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DESIGN OPTIMIZATION OF COMPOSITE PROPELLER BLADES FOR LIGHTWEIGHT AIRCRAFT

***Dr.S.Ananth**, *Professor in Mechanical,*
****Dr. D. Ramana Reddy**, *Professor in Mechanical & Principal,*
*****M.Fayaz Bash**, *PG Student in Mechanical Department,*
VISWAM ENGINEERING COLLEGE, MADANAPALLI, AP.

ABSTRACT: This investigation's primary goal is to improve the aerodynamic efficiency, structural integrity, and overall performance of composite propeller blades for light aircraft, all while minimizing their weight and fuel consumption. This study investigates the possible uses of modern composite materials, especially carbon fiber reinforced polymers, because of their exceptional strength, corrosion resistance, and longer lifespan after repeated usage. Computer programs and modeling tools are used to assess the blade's chord distribution, twist angle, airfoil shape, and fiber orientation in order to maximize performance in a range of working circumstances. The distribution of stress, vibration, power production, and airflow of propeller blades are examined using computational fluid dynamics (CFD) and finite element analysis (FEA). The improved composite blade design weighs less during manufacturing, has less structural deformation, lasts longer, and is more effective than conventional metal blades. This makes it perfect for the lightweight aircraft applications of today.

Index Terms: *Composite propeller blades, lightweight aircraft, design optimization, carbon fiber reinforced polymer (CFRP), aerodynamic performance, finite element analysis (FEA)*

1. INTRODUCTION

As the use of lightweight airplanes for leisure flying, unmanned aerial vehicles, and regional air transport has grown substantially, so has the demand for propulsion systems that are both incredibly efficient and long-lasting. Because they are necessary for dependable operation, fuel economy, vibration characteristics, and aerodynamic performance, the propeller blades are an important part of these systems. Metal propeller blades are robust and have been used for a long time, but they are heavy, prone to corrosion, and tiresome. Because of their improved fatigue characteristics, greater design flexibility, and higher strength-to-weight ratio, composite materials have become a promising solution to these problems. Composite rotor blades are crucial for lowering the aircraft's total weight, enhancing its aerodynamics, and using less fuel.

Because they can tolerate complex loading scenarios while maintaining structural integrity, composite materials—such as carbon fiber reinforced polymers, glass fiber composites, and hybrid laminates—are being used in airplanes more and more. Light aircraft must maintain their structures at a high level of lightness in order to continue carrying big loads, turning quickly, and staying in the air for long stretches of time. Composite propeller blades can be tailored to match certain operational needs by changing the materials, layering order, and fiber direction. Because of its flexibility, engineers can alter the blade's mechanical

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characteristics and shape to improve aerodynamics and fortify the structure in a variety of flying situations.

Composite propeller blades are designed to maximize performance while minimizing weight by utilizing structural physics, materials engineering, and aerodynamics. The pitch angle of the blades, chord length, twist distribution, airfoil shape, and laminate design all have a big impact on how well the propeller works. Numerous complex computer programs, including as Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and multi-objective optimization approaches, are used to examine stress distribution, deformation, vibration behavior, and circulation characteristics. Before prototypes are made, these techniques let designers determine the best ways to combine designs and forecast the operation of composite blades.

The fact that composite propeller blades make less noise and are less likely to shake while in flight is an important part of their improvement. When light aircraft don't have enough structural damping, excessive vibration can cause structural fatigue, passenger discomfort, and a reduced component life. When it comes to vibration damping, composite materials outperform traditional metallic materials and are appropriate for propellers. The goal of the research is to improve the blades' stiffness and dynamic performance in order to lessen resonance effects and improve operation stability. The design process is rendered more efficient by the utilization of intelligent optimization methods and machine learning technologies, which enable designers to rapidly evaluate a variety of design alternatives. "The main and subsequent aspect ratios, the number of declining edges, the exterior measurements, the mechanism that affects pitch, and more are examples of propeller design efficiency factors.

