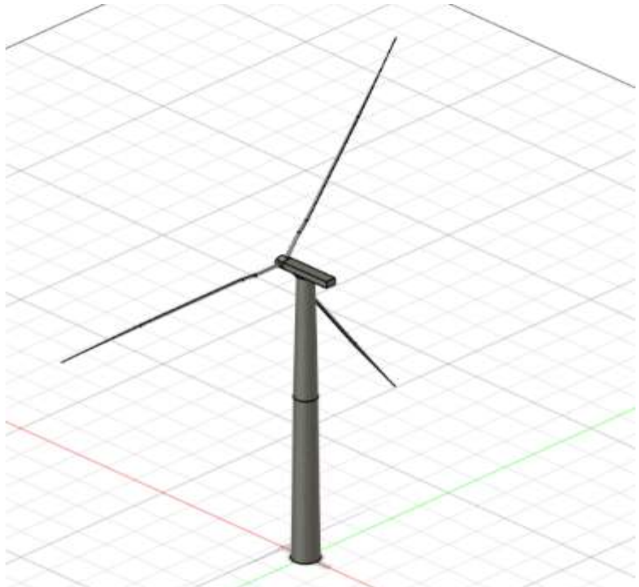

Fig. 2. Model 5 MW Horizontal axis wind turbine tower

FEA Technique

You can use FEA software such as Autodesk Fusion 360, ANSYS, an as well as ABAQUS in to do modal analysis, which gives you useful information about how a structure moves. Some of the most important procedures are meshing, setting the material properties, setting the boundary conditions, and choosing a solver, such picking the right one for eigenvalue extraction. In Fusion 360, modal analysis meant solving the eigenvalue problem to get the NREL HAWT structure's natural frequencies and mode shapes for each material. This method is in agreement with established FEA methodologies, which may be used to look at how the structures of wind turbines variation dynamically when they are loaded in different ways.[5]. The qualities of the materials employed in the modeling process are very important to achieve the right results. Steel is a strong and sturdy material that is often used to build wind turbines. CFRP is a good choice for lowering weight while keeping the structure strong since it has a very high stiffness-to-weight ratio. GFRP is another common composite material that strikes a good mix between the stiffness, bulking strength.

1.2 Simulation settings

The variables for a simulation were set up so that they could realistically show how a NREL HAWT structure changes over time. We did the convergence study for the mesh to make sure that the simulation results were correct and that the mesh size had been big enough to show the structural features and geometry [6]. This study aims to find out more about how the NREL HAWT structure made of different materials behaves when it is in motion.
It does this by using Fusion 360's simulation features and building on existing FEA methods. The results will help with choosing materials and optimizing designs for wind turbines. Using Autodesk Fusion 360, we made a three-dimensional model of a wind turbine tower that met the NREL requirement. The tower's height is 87.6m, its base diameter is 6m, its top diameter

is 3.87m, and its wall thickness is 0.027m. The tower's diameter gets smaller by 10 meters from the bottom to the top. We used Fusion 360's simulation features to do modal analysis and find the typical frequencies and mode shapes.

1.3 Material properties

Three materials were considered for the tower material in the study, such as standard structural steel, CFRP and GFRP. The mechanical and thermal properties of the materials is listed in Table 1. For steel, the overall mass of the tower is 317,460 kg and tower height are 87.6 meters. The moment of inertia values at centre of mass and the origin of the tower are in good agreement with the standards. The model resembles NREL baseline tower [7]. Material properties and geometric parameters have a significant effect on modal frequencies. Mesh size settings also had a considerable effect on modal frequencies.[8]

