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Numerical Comparison of Tilt Rotor Propeller Composites Materials of Carbon Fiber-Reinforced Plastic (CFRP), Wood, and Plastic

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Abstract: *CFRP, wood and plastic are all alternative materials for manufacturing propellers. As for the type of material used in the research, it mainly depends on its physical and mechanical properties, manufacturing method and cost. In this study, the performance of tilting propellers of different materials is compared, and the technology of noise level, durability and stiffness of the three materials is optimized through the comparative test of tilting propellers. Firstly, this article provides a detailed introduction to typical samples of CFRP, wood, and plastics, as well as their physical and mechanical properties and manufacturing processes. Physical and mechanical properties include density, tensile strength, compressive strength, elastic modulus, impact strength and thermal expansion coefficient. Because tilting propeller is an important power plant, its basic performance is silence, and the problem of unstable tilting often fails for a long time. Noise level test checks the noise level of three materials. Further measuring the stiffness after completing the stiffness experiment leads to the reduction of redundant items in the stiffness experiment. The stiffness, noise level and durability of the three materials are compared by statistical software analysis method to evaluate the overall performance of the three materials. The experimental results show that the composite CFRP material is poor in fin material. The maximum noise level of the propeller made of CFRP is only 88dB, the minimum pressure level is 400MPa, and the maximum stiffness is 270 N/mm. In addition, the noise level in the middle position of the propeller is also very low, which means that CFRP has a good potential to be applied to high-performance inclined propellers. Although CFRP is expensive, its excellent performance may make it the most economical choice in the long run. This work provides a scientific method for the material selection and process optimization of tilting rotor, which is helpful to promote the development of propeller aircraft towards more energy-saving and environmental protection.*

Keywords: *CFRP; Tilting Propeller; Performance Evaluation; Process Optimization*

1. Introduction

As a key propulsion device, the design and material selection of tilting propeller directly affect the performance of aircraft machinery. With the development of lightweight, high-strength and durable materials, it is difficult for traditional materials to meet the material requirements of modern aircraft. CFRP, wood and plastic are three new materials that meet the requirements, and these three materials have strong performance advantages. At present, the performance and technology of existing materials have not reached the optimal value of propeller, so it needs further study.

In this paper, the properties of CFRP, wood and plastic in manufacturing tilting propeller are studied through comprehensive experiments and data analysis. The experimental results show that the three materials show different noise, durability and stiffness, and there are obvious differences. The test shows that the CFRP propeller has the best noise, the lightest weight and the structure is not easy to break. In addition, this paper also discusses the manufacturing process characteristics and cost-effectiveness of different materials, which provides practical reference for equipment manufacturers in material selection and manufacturing process.

This article first introduces the background and significance of the research, clarifies the importance of tilting propellers in aircraft, and the key role of material selection. Next, this article elaborates on the characteristic analysis of CFRP, wood, and plastic materials, compares their manufacturing processes, and describes process optimization strategies. In the Results and Discussion section, this article presents experimental data, compares and analyzes the properties of different materials, and discusses process optimization strategies. Finally, the article summarizes the research findings and proposes future research directions and practical application suggestions. The reference section lists the literature materials used for writing and research processes.