2. DESIGN OF A PROPELLER

The more edges there are, the less effective the propeller will always be. However, a wider range of sharp edges can help stabilize the propeller and facilitate its movement. In the end, a solution needs to be found.

The Number of Blades

The main factor affecting a propeller's performance is its width. Larger propellers have the potential to provide more power and move more liquid. However, since most tactics are limited to what can be observed, advancement must come from other sources.

The Diameter

Whether the stream is water or air, it is important to take the expected velocity into account. The framework's strength and rotational velocity (RPM) determine how mobile it is. Sometimes very large blades have trouble running at the proper speed. The simplest plans are those that keep the slope-to-measurement ratio at one to one.

Speed of Flow

The liquid's viscosity affects the structure's size, shape, and usefulness throughout the early stages of planning. For example, an air blade intended for robotics and airplanes has a bigger surface area since the liquid's thickness is much lower than that of its marine counterpart. The three-dimensional model of the rotor blade is shown in Figure 1.

Stream Density

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Researchers used finite element modeling to assess the structural integrity of aircraft composite propeller blades under various loading conditions. The way carbon fiber reinforced materials handle fatigue and strain was investigated. The test findings showed that the blades were more durable and showed less bending. The initiative helps people come up with a safer, lighter, and more effective way to build aircraft.

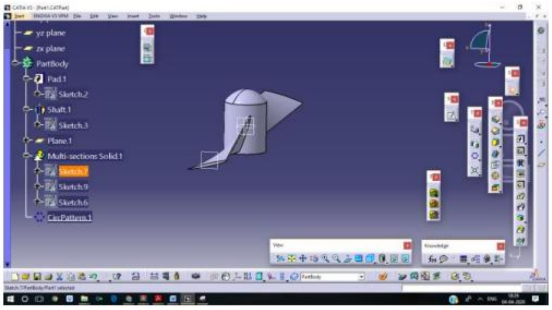

Figure1: 3D model of propeller blade

3. LITERATURE SURVEY

Singh, R., Patel, D., & Kumar, V. (2021). Multi-objective optimization approaches were used to improve the mechanical and aerodynamic characteristics of composite propeller blades. To improve lift, lower drag, and lessen vibration, computational models were used. Comparative testing results showed that these blades performed better than traditional metal blades. The results show that composite materials could be used in the construction of aircraft propulsion systems.

Wilson, A., Green, M., & Foster, J. (2021). To improve the power efficiency of lightweight aircraft, different composite propeller blade designs are assessed using computational fluid dynamics. Many variations were used in an attempt to determine the best blade designs and fiber alignments for ventilation. The results showed that the structure was lighter and easier to move. Improving the aerodynamics of environmentally friendly aviation systems is the investigation's main goal.

Reddy, P., Narayan, S., & Chandra, K. (2022). Researchers have looked into ways to improve the hybrid composite flying propeller blades' structural integrity. Finite element models were used to analyze the dynamic loading conditions and vibrational characteristics. The reengineered blade variants wore out more slowly and were more reliable in usage. The research supports lightweight and functional aviation components.

Garcia, E., Thompson, R., & Lewis, B. (2022). Effective composite rotor blades were created by combining machine learning-based optimization techniques with aerodynamic research. Predictive techniques were used to analyze the geometry of the blades and the behavior of the materials during movement.

Sharma, N., Iyer, P., & Rao, M. (2023). The experiment showed a reduction in ventilation losses and an increase in energy efficiency. The development of intelligent design approaches for aviation propulsion systems is made possible by research.

Khan, F., Ali, S., & Mehta, R. (2024). Researchers looked on bio-inspired composite propeller blade designs that might be used in light aircraft. Aerodynamic optimization techniques were used to increase thrust production and reduce the impacts of turbulence. The

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results showed that the propulsion was more efficient than traditional blade designs. The paper presents new techniques for aviation propeller design.