Table 1. Physical properties of materials used for the Tower

	Structural Steel	**CFRP**	**GFRP**
Density	7.850E-06 kg /	1.430E-06 kg / mm^3	1.750E-06 kg / mm^3
Young's Modulus	210000 MPa	133000 MPa	13900MPa
Poisson's Ratio	0.30	0.39	0.39
Yield Strength	207 MPa	300.00 MPa	58.10 MPa
Ultimate Tensile Strength	345 MPa	577.00 MPa	194.00 MPa
Thermal Conductivity	0.056 W / (mm C)	0.105 W / (mm C)	2.300E-04 W / (mm
Thermal Expansion	1.200E-05 / C	9.930E-06 / C	7.310E-05 / C
Specific Heat	480.00 J / (kg C)	1130.00 J / (kg C)	1000.00 J / (kg C)

CFRP's high stiffness: High Young's modulus contributes to higher modal frequencies. GFRP's low stiffness: Lower Young's modulus results in lower modal frequencies. Steel's density: High density doesn't directly correlate with highest modal frequencies. Material properties significantly influence modal frequencies. CFRP's high stiffness-to-weight ratio makes it suitable for high-frequency applications. GFRP's lower stiffness may require additional design considerations.

2. Modal frequency analysis settings

In this study, four main settings were considered in the modal analysis conducted in Autodesk Fusion 360, such as Element size, Element type: Shell or plate elements depending on Fusion 360's default settings for tubular structures, Boundary conditions like Fixed base, and Modal frequency range [9]. The basic mesh settings used in this work such as mesh size ratio, turn angle on curves, aspect ratio, is enlisted in Table 2.

Table 2. Mesh settings used in common for structural steel, GFRP and CFRP

Average Element Size (% of model size) solids	8

Scale Mesh Size Per Part	No
Average Element Size (absolute value)	-
Element Order	Par
Create Curved Mesh Elements	Yes
Max. Turn Angle on Curves (Deg.)	60
Max. Adjacent Mesh Size Ratio	1.5
Max. Aspect Ratio	10
Minimum Element Size (% of average size)	20

The accuracy of modal analysis results heavily relies on the mesh size setting. A sufficiently refined mesh is crucial to capturing the structural details and geometry, while ensuring convergence of results. Ideally, element sizes should be less than 10% of the structural features, with further refinement near critical areas such as joints and boundaries. A mesh convergence study is also essential to validate the reliability of the simulation results. The Model frequencies study uses solid mesh elements with 101275 nodes and elements 50762: Result convergence Tolerance 20% and Frequency mode equals to 1.0. Further, contact tolerance 0.1 mm and number modes taken as 8.

2.1 Modal Analysis

Fusion 360's frequencies analysis tool is used to determine the modal frequencies and mode shapes of the tower for each material. The analysis assumes a fixed base and neglects aerodynamic loads. The outcomes are then compared to assessing the impact of material properties on the tower's dynamic behavior. Mode shapes show how a structure changes shape at certain natural frequencies, which shows how it vibrates. Engineers can use these forms to find weak spots and places with a lot of stress, which helps them improve designs and reduce problems caused by resonance. Frequencies, which are measured in Hertz (Hz), tell you how many times a vibrating structure moves back and forth or cycles through a second. Natural frequencies are built into a structure, but excitation frequencies are outside factors that can make resonance happen if they correspond to the natural frequencies. Wind loads, loads due to gravity, aerodynamic forces, and turbulence are all external factors that act on Horizontal Axis Wind Turbines (HAWTs) [10]. These forces can affect how well the turbine works and how strong it is, therefore they need to be taken into account while designing and analyzing it. Fig. 3 shows the mode shapes for steel at different modes, like Mode 1, Mode 2, and Mode 8. Composite materials exhibit similar mode structures, although the modal frequencies are different [11].

