

Trends in Mechanical Engineering and Technology

Volume- 16, Issue- 3 (2026)

eISSN-2231-1793

Article Type: Review

Received Date: 17 July 2026

Accepted Date: 18 September 2026

Published Date: 10 October 2026

A Review on Design and Flow Analysis of Quadcopter Propellers

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Abstract—The quadcopter is a complex system in which propeller blades, aerodynamics, and structural behavior are tightly interlinked. Changing a small detail, such as blade angle or material, can significantly affect performance parameters like thrust and efficiency, as well as the drone's vibrations and stability in flight. Because quadcopters typically operate at Reynolds numbers between roughly 20,000 and 150,000, propeller theories developed for full-scale aircraft often fail to translate directly, making low-Reynolds-number behavior a recurring theme across the literature. This review surveys recent studies that focused on UAV propeller designs and analyzed the influence of a variety of parameters, such as chord, twist, angle of attack, number of blades, and propeller materials. An overview of analytical solutions, including the Blade Element Momentum Theory (BEMT), as well as thrust sizing relations, is presented briefly, along with evidence that properly corrected BEMT predictions typically carry thrust errors near 10% and efficiency errors under 5%. In this work, numerical methods such as CFD and FEA are applied to study isolated propellers and the entire quadcopter configuration, while material comparisons spanning PLA, carbon-fiber composites, and advanced 3D-printed resins illustrate how stiffness and fatigue life directly influence blade deformation and flight endurance. Based on previous literature, the identified research gaps in the reviewed studies are mainly the ones that indicate the necessity of a holistic design approach that should involve geometric modification, material substitution, and combined aerodynamic–structural evaluation, particularly through coupled BEMT-CFD-FEA frameworks that remain rare for sub-100 mm diameter UAV propellers operating below a Reynolds number of 100,000.

Keywords—Quadcopter, UAV propeller, Blade Element Momentum Theory, CFD, chord length, inflow angle, material selection

I. INTRODUCTION

As quadcopters become more widely used for aerial imaging, aerial inspections, agriculture monitoring, and logistics, it is increasingly important to understand their capabilities. Of all the quadcopter's systems, the propeller has the most profound impact on the quadcopter because it affects thrust, endurance, noise, and stability in a particular motor–battery combination.

UAV propeller researches can generally be divided into three main categories: (i) aerodynamic design and performance prediction using analytical or semi-empirical models such as BEMT, (ii) detailed flow-field analysis using CFD for single rotors and multi-rotor configurations, and (iii) structural and material studies using FEA and modal analysis. Each method provides their own useful results, yet most existing studies consider the topics independently. The present paper seeks to pointing out the possibility of integrated design studies, showing how the propeller geometry and material selection together define its performance and how can we optimally combine these two elements.

The scale of operation is an important factor to consider when developing propellers for small UAVs. For quadcopters in particular, the Reynolds number lies roughly between 20,000 and 150,000. Propeller designs for full-scale aircraft propellers are not reliable in this scale of operation due to laminar-to-turbulent transition, increased viscous drag and early flow separation. Also, the performance prediction using BEMT and CFD is different from that for full-scale propellers and requires special calibrations for low-Reynolds-number operation.

II. THEORETICAL BACKGROUND FOR UAV PROPELLER DESIGN

A. Blade Element Momentum Theory (BEMT)

Blade Element Momentum Theory is commonly utilized to forecast propeller and rotor performance. In BEMT, the blade is divided into radial elements, and aerodynamic forces are computed using the two-dimensional airfoil data that are combined with axial and tangential momentum theory. The elemental forces are added along the span of the blade to calculate the total thrust and torque. Among the studies validating BEMT, there are small-scale UAV propellers with the proper low-Reynolds-number airfoil data and the loss corrections [1]. Enhanced BEMT formulations incorporating tip-loss corrections and improved airfoil extrapolation have shown thrust prediction errors of about 10% with efficiency errors below 5% compared to experimental results [2]. These findings illustrate that BEMT can serve as a trustworthy instrument during the initial design stage and also in the parametric analysis of UAV propellers (fig 1).