2. Related Work

In the fields of aviation and composite material manufacturing, with the continuous progress of technology, researchers are committed to exploring and optimizing various innovative technologies and material applications. Liao Yixiao adopted a distributed electric propulsion wing configuration similar to X-57 and studied the effect of distributed propeller tilt on the aerodynamic characteristics of the wing through the equivalent disk method. In addition, he also introduced the equivalent disk method and validated it with experimental data and Computational Fluid Dynamics calculation data, comparing the lift and drag characteristics of takeoff and landing configurations with and without the influence of sliding flow at different angles of attack[1]. Yan Wenhui studied the complex aerodynamic interference between rotor propellers and wings in order to optimize the aerodynamic layout of tiltrotor aircraft. Taking into account the three-dimensional effects of finite wingspan and wingtip small wings, the aerodynamic interference law between rotor propellers and wings was studied by changing the length of the outer wing segment of the wings[2]. Huo Yujia proposed a buoyancy estimation model for cross domain robots propelled by tilting propellers in a near water environment to address the issue of surface takeoff. On this basis, in order to solve the problem of the dynamic attenuation of the robot propeller near the water surface affecting the water surface takeoff, he proposed a cross domain robot phased water surface takeoff method based on deep reinforcement learning[3]. Cong Qing had developed a large-sized composite material propeller for ships based on the vacuum bag pressing process of pre impregnated and semi pre impregnated materials, solving key problems such as mold design, process control, and cost control. This had accumulated practical experience for the low-cost and rapid manufacturing of large-sized composite material propellers[4]. Sun Zongyan modified the wing parameters of the Y-12F aircraft modified to a distributed propeller aircraft based on momentum theory, with the cruising performance as a constraint. He comprehensively evaluated and determined the number of distributed electric propulsion propellers from three aspects: propeller disc area, matching relationship between propeller and electric motor, and propeller quality[5].

Not only that, Adeniran O reported the effect of environment (temperature and relative humidity) on the mechanical properties of additive manufactured CFRP composites exposed to three different environmental conditions (temperature and humidity, warm dry, and cold dry). Compared with samples immediately tested under normal environmental conditions, high temperatures had no significant effect on the mechanical properties of composite materials, while low temperatures near zero degrees had a significant impact on the short-term exposure period of composite materials[6]. Morkavuk S investigated the drilling workability characteristics of CFRP pipes produced by filament winding method and compared them with CFRP plates produced by vacuum bagging method. The experimental results showed that compared with the pipe material, the composite plate generated greater force and damage during drilling, making its machinability more difficult[7]. Adeniran O investigated acrylonitrile butadiene styrene and polyamide matrices, which represented the majority of amorphous and semi crystalline engineering grade thermoplastic matrices used in CFRP composite applications[8]. Morkavuk S conducted experimental research on the drilling workability of flat, convex, and concave curved carbon fiber reinforced plastics. The experimental results indicated that the maximum thrust and damage were generally achieved when drilling on a flat surface, while the minimum thrust and damage were achieved when drilling on a concave surface[9]. Qin T explored a low damage gas assisted laser processing method for carbon fiber reinforced plastics, using a quasi-continuous fiber laser cutting machine (with a maximum peak power of 4500 W) and three methods of coaxial nitrogen, coaxial oxygen, and coaxial oxygen near axis nitrogen composite gas assisted laser marking for carbon fiber reinforced plastics, and studies their impact on cutting quality[10]. Although the above research has made significant progress in the manufacturing of composite propellers and CFRP composite materials, there is still insufficient research on the comprehensive process comparison and optimization of different material systems (such as CFRP, wood, and plastic) in the manufacturing field of tilting propellers. The purpose of this study is to fill this gap by comparing the process characteristics of CFRP, wood, and plastic in the manufacturing of tilting propellers, and evaluating their comprehensive performance in terms of performance, noise level, and durability.

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3. Method

3.1 Material Characteristic Analysis

In the process comparison and optimization research of tilting propeller manufacturing, the first step is to analyze the characteristics of CFRP wood and plastic materials. The analysis content includes a comparison of physical and mechanical properties, while also considering the fatigue life and impact damage resistance of materials, as these factors are crucial to the performance of tilting propellers[11-12]. The results are shown in Table 1:

Table 1: Performance analysis of CFRP wood and plastic.

