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"FINITE ELEMENT ANALYSIS OF WIND TURBINE BLADE UNDER STATIC AND DYNAMIC LOADING CONDITIONS"

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ABSTRACT

This study presents a detailed structural analysis of a wind turbine blade using Finite Element Analysis (FEA) to evaluate its deformation and stress behavior under static and dynamic loading conditions. Wind energy has emerged as a sustainable and environmentally friendly alternative to fossil fuels, necessitating the development of efficient and reliable turbine components. In this work, ANSYS Workbench is utilized to model, mesh, and analyze the turbine blade subjected to aerodynamic loading. The results indicate that the maximum deformation of the blade occurs at the free end, with values of approximately 2.010 × 10⁻⁸ m under static conditions and 2.1157 × 10⁻⁸ m under dynamic conditions, while the fixed end experiences negligible displacement. The analysis further reveals the development of biaxial stress due to deformation in multiple directions, with maximum equivalent stress reaching 2288.8 units at the blade root. Principal stress distribution shows both tensile and compressive stresses concentrated near the fixed end, indicating critical regions for structural integrity. The findings confirm that the blade does not behave as a rigid body and is susceptible to deformation and vibration under wind loading. This study provides insights into stress distribution and deformation patterns, which are essential for improving blade design, enhancing durability, and ensuring safe operation of wind turbines.

Key Words: *Wind Turbine Blade, Finite Element Analysis (FEA), ANSYS Workbench, Structural Analysis, Deformation, Equivalent Stress, Dynamic Analysis, Renewable Energy.*

I. INTRODUCTION

The wind turbine was used to pull the water from low levels, and to grind the grains. It is found that the wind mills were used in eastern region like China Tibet, Iran, India earlier than western region of world. The horizontal axis wind mills were used in 200BC and Iranians were use vertical axis turbine in 700 BC, it is also found Babylonians used the wind mills for irrigation purposes. Availability of wind mills moved from Asia to Europe near about 10Th century when the application of wind mill was found in England.

After invention of Steam Engine, a New Industrial revolution come in picture and new Industrial era is Started worldwide and sudden demand of increase and new resources of fossil fuel were discovered and these machines were very useful for Development . The demand of energy is increasing day by day and dependency on wind energy is also increasing day by day. This is because the wind energy does not require and Raw material for operation , as well as operating cost is also low . The use of wind energy to generate electricity first started in Denmark. The 89-Watt wind power plant for electricity generation was built by Danish meteorologist Paul La in 1897. and later on, in 1940-1950s

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An Engineering Firm F L Smith Build wind turbine with two and Three Blades while these power plant Produces DC Current.

The origins of alternating current (AC) wind power can be attributed to Johannes Juul, a student of Paul La Cour, who designed the first AC-based wind power plant [Ref]. A significant milestone in modern wind energy was achieved in 1956 with the establishment of the Gedser wind power plant in southern Denmark, which had an installed capacity of 200 kW. Notably, the facility operated for 11 years without requiring maintenance, demonstrating both reliability and efficiency [3]. Following this development, progress in wind energy technology remained limited until the 1970s, when the global oil crisis intensified the demand for alternative energy sources. The growing awareness of environmental issues during the 1980s further reinforced this transition towards renewable energy [4]. In the 1990s, attention shifted to offshore wind turbines due to the availability of stronger and more consistent wind resources at sea. The first experimental offshore wind project was commissioned in Nogersund, Norway, in 1990 . Subsequently, in 1991, the world's first commercial offshore wind farm was established at Vindeby, Denmark, comprising 11 turbines, each with a capacity of 450 kW [5].

Research and investments in offshore wind turbines gained momentum during the 1990s. The first experimental offshore wind turbine was installed in Nogersund, Norway, in 1990, taking advantage of the stronger wind conditions over the sea. Shortly after, in 1991, the first commercial offshore wind farm was developed in the Vindeby region of Denmark, consisting of 11 units, each with a capacity of 450 kW. During the 2000s, several factors encouraged the expansion of offshore wind energy, including the growing global demand for renewable power, the scarcity of suitable onshore sites, and the rising costs of maintenance and transportation in remote high-wind areas. Consequently, offshore wind turbine installations expanded significantly in countries surrounding the North Sea, particularly Norway, Denmark, Germany, the Netherlands, and the United Kingdom.