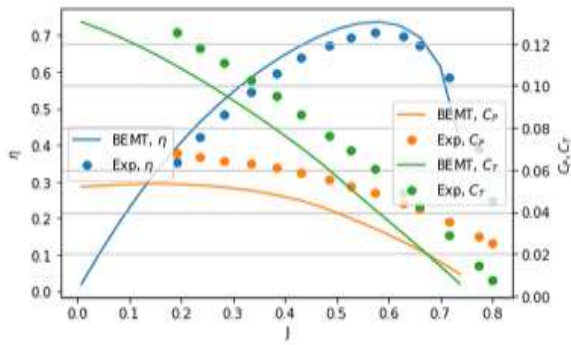


Fig. 1. Comparison of simulated and experimental results

B. Take-off and Sizing Relations

As well as performance prediction, thrust and power relations play the key role during the initial stages to estimate. The momentum-theory-based equations for thrust, which are related to the propeller diameter, air density, and shaft power, shall be taken into consideration, and they shall be validated with empirical tools. The generally accepted guideline is that the total available thrust should be at least two times the total weight of the quadcopter in order to take off and to maneuver safely [3]. Such relations enable the connection between propeller design options and system-level constraints practically. Another important set of sizing parameters is the disc loading (thrust per unit rotor disc area) and the figure of merit (hovering efficiency of rotor to ideal actuator disc). In the particular case of small quadcopters, the non-optimally designed rotors achieve efficiencies of 0.30-0.55, while optimized rotors for full scale aircraft can reach efficiencies of up to 0.80. By minimizing the disc loading and maximizing the figure of merit through rotor design, it is possible to achieve large hover endurance improvements without increasing motor power. Typically this can be achieved with larger propellers at lower RPM.

C. Thrust and Power Coefficients

Non-dimensional performance coefficients, like thrust coefficient (CT), power coefficient (CP), advance ratio (J), and propulsive efficiency (η) are quite helpful in the comparison of different propeller geometries and operating conditions. $CT = T / (\rho n^2 D^4)$, $CP = P / (\rho n^3 D^5)$, $J = V / (n D)$, and $\eta = J \cdot CT / CP$ are equations that help one to find

thrust, propeller shaft power, air density, rotational speed in rev/s, propeller diameter, and flight speed forward. The current literature identifies that even though these coefficients are fully validated for classical propellers, the wing propellers in the low Reynolds number hydrodynamic regime remain majorly unsupported, thus calling for the studies in the said area to be extended [4].

The nonexistence of verified low-Re propeller performance databases puts in place a challenge for design engineers, as BEMT calculations take for granted existing 2D airfoil polars at Reynolds numbers that are typical for every blade section. In the lack of this specific data, the forecast of performance displays a large error at low advance ratios where thrust and efficiency are overestimated, thus resulting in the design of equipment that work below the bench mark in reality. This situation puts emphasis on utilizing CFD generated airfoil data and thoroughly drafted experimental measurement campaigns.

III. EFFECT OF GEOMETRIC PARAMETERS ON PROPELLER PERFORMANCE

A. Mathematically Designed Versus Commercial Propellers

The implementation of mathematically designed propellers has been found to be more beneficial compared to commercial propellers and studies have also revealed that geometry optimization is beneficial. Blade element theory derived propellers with optimized chord and twist distributions based on low Reynolds number airfoils (Eppler E63) are more efficient and better performing than standard commercial APC propellers [5]. The results from CFD, BEMT and physical testing validate the capabilities of analysis design methods.

Mathematically designed E63-based propeller experimentally showed a peak propulsive efficiency of about 70% at an advance ratio of 0.58. It outperformed APC Slow Flyer and NACA based designs for all tested operating conditions [5]. The Blade Element Theory (BET) predictions were found to coincide with the CFD simulation results within 10 percent error at higher RPM ranges and the error decreased at lower rotational speeds. These findings support the idea of BEMT to inform the choice of propeller geometry with reasonable precision, and CFD offers the extra fidelity required to resolve pressure distributions and local flow details which are inaccessible to analytical approaches.

B. Angle of Attack and Inflow Angle (Twist)

The inflow angle and the local angle of attack are different along the span of the blade because of rotational and induced velocities. It has been observed that with comparisons between untwisted and twisted propellers, that the performance of the propeller with spanwise twist is much better due to a uniform effective angle of attack [6]. Although higher angles of attack enhance thrust, they also enhance drag and power consumption, meaning that the twist distributions should be optimized as opposed to uniform blade angles (fig 2).