Material Property	Carbon Fiber Reinforced Polymer (CFRP)	Wood	Plastic
Density (g/cm³)	1.5-2.0	0.5-0.8	1.04
Tensile Strength (MPa)	1000-3000	30-200	24-55
Compressive Strength (MPa)	80-170	10-70	50-80
Modulus of Elasticity (GPa)	40-140	10-20	2-4
Impact Strength (J/m)	50-500	0.5-5	80-150
Coefficient of Thermal Expansion (μm/m/°C)	1-10	6-30	60-80
Fatigue Life (cycles)	High	Medium	Low
Cost ($/kg)	High (20-100)	Low (0.1-1)	Medium-Low (1-10)
Machinability	Difficult	Easy	Moderate
Availability	Moderate to High	High	High
Environmental Impact	Recyclable	Biodegradable	Limited recyclability
Sustainability	High	High	Medium to High

The major physical and mechanical properties of CFRP, wood, and plastic materials used in the development of tilting propellers are listed in Table 1. This provides a significant reference to researchers and engineers to properly choose such materials meeting the needs of the applications they intended and optimize the design and manufacturing process of propellers according to the cost, performance, and environmental concern. Material cost C includes material cost C_m, processing cost C_p, and transportation cost C_t:

$$C = C_m + C_p + C_t \tag{1}$$

In terms of CFRP, the process of sequence and production complexity and cost also needs to be regarded when compared to wood with low availability and cost, and its environmental resistance, and plastic with lower cost and process ability, as well as CFRP has an impact on the decision. Meanwhile, economic and environmental considerations also need to be taken into account[13-14]. Hence, the collection and comparison of data on these materials by researchers in this field is expected to propose a solid base for further process optimization. In addition, this can facilitate the determination of the most suitable material for the system under consideration, so that the existing model can be well adjusted to the conditions and achieve the maximum degree of performance optimization and cost-effectiveness. The cost-benefit analysis formula is:

$$\text{Cost Benefit Ratio} = \frac{\text{Benefits - Costs}}{\text{Costs}} \tag{2}$$

$\text{Cost Benefit Ratio}$ is the cost-benefit ratio, Benefits is the total income, Costs is the total cost.

3.2 Comparison of Manufacturing Processes

CFRP, wood, and plastic each exhibit different process characteristics and performance advantages[15-16]. The manufacturing process of CFRP includes key steps such as material cutting, lamination, curing, and post-treatment. Its advantages lie in high specific strength and stiffness, which can produce lightweight, high-strength propellers with good fatigue resistance and impact resistance. However, it also comes with high manufacturing costs and complex process. The calculation formula for tensile strength σ is:

$$\sigma = \frac{F}{A} \tag{3}$$

F is the applied force, and A is the cross-sectional area.

The manufacturing of wood propellers relies on traditional wood craftsmanship techniques, such as carving and polishing, which have lower costs and simpler processes. Although they are not as strong, rigid, and durable as CFRP, they have certain aesthetics and are greatly affected by environmental temperature and humidity[17-18]. The manufacturing of plastic propellers is achieved through methods such as injection molding, thermoplastic molding, or 3D printing, which have the characteristics of high manufacturing efficiency and low manufacturing cost. They are suitable for large-scale production. Although their strength and stiffness are relatively low, using high-performance plastics such as ABS can improve performance to a certain extent. In terms of process optimization, automated layer rapid solidification technology or the use of advanced 3D printing materials can effectively improve manufacturing efficiency and reduce costs. At the same time, it is necessary to comprehensively consider the performance, cost, manufacturing efficiency of materials, and the application requirements of the final product, to ensure that the selected process can meet both performance requirements and economic benefits. In addition, sustainability factors such as material recycling and energy consumption during the production process are also important aspects that must be considered.

3.3 Process Optimization Strategy

The process optimization strategies for CFRP, wood, and plastics include optimizing process parameters and improving quality control and performance testing methods. For CFRP propellers, optimizing the curing temperature and time can improve the degree of resin curing and the mechanical properties of the propellers，The curing reaction formula of CFRP is:

$$k(T) = A \cdot e^{-\frac{Ea}{R \cdot T}} \tag{4}$$

$k(T)$ is the curing reaction rate constant at temperature T, A is the frequency factor, Ea is activation energy, R is the gas constant, e is the base of the natural logarithm.