Over the past four decades, the depletion of fossil and nuclear resources, rising oil prices, and the challenges of global warming and climate change have significantly accelerated the demand for alternative, clean energy sources. Among these, wind power has emerged as one of the most sustainable options from economic, social, and environmental perspectives, as demonstrated by its rapidly expanding installed capacity over the last two decades.

The year 2020 marked a milestone for the global wind industry, recording its strongest growth in history with a 53% annual increase. Despite disruptions to supply chains and project execution caused by the pandemic, more than 93 GW of new wind capacity was added, raising global cumulative capacity to 743 GW. This expansion contributes to an annual reduction of approximately 1.1 billion tons of CO_2 emissions. Onshore wind capacity alone grew by 59% compared to 2019, reaching 86.9 GW, with China and the United States dominating the market. Together, these two countries increased their market share by 15%, accounting for 76% of global onshore installations. Over the past decade, global wind power capacity has nearly quadrupled, establishing wind as one of the most competitive and reliable renewable energy sources worldwide [6].

II. LITERATURE REVIEW

Research on wind turbines or wind mills systems has spanned a wide range design optimization, structural reliability, control strategies, and application-specific implementations. Considerable efforts have been directed toward improving turbine performance, durability, and efficiency while addressing challenges arising from complex aerodynamic and structural interactions.Wind turbines blade operated under high turbulence zone, with lower layers atmospheric turbulence or wakes of other wind turbines. A wind turbine blade airfoil operating in turbulent inflow is significantly influenced by turbulence intensity, typically ranging between 0.5% and 16%, and by the angle of attack, which can extend up to 90°. Both the **qualitative and quantitative aerodynamic behavior** of the airfoil are strongly dependent on these factors. This influence becomes most evident in the stall region, where the boundary layer separation point moves forward along the leeward surface of the airfoil [1].

In horizontal-axis wind turbines (HAWTs), the wake dynamics further illustrate these effects. While negative angular momentum (associated with power extraction) is removed from the flow, an equal and opposite positive angular momentum is carried within the tip vortices, ensuring overall momentum balance. Additionally, the mean axial velocity

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passing through the rotor plane increases with radial distance from the hub, unlike the nearly uniform velocity distribution observed at peak power operating conditions.

The circulation in the wake is governed by the imbalance between the circumferential components of lift and drag forces acting along the blade span, linking wake dynamics directly to airfoil aerodynamic performance. [2], various investigation has focused on passive regulation mechanisms for small wind turbines.

A study introduced a rigid short tail with an aerodynamic rotating vane, supported by a bumper and spring, designed to control angular velocity by yawing the rotor smoothly under strong wind or gust conditions. This regulator was shown to reduce gyroscopic loads, improve strength compared to conventional vanes, and enhance energy capture efficiency. Field tests further confirmed strong agreement between simulations and experimental outcomes for horizontal-axis wind turbines with rotor diameters between 2 and 12 meters.[3]

Beyond mechanical enhancements, researchers have also explored advanced control techniques for improving wind power plant performance. One such study modeled a standalone wind energy system comprising a turbine and a three-phase synchronous generator connected via a gearbox. To achieve reliable operation, an estimator-based adaptive fuzzy logic control approach was implemented, with test cases demonstrating its effectiveness in ensuring stable and efficient system operation in isolated environments.[4]

In addition to electricity generation, the application of wind turbines for water pumping has been studied extensively, particularly in regions lacking fossil fuel resources. Investigations in Jordan demonstrated the feasibility of both direct mechanical pumping and electricity-driven pumping systems, highlighting wind energy as a practical alternative for meeting the needs of remote villages, settlements, and agricultural farms. These works underscore the socio-economic value of wind energy in rural and resource-constrained regions.[5].