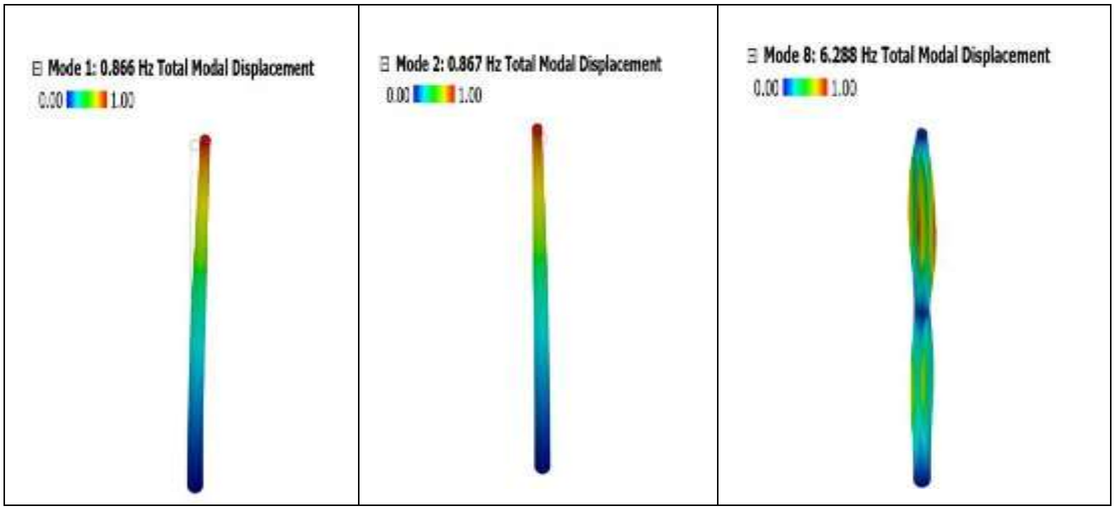

Fig. 3. Mode shape images at (a) Mode 1 -left (b) Mode 2 -middle and (c) Mode 8 -right

Mass participation refers to the proportion of a structure's mass that participates in a particular mode shape. It's a measure of how much of the structure's mass is involved in the vibration pattern of a specific mode [12]. High mass participation indicates that a mode is likely to be significant in the structure's dynamic response.

Modal Frequencies results summary for structural steel is shown in Table 3. When a structure's natural frequency matches excitation frequency (resonance), modes with high mass participation factors are more likely to: Dominate the response, amplify vibrations and Increase stress and potential damage. High mass participation factors can indicate which modes are most critical during resonance, helping engineers prioritize design modifications or mitigation strategies.

Table 3. Modal Frequencies results summary for Structural Steel

Frequency, Hz	Participation X	Participation Y	Participation Z
Mode 1: 0.866	5.15360013	51.0636985	0
Mode 2: 0.867	51.1110008	5.15579991	0
Mode 3: 4.471	0.0092	19.4340006	0
Mode 4: 4.476	19.3416998	0.0091	0
Mode 5: 4.924	0.001	0.0001	0
Mode 6: 5.324	0.0001	0.0004	0
Mode 7: 5.901	0	0	0
Mode 8: 6.288	0	0	0

It has been identified that Low-frequency modes (0.866 Hz, 0.867 Hz): Dominant in Y and X directions, respectively, with significant mass participation (>51%). Further Mid-frequency modes (4.471 Hz, 4.476 Hz): Show notable participation in Y and X directions.

Key Findings:

1. Modes 1 and 2 are critical due to high mass participation.
2. Modes 3 and 4 contribute significantly to dynamic response.

This data provides valuable insights for structural design optimization and resonance mitigation. The result summary of modal frequencies with mass participation factors are listed in Table 4.

Table 4. Modal Frequencies results summary for CFRP

Frequency, Hz	Participation X	Participation Y	Participation Z
Mode 1: 1.615	5.02000004	51.2166023	0
Mode 2: 1.617	51.2634993	5.02230003	0
Mode 3: 8.324	0.0088	19.4878995	0
Mode 4: 8.334	19.3957001	0.0086	0
Mode 5: 9.584	0.0004	0.0001	0
Mode 6: 10.63	0	0.0001	0
Mode 7: 11.461	0	0	0
Mode 8: 12.442	0	0	0

It is observed that Low-frequency modes (1.615 Hz, 1.617 Hz): Dominant in Y and X directions, with significant mass participation (>51%). Further, Mid-frequency modes (8.324 Hz, 8.334 Hz): Notable participation in Y and X directions.