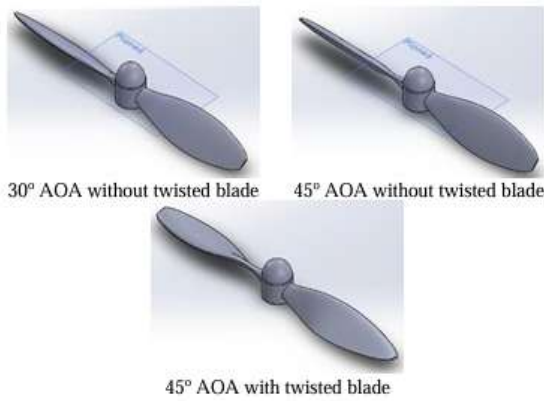


Fig.2 – Effect of variation in AOA and twisting

From a physical standpoint, an ideal twist distribution follows the condition that each blade section operates close to its best lift-to-drag angle throughout the span. The inner parts of a fast-rotating propeller are likely to run at very high angles of attack and can stall, whereas the outer parts can run at sub-optimal, low, angles. At faster rotational rates the discrepancy between local inflow angles and blade pitch is worse, leading to higher levels of drag and less efficiency. The CFD results confirm the untwisted blades exhibit high separated flow area at the root at operating RPM, and this is not the case with twisted designs [6]. This shows that the scheduling of the spanwise pitch is one of the design variables used in the optimization of UAV propellers.

C. Chord Length and Rotor Configuration

The length of the chord is directly related to the blade loading and thrust generation. A general increase in chord tends to increase thrust at the cost of efficiency when drag prevails [2], [5]. The ratio of the total blade area to the disk area, called the blade solidity ratio, rises with chord, and too high solidity results in high adverse pressure gradients and separations at inner parts. Single and coaxial rotor designs CFDs indicate that coaxial designs provide increased thrust density but with increased interaction losses in the wake. This means that the optimization of chords and pitch must be considered in addition to rotor arrangement and mission requirements.

D. Blade Number and Vibration Characteristics

The number of blades of a propeller influences not only its performance but also its vibration. A structural vibration test for three kinds of propellers with 2 blades, 3 blades and 4 blades, were conducted by a modal test. As a result, it was found that the natural frequency of the propellers became higher as the number of blades increased. In addition, the possibility of the resonance with a motor exciting frequency decreased. It is observed that propeller with three-blades exhibit superior vibration characteristics than two- or four-blade designs [7], [8]. The modal analysis with CFRP propellers also shows that the first natural frequency of three-bladed designs is usually 1525 higher than the first natural frequency of two-bladed designs. Four-blade designs, although providing the highest thrust density at a given diameter and RPM, can add to the overall loading per span to the airplane and produce higher tip vortices which may

contribute to noise. Three-bladed CFRP propellers are a good trade-off between structural stability and aerodynamic performance in small quadcopters with vibration and acoustic signature concerns [7], [8].

IV. EFFECT OF MATERIAL ON STRUCTURAL AND AERODYNAMIC PERFORMANCE

A. Plastic Versus Composite Materials

The choice of material has a strong effect on propeller stiffness, deformation, and fatigue behaviour. The comparison of typical plastics like PLA and composite materials like carbon-fiber-reinforced polymer (CFRP) in research papers demonstrate that composite materials are subjected to significantly lower deformation and stress when subjected to the same load [7], [9], [10]. High deformation of plastic blades may change the aerodynamic shape of the blades which reduces the performance in high rotational speed. Simulations in finite elements when subjected to centrifugal and aerodynamic loading conditions reveal that PLA propellers undergo overall deformations multiple times that of CFRP propellers under the same boundary conditions [9]. As an example, at rotational speeds that are typical of small quadcopters (5,000-8,000 RPM) CFRP blades can deflect by fractions of a millimetre, whereas PLA blades can deflect by millimetres. These distortions change the local pitch angle across the blade span, which is virtually reducing the angle of attack at the tips and is reducing the thrust. Also, Von Mises stress in PLA blades often tends to reach the yield strength during peak loading situations, which poses fatigue failure issues. With its high stiffness to weight ratio and better fatigue resistance, CFRP ensures that the geometry of the blades does not change throughout the full operating range and offers a much longer service life [10].

B. Advanced Resin Materials and Fatigue Performance

In terms of tensile properties, deformation, and fatigue life, recent research on high-strength 3D-printable resins points out that XMODEL15 resin has excellent tensile properties, less deformation, and longer fatigue life than ABS and ABS-like resins [11]. CFD-FEA coupled studies and flight tests demonstrate that material improvements could result in quantifiable improvements in speed, endurance and durability, indicating that material selection is a significant design consideration. The 3D-printed drone blade flight tests based on a DJI Phantom platform demonstrated that drones with XMODEL15 resin blades had the highest flight speed at 34.9 km/h, whereas the Industrial ABS and ABS-Like resin blades had flight speeds of 18.4 km/h and 15.3 km/h, respectively [11]. Life test of fatigue further indicated that XMODEL15 blades could withstand up to 118,750 loading cycles before failure, which is far much better than the Industrial ABS (90,655 cycles) and the ABS-Like blades (70,384 cycles). The CFD simulations estimated a maximum air velocity of about 3.7 m/s near the surfaces of the blades, which validates the conclusion that aerodynamic pressure loads are crucial and that the rigidity of blades directly affects the local flow conditions. These findings confirm the hypothesis that the choice of resin material has a first-order influence on both the metrics of flight performance and component lifespan in small UAVs (fig 3).