The structural reliability of wind turbine under extreme load has also been analyzed using probabilistic approaches. A procedure based on inverse reliability was developed to establish nominal load within a load cum resistance-factor-design framework, accounting for randomness in both wind conditions and turbine responses. Using 600-kW horizontal-axis turbine as a case study, the method demonstrated that while complete random characterization yields the most accurate extreme load predictions, simplified models that include only wind environment randomness augmented with higher-than-median fractals of extreme responses can provide sufficiently reliable design estimates. This highlights the importance of probabilistic methods in ensuring safe and cost-effective turbine design [6].

III. METHODOLOGY

ANSYS, a product of ANSYS Inc., is a world's leading, widely distributed, and popular commercial CAE package. It is widely used by designers/analysts in industries such as aerospace, automotive, manufacturing, nuclear, electronics, biomedical, and many more. ANSYS provides simulation solutions that enable designers to simulate mulate design performance directly on the desktop. In this way, it provides fast, efficient, and cost-effective product development from design concept stage to performance validation stage of the product development cycle.

It helps accelerate and streamline the product development process by helping designers to resolve issues related to structural, thermal, fluid flow, electromagnetic effects, a combination of these phenomena acting together, and so on. the basics of FEA concepts, modeling, and the analysis of engineering problems using ANSYS Workbench. In addition, description of important tools and concepts is given whenever required.

Finite Element Analysis (FEA) is a computational technique used to obtain approximate solutions for boundary value problems. It is based on the Finite Element Method (FEM), a numerical approach that divides complex structures into smaller, manageable elements. FEA allows engineers to model a design in a computer environment and analyze it under specific conditions to determine responses such as stress, strain, deformation, deflection, natural frequencies, mode shapes, and temperature distributions.