For wood propellers, optimizing the drying process can prevent cracking and deformation, while coating technology can improve their durability. The adjustment of manufacturing parameters such as injection speed, pressure, and cooling time for plastic propellers can help reduce defects and improve production efficiency. In terms of quality control, strict quality control processes are implemented, including monitoring of raw material inspection processes and final product testing, ultrasonic testing and mechanical performance testing of CFRP propellers to ensure they meet high strength and stiffness requirements, moisture and durability tests are conducted on wooden propellers to ensure their adaptability to different working environments, while impact and thermal stability tests are required on plastic propellers to ensure their long-term reliability[19-20].

The optimized process flow includes the preparation of pre impregnated materials for CFRP propellers, automated laying, hot pressing, curing, mechanical processing, surface treatment performance testing and quality inspection, wood drying design, cutting, manual polishing, coating protection, assembly testing, performance evaluation and packaging for wood propellers, as well as mold design for plastic propellers, preparation of plastic particles for injection molding, cooling, curing, post-treatment quality inspection and performance verification. Through these optimization strategies, production efficiency can be improved, manufacturing costs can be reduced, and the performance and quality of the final product can be improved. Automated layering and rapid curing technology can reduce the production cycle of CFRP propellers, while optimized drying and coating processes can improve the durability and aesthetics of wood propellers. For plastic propellers, precise control of injection molding parameters can reduce material waste and improve product yield. The optimized process will combine material characteristics, cost-effectiveness, and market demand to achieve efficient, economical, and reliable production of tilting propellers.

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4. Results and Discussion

CFRP, wood, and plastic are candidate materials for the manufacture of tilting propellers, each with unique physical properties and manufacturing advantages. In the previous text, the optimization of performance parameters for these three materials was achieved. In order to understand the differences in key performance indicators such as noise level, durability, and stiffness among these three materials, this study aims to reveal their potential and limitations in practical applications through comparative experiments. Through a comprehensive evaluation of these materials, this study aims to provide scientific decision-making basis for the design and manufacturing of high-performance tilting propellers, thereby promoting the development of aircraft towards a more efficient and environmentally friendly future.

At the beginning of the experiment, 18 optimized samples of CFRP, wood, and plastic propellers of different sizes were obtained. These steps ensure the rigor of the experiment and help accurately evaluate the performance of CFRP wood and plastic in the manufacture of tilting propellers, providing scientific basis for selecting the most suitable materials.

4.1 Noise Level

Noise pollution has become one of the important indicators for measuring aircraft performance, especially in urban aviation and military applications, where noise level control is particularly crucial. Therefore, the importance of noise level comparison experiments is self-evident, as shown in Figure 1:

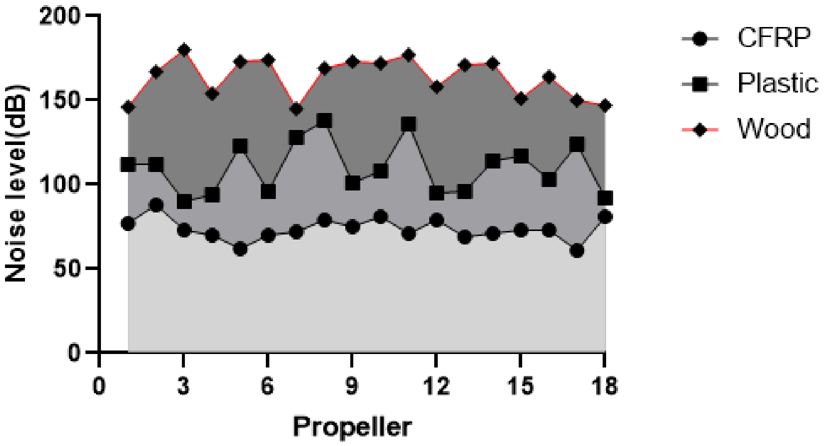

Figure 1: Comparison of noise levels

As shown in Figure 1, the noise level of tilting propellers manufactured from CFRP raw materials is lower than that of propellers made from plastic and wood raw materials. The maximum noise level of CFRP tilting propellers is only 88dB, and the minimum is only 61dB. However, the highest noise levels for plastic and wood are 138dB and 180dB, respectively. The low noise characteristics of CFRP propellers make them an ideal choice for high-performance aircraft, especially in applications with strict noise requirements, such as urban air traffic and special operations aircraft.