Fig. 3 – Different 3-D printed materials used in UAVs

V. CFD METHODS FOR PROPELLER AND QUADCOPTER FLOW ANALYSIS

A. Single-Propeller CFD Analysis

CFD simulations of isolated propellers typically employ a rotating inner domain coupled with a stationary outer domain, using turbulence models such as SST $k-\omega$. All these experiments contribute to the flow structures, pressure distributions and performance trends and the predictions of thrust coefficient are usually within 15-20 percent of experimental results [12]. Reynolds-stress models are more faithful at a greater computational cost, and $k-\epsilon$ or SST $k-\omega$ is often seen as a pragmatic option in engineering application [13]. SST $k-\omega$ model is favoured over the standard $k-\epsilon$ model when modelling propeller flows due to its ability to better resolve adverse pressure gradient regions and boundary-layer separation in the regions near the blade surfaces that are of critical importance in determining the correct predictions of propeller thrust and torque at low Reynolds numbers [13]. Mesh independence experiments are critical and generally indicate the convergence of predictions of thrust coefficient beyond a certain number of elements, which in the case of one propeller domain is around one million elements. The differences between the numerical prediction and experimental data are more likely to be higher at higher rotational speeds with stronger tip vortices and more complicated wake structures.

B. Full Quadcopter CFD and Rotor Interaction

Full quadcopter simulations indicate that there are strong interactions between rotors in the wake resulting in increased induced velocities and pressure fields altered relative to those in single-rotor configurations [14]. Hover performance and ground-effect phenomena have been captured both with Multiple Reference Frame (MRF) and sliding-mesh approaches. Further experimental and numerical comparisons demonstrate that rotor spacing and configuration are significant factors in efficiency and noise characteristics [15].

VI. RESEARCH GAPS AND RELEVANCE TO THE PRESENT STUDY

From the literature reviewed, it can be understood that the geometry and material are very important in propeller performance. Most studies however concentrate on either the geometric optimization or material evaluation independently. Combination of BEMT-based geometric redesign, material substitution, and CFD-solved flow analysis, especially at small UAV scales, remain rare [1], [5], [7], [11], [15]. To be more precise, the review leads to the three research gaps. To begin with, BEMT tools have been demonstrated to predict overall thrust and efficiency, although little has been done to optimize a multi-variable (chord, twist, and blade number) optimization on sub-100mm diameter UAV propellers. Second, coupled CFD/FEA analyses with the BEMT aerodynamic pressure field as structural loading input to FEA are uncommon, i.e. the aeroelastic coupling between blade deformation and aerodynamic performance is not modelled. Third, systematic experimental data sets at the lower Reynolds numbers ($Re < 100,000$) of small quadcopter propellers are conspicuously absent, which restricts the validation of BEMT corrections, and CFD turbulence models, at these lower Reynolds numbers. The current project will fill this gap by redesigning a quadcopter propeller by controlled adjustments of chord length and inflow angle, using alternative materials and assessing the performance of the propeller by BEMT, CFD, and optional structural analysis. This strategy is similar to the needs identified in the existing research.

VII. CONCLUSION

From this review, it can be concluded that the performance of quadcopter propellers is extremely sensitive to aerodynamic geometry as well as material properties. Optimized chord and twist distributions enhance thrust and efficiency and careful choice of the number of blades optimizes vibration properties. The improvement of materials to composites or high-end resin used in place of traditional plastics will greatly decrease deformation and increase fatigue life. Tools like BEMT are efficient in terms of early design capability and tools like CFD and FEA give detailed information regarding flow behaviour and structural integrity. The accuracy of BEMT is sensitive to the quality of low-Reynolds-number airfoil data and stall corrections used, otherwise the predictions of thrust can overestimate performance by 20-30 percent at low advance ratios. Because of the lack of fully integrated studies in geometry, material, and CFD, this work is aimed at filling this gap. Through a single design and analysis framework, it is hoped that this work will lead to a more efficient and structurally sound quadcopter propellers.

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