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Modeling and Meshing

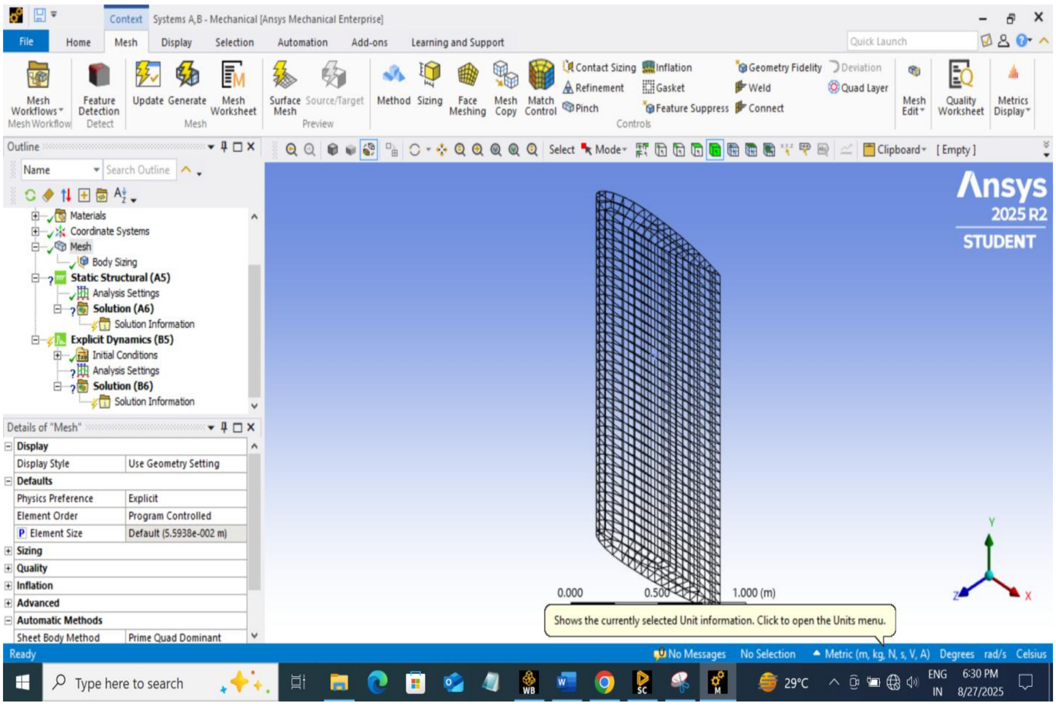

Figure 1 Modeling and Meshing

IV. Result and Discussion

It is seen from the result in figure 2 and figure 3 that deflection of the wind turbine blade is 2.010x10^{-8} at free end and 0 at fixed end.The interpretation of this result is that the wind turbine blade is not behave as a rigid body. It gets deflection under the action of wind pressure.and due to variation in air pressure vibration is generated on the turbine blades

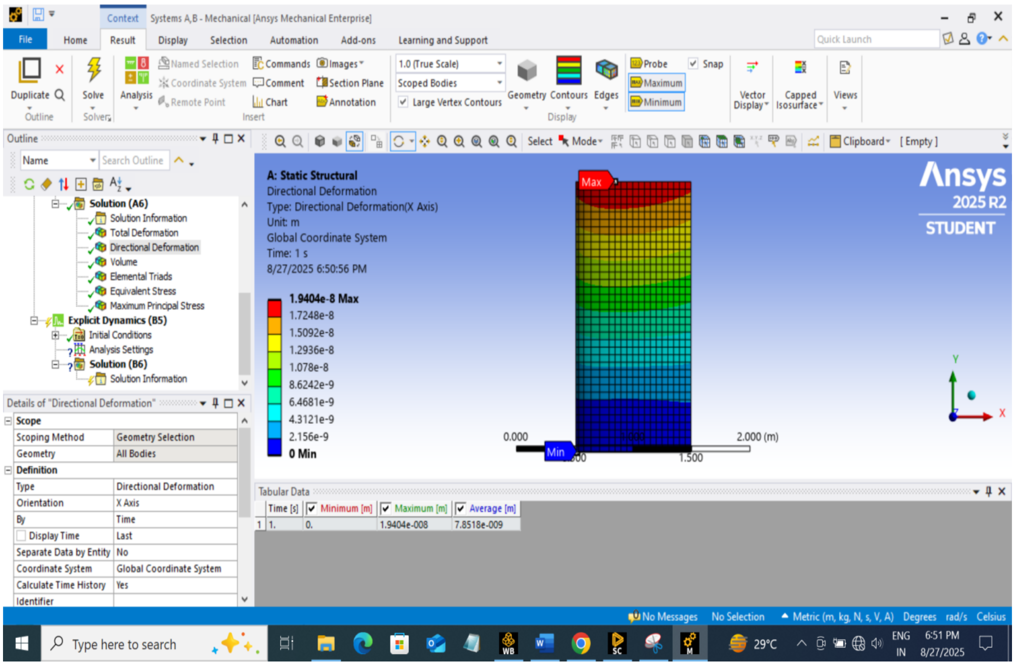

Figure 2 Directional Deformation of Blade

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It is also observed that the blade deflects in third direction also and maximum deformation is 1.940 x 10^{-8} at free end and 0 at fixed end so it is concluded from above both results that the wind turbine blade deflects in both direction the resulting of which biaxial stress is generated at blade . the amount of equivalent stress generated is 2288.8 at the bottom end of the turbine blade and minimum stress 0.67588 at the free end.
While the maximum principal stress developed at the wind turbine blade is 2335.6 at the one end of the bottom side blade and -1133.6 (Compressive in Nature) min. at the other end of the bottom side here both maximum and minimum principal stress generated at bottom side of the blade.