4.2 Durability

For tilting propellers, their materials must be able to withstand long-term cyclic loads and various environmental conditions. The durability performance of CFRP, wood, and plastic materials will directly affect the service life and maintenance cost of propellers. This study measured it using load levels, and the experimental results are shown in Figure 2:

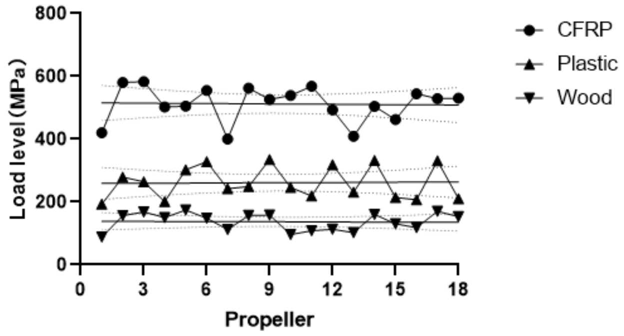

Figure 2: Durability comparison

As shown in Figure 2, it is evident that the load level of CFRP tilting propellers is higher than that of wood and plastic. According to the data in Figure 2, the lowest load level of CFRP tilting propellers is 400 MPa, while the highest load levels for wood and plastic are only 193 MPa and 88 MPa. The high load level of CFRP propellers means they can withstand greater aerodynamic loads, making them suitable for higher performance aircraft.

4.3 Stiffness

The stiffness directly affects the vibration characteristics, handling stability, and overall structural reliability of the propeller. The comparative data is shown in Figure 3:

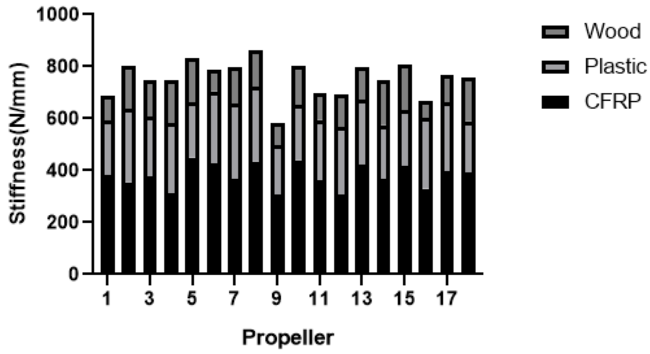

Figure 3: Comparison of stiffness.

After analysis in Figure 3, it is found that among all tilting propellers made of CFRP as raw material, the highest stiffness reaches 449N/mm and the lowest is 307N/mm. The highest stiffness of plastic propellers reaches 270N/mm and the lowest is 239N/mm. In the same situation, the maximum stiffness of wood is only 178N/mm. The high stiffness of CFRP propellers also means that they are less prone to fatigue damage during long-term operation, which helps improve the durability and reliability of propellers and reduce maintenance costs.

5. Conclusion

In this study, through the comprehensive process comparison and performance evaluation of the application of CFRP wood and plastic in the manufacture of tilting propeller, the following conclusions are drawn: After process optimization, CFRP shows excellent performance in key performance indexes such as noise level durability and stiffness, and its tilting propeller has the lowest noise level durability and the highest stiffness performance; although wood and plastics are attractive in some applications because of their cost-effectiveness, there is a significant gap between their performance indexes and CFRP. The process optimization strategies put forward in this study, including process parameter optimization, quality control and performance test method improvement, provide feasible ways to improve production efficiency, reduce costs and improve product quality; future research can explore the manufacturing process of CFRP and how to reduce costs and improve production efficiency and product performance through material innovation and process improvement.

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