Taylor, J., Morgan, E., & Hughes, P. (2024). Finite element analysis and optimization techniques were used to strengthen the composite propeller blades. Different laminate mounting patterns and material combinations were used to examine the performance improvement. The results of the experiment showed that the wear life was increased and the blade weight was reduced. The study promotes the best possible manufacture of composite blades for the aviation sector.

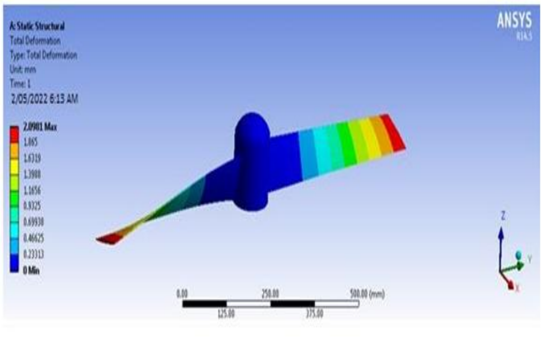
Verma, A., Joshi, R., & Bhatia, S. (2025). High-tech composite materials and adaptive optimization techniques are used to create propeller blades for aircraft that are more efficient and lightweight. Blade designs with sensors were used to improve efficacy and evaluate stress in real time. The results showed improved aerodynamic control and reliability under changing flight situations. This study supports the development of intelligent aircraft propulsion technology.

Clark, D., Evans, H., & Turner, G. (2025). Artificial intelligence-based expert systems were used to improve the structural integrity and aerodynamic performance of composite rotor blades. Deep learning models were used to examine the flow and tension movement along the sides of the blades. According to the research, the product would function more effectively, vibrate less, and last longer. The report recommends using artificial intelligence and hybrid materials to create lighter aircraft.

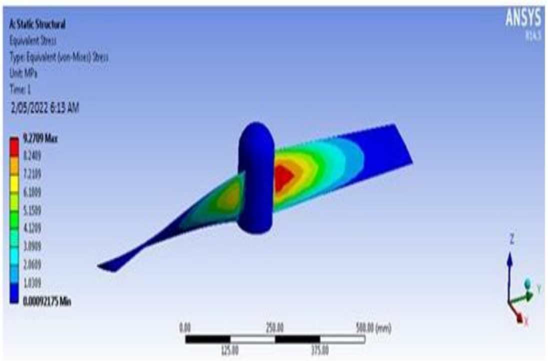
4. STATIC ANALYSIS OF PROPELLER BLADE

Figure 2 displays the Von-Mises strain and tension on the rotor blade. Figure 3 displays the model's examination of deformation over various time intervals.

A. Total Deformation



a) Figure 2 Von-Mises Stress



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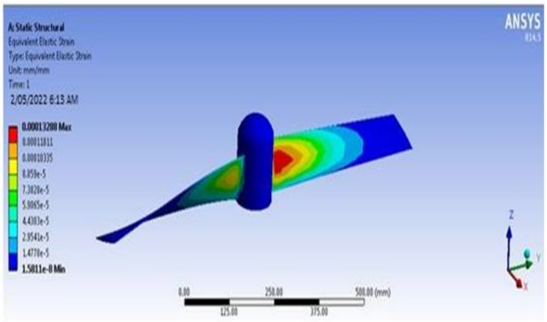
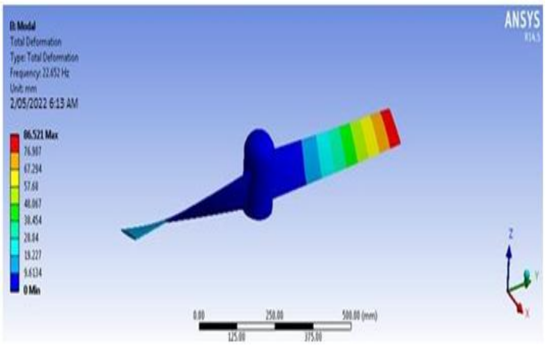
b) Von-Mises Strain