Key Findings

- ✓ Modes 1 and 2 are critical due to high mass participation.
- ✓ Modes 3 and 4 contribute significantly to dynamic response.

This data informs structural design optimization and resonance mitigation strategies. The results of modal frequencies and participation in X, Y and Z axes were depicted in Table 5.

Table 5. Modal Frequencies results summary for GFRP

Frequency, Hz	**Participation X**	**Participation Y**	**Participation Z**
Mode 1: 0.472	5.02020009	51.2163997	0
Mode 2: 0.472	51.2633026	5.02250008	0
Mode 3: 2.433	0.0088	19.4878995	0
Mode 4: 2.435	19.3957001	0.0086	0
Mode 5: 2.801	0.0004	0.0001	0
Mode 6: 3.106	0	0.0001	0
Mode 7: 3.349	0	0	0
Mode 8: 3.636	0	0	0

It has been observed that Low-frequency modes (0.472 Hz): Dominant in Y and X directions, with significant mass participation (>51%). And Mid-frequency modes (2.433 Hz, 2.435 Hz): Notable participation in Y and X directions.
Key Findings:

- Modes 1 and 2 are critical due to high mass participation.
- Modes 3 and 4 contribute significantly to dynamic response.

This information helps in optimizing structural design and reducing resonance. We look at the modal frequencies we got from the research and compare them across various materials to find trends and patterns. With this comparison, we can Fig. out which material is best for designing wind turbine towers.

3. RESULTS AND DISCUSSION

The comparative modal analysis reveals that steel, CFRP, and GFRP constructions behave very differently, when they are dynamic. As CFRP is stiffer than GFRP, it has greater modal frequencies. On the other hand, GFRP has lower modal frequencies because it is less stiff.
These results can support in choosing materials and make designs better for structural practices. The National Renewable Energy Laboratory (NREL) Horizontal Axis Wind Turbine (HAWT) has to deal with different outside forces, like gusts, turbulent wind flows, wind shear, and gravitational and aerodynamic pressures. When you apply these outside forces to the modal frequencies of different materials, like steel, carbon fiber reinforced polymers and glass fiber reinforced polymer, it can be observed that an impact risk can happen, if the frequencies of these external forces match the modal frequencies of the structure. The modal frequencies of GFRP are 0.472 Hz, steel is 0.866–0.867 Hz, and CFRP is 1.615–1.617 Hz which may be comparable with the frequencies of outside forces. This shows how important it is to choose the right materials and design the structure sensibly to avoid resonance problems and make sure the wind turbine works appropriately.
Results summary:

Material Comparison:

- Steel: 0.866-0.867 Hz
- CFRP: 1.615-1.617 Hz
- GFRP: 0.472 Hz

- ✓ The modal frequency of CFRP is 86% greater than that of steel 242% higher than that of GFRP.
- ✓ Steel's modal frequency is 84% higher than GFRP.
- ✓ GFRP outside forces excite frequencies close to 0.472 Hz, there is a good chance of resonance.
- ✓ Steel (0.866–0.867 Hz): If outside forces stimulate frequencies around 0.866–0.867 Hz, there is a mild to high risk of resonance.
- ✓ CFRP (1.615–1.617 Hz): There is a lower probability of resonance unless outside stimuli explicitly excite frequencies in this range.

4. CONCLUSIONS

The study used Autodesk Fusion 360 to analysed the modal frequencies of a 5MW HAWT structure at NREL reference using structural steel, CFRP, and GFRP materials respectively. The important findings of the study include,

- CFRP had the highest modal frequency (1.615-1.617 Hz), followed by structural steel (0.866-0.867 Hz) and GFRP (0.472 Hz).
- CFRP may be less prone to resonance issues, while GFRP is more susceptible.
- The study highlights the importance of material dynamic behavior in wind turbine design in order to optimize structural performance and minimize resonance risks.
- The results suggest material selection and design optimization strategies, contributing to the development of more efficient, reliable, and sustainable wind energy systems.

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