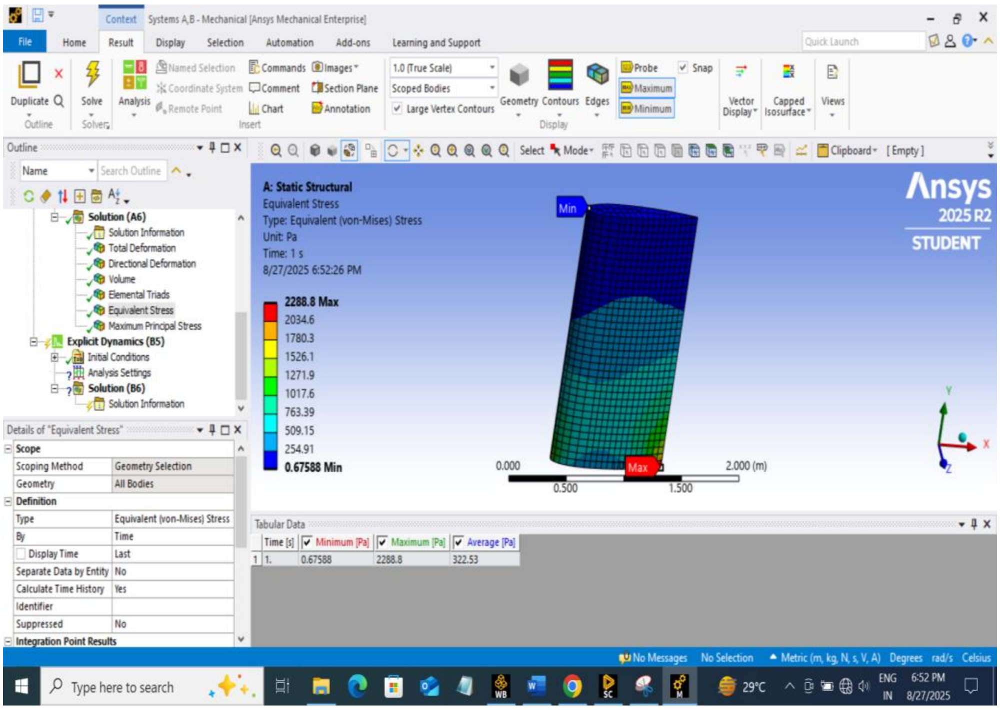

Figure 3 Equivalent Stress Developed in Blade

The total deformation of wind turbine blade under dynamic analysis is 2.1157 x 10^{-8} at the free end of the blade and minimum at 1.019 x 10^{-11} at the bottom end of the blade. Lateral deformation of blade is 1.940 x10^{-8} max and 0.0266 x 10^{-12} minimum at the bottom of the wind turbine blade.the resulting of which biaxial stress is generated in the wind turbine blade the max principal stress generated is 1097.4 and min stress generated is -157.95 at the lower end of the turbine. The conclusion of the statical and dynamical analysis of wind turbine blade is that a wind turbine blade deflects in both directions as shown in the above figure 3.

V. Conclusion

The present study investigates the structural behavior of a wind turbine blade using finite element analysis under both static and dynamic loading conditions. The results demonstrate that the blade undergoes noticeable deformation when subjected to aerodynamic forces, with maximum displacement occurring at the free end and minimum at the fixed support. This behavior confirms that the blade cannot be treated as a rigid body and must be analyzed considering elastic deformation effects.
The stress analysis reveals that the highest equivalent and principal stresses are concentrated near the root of the blade, which acts as the critical region for failure. The presence of both tensile and compressive stresses indicates the development of complex biaxial stress states due to multi-directional deformation. Under dynamic conditions, the deformation slightly increases, highlighting the influence of vibration and fluctuating wind loads on blade performance.

From the results, it is evident that structural integrity and fatigue life of the blade are strongly influenced by stress concentration and deformation patterns. Therefore, proper material selection, geometric optimization, and

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reinforcement at critical regions are essential to enhance performance and durability. The study provides a foundational understanding for further research on aerodynamic optimization, fatigue analysis, and advanced composite blade design. Overall, this work contributes to improving the reliability and efficiency of wind turbine blades, supporting the broader goal of sustainable energy generation.

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