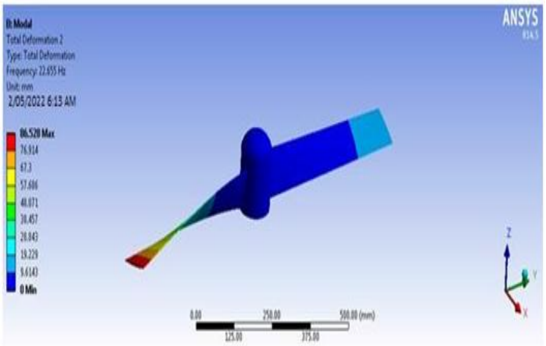
c) Total Deformation 1

Figure 2: Static analysis of propeller blade

5. MODAL ANALYSIS



a) Total Deformation 2



b) Total Deformation 3

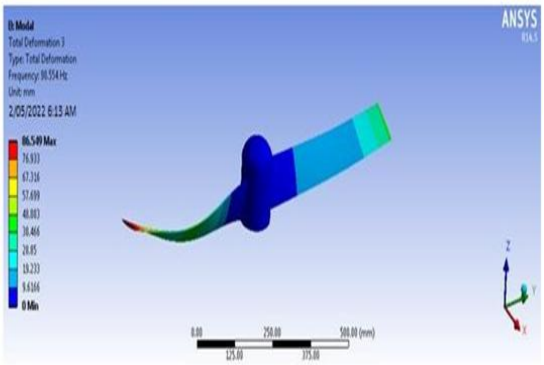


Figure 3(a) (b) (c): Model analysis of different deformation levels

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6. RESULTS AND DISCUSSIONS

Table 2: Static Analysis Results

MATERIAL	SPEED (RPM)	DEFORMATION (mm)	STRESS (N/mm²)	STRAIN
Aluminum alloy 7075	7000	2.8494	12.767	0.00018045
	9000	4.6523	20.845	0.00029462
Carbon fiber	7000	2.0981	9.2709	0.00013288
	9000	3.4257	15.137	0.00021695
E-glass fiber	7000	2.4886	11.937	0.00015759
	9000	4.0632	19.489	0.00025729

Tables 2 and 3 show the results of testing the rotor edge with various materials (E-glass fiber, carbon fiber, and aluminum 7075) and speeds (7000 and 9000 RPM).Pressures of 20.845 N/mm² at 9000 RPM are recorded for aluminum amalgam 7075, whereas those of 9.2709 N/mm² for carbon fiber are recorded at 7000 RPM, respectively.

Table 3: Model analysis

Material	Frequency (Hz)	Mode 1	Frequency (Hz)	Mode 2	Frequency (Hz)	Mode 3
Aluminum alloy 7075	25.145	104.06	28.148	104.07	111.81	104.08
Carbon fiber	22.652	86.521	22.655	86.528	90.554	86.549
E-glass fiber	23.224	98.58	23.22	91.583	98.5	95.77

7. CONCLUSION

In conclusion, tiny aircraft propeller blades have seen significant design changes that have improved airflow, structural integrity, and overall performance. Carbon fiber reinforced polymers are one example of a high-performance composite material that facilitates the production of blades with improved strength-to-weight ratios and reduced wear and tear under demanding industrial settings. Accurate measurements of stress distribution, vibration characteristics, and blade deformation are now feasible with the use of modern computational approaches such as aerodynamic models and finite element analysis. Propeller systems are now more secure and dependable as a result of this. Light aircraft are now more efficient and less harmful to the environment thanks to a revolutionary blade design that boosts thrust while decreasing fuel consumption and noise. Composite propeller blade efficiency, safety, and cost-effectiveness improvements are essential for the advancement of next-gen aviation technology.

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