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Original Article

Aerodynamic analysis of a small-scale drone propeller using the blade element momentum method

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ABSTRACT

In this study, the aerodynamic performance of a small-scale drone propeller (Tmotor28 propeller) in axial flight has been analyzed using the Blade Element Momentum Theory (BEMT). Which is a powerful tool to model the aerodynamic interaction between the rotor/propeller and the fluid flow. The aim of this paper is to propose a BEMT model for the Unmanned Aerial Vehicle (UAV). An open-source tool known as pyBEMT (Python programming language) has been used to calculate the aerodynamic performance of the propeller. The XFoil, which is based on the panel-vortex methods, has been used to find the lift and drag coefficients (CD and CL) of the propeller airfoils. The numerical results have been validated with experimental results. Good agreements have been found. This study introduces a straightforward and powerful calculation method for predicting and optimizing the aerodynamic performance of drones.

1. Introduction

In recent years, there has been a notable surge in research and development efforts aimed at creating aerial vehicles capable of operating beyond the line of sight. These endeavors seek to enhance production efficiency, reduce expenses and risks, ensure site safety and security, and maintain regulatory compliance. Notably, these innovations have proven invaluable in safeguarding the human workforce during pandemic situations. Autonomous drones have emerged as transformative technologies across a diverse array of applications, including agriculture, territorial planning, inspection, logistics, security, hobbies, and audiovisual professions [1-2].

When it comes to evaluating the aerodynamic performance of Unmanned Aerial Vehicles (UAVs), a multitude of methodologies are at researchers' disposal. These approaches encompass Computational Fluid Dynamics (CFD) simulations, Vortex methods, and Blade Element Momentum Theory (BEMT) [5]. CFD-RANS-based simulations have been extensively employed, leveraging various turbulence models to simulate airflow around UAVs, such as the k-ω SST and Spalart-Allmaras models [3-4]. To model the rotational dynamics of propellers, the Multiple Reference Frame (MRF) method has commonly been employed [6].

In the context of UAV design, BEMT serves as a valuable method, not only for optimizing propeller airfoil shapes but also for determining the ideal configurations for UAVs based on lift and drag coefficients associated with specific airfoils [7-9]. Numerous techniques have been employed to obtain these coefficients, with CFD simulations being one of the prominent approaches, albeit with a substantial CPU computational cost. Alternatively, a mesoscopic approach, known as the Lattice Boltzmann Method (LBM), has been utilized to resolve fluid dynamics in highly complex geometrical domains, offering potential computational advantages, particularly when GPU resources are available [10].

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However, it's worth noting that BEMT remains an economically advantageous approach, delivering rapid results with commendable accuracy. This technique primarily relies on integrating key parameters like CL (lift coefficient) and Cd (drag coefficient) into its algorithm. These coefficients can be sourced from a wealth of experimental data, including the NACA open library for airfoil information. Numerically predicting these coefficients can be accomplished through various methodologies, such as Convolutional Neural Network techniques, CFD simulations, or vortex-based methods. In this particular study, XFoil has been utilized as a tool leveraging vortex methods to attain the intended objective.

2. Propeller Design

The designed propeller was custom-tailored to correspond to the dimensions and characteristics of the widely utilized APC10x7 propeller, a common component in practical drones like the MavicPro. This alignment enables a direct comparative analysis between the Blade Element Momentum Theory (BEMT) model and the experimental data presented by Brandt in 2005 [12].
To provide a clear reference, the specific dimensions of the APC10x7 propeller are summarized in Table 1 and 2 below:

Table 1: Dimensions of the propeller [12].

Number of blades	2
Diameter [in]	10
Hub radius [cm]	3

Table 2: Section partition for [Brandt 2005][12].

Airfoil	**Radius (cm)**	**Chord (cm)**	**Pitch (Degrees)**
NACA 4412	1.25	0.78	36.15
NACA 4412	1.50	0.88	33.87
NACA 4412	1.75	0.96	31.25
NACA 4412	2.00	1.03	28.48
CLARKY	2.25	1.08	25.6
CLARKY	2.50	1.11	22.79
CLARKY	2.75	1.13	20.49
CLARKY	3.00	1.12	18.7
CLARKY	3.25	1.10	17.14
CLARKY	3.50	1.05	15.64
GOE 450	3.75	0.99	14.38
GOE 450	4.00	0.90	13.11
GOE 450	4.25	0.80	11.83
GOE 408	4.50	0.67	10.65
GOE 408	4.75	0.46	9.53

The fluid employed in this work is air, characterized by the following properties: ρ = 1.225 [kg / m^3] and μ = 1.81E-5 [Pa.s].

3. Blade Element Momentum Theory

In this section, a concise overview of the Blade Element Momentum Theory (BEMT) is provided, with an emphasis on presenting comprehensive expressions applicable to both turbines and propellers. For more in-depth derivations, readers are referred to other sources, such as [13] for wind turbines and [14] for helicopter propellers.
BEMT represents the fusion of two foundational theories: the blade element theory and the momentum theory. Within the blade element theory, the approach assumes that each infinitesimal section of a blade operates independently, allowing for the calculation of forces acting upon it based on established lift and drag values for the airfoil. Conversely, in the momentum theory, the rotor is conceptualized as a disk, with the rotor's actions leading to a loss of momentum as a result of the work it performs.

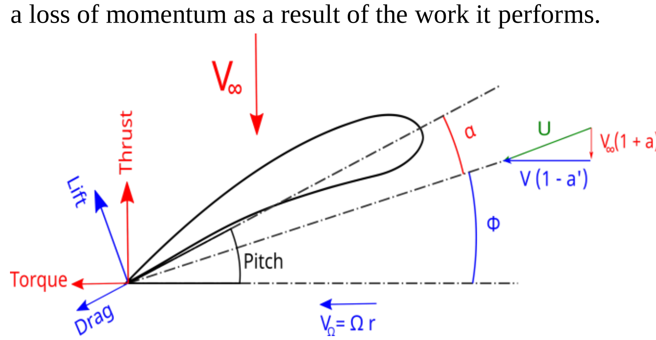

Fig 1. Rotor force diagram illustrating the impact of airfoil pitch, as well as the forces of thrust, torque, lift, and drag.

In the case of a propeller, power is applied to the rotor to produce thrust along the rotational axis. In contrast, for a turbine, power is harnessed from the incoming flow through the torque generated by the rotor's rotation. Fig. 1 presents a force diagram illustrating these two scenarios.
A pivotal concept within the framework of BEMT revolves around induction factors. The velocity perceived by a blade section does not align with the actual incoming flow velocity in the axial direction or the rotor's angular velocity in the tangential direction. In the context of a propeller, the axial velocity experiences an increase due to the rotor's presence, while the tangential velocity diminishes due to the swirling motion.
These local velocities can be mathematically expressed as follows:

$$V = (1 + a)\, V_\infty \quad (1)$$

$$V' = (1 + a')\, V_\Omega \quad (2)$$

$$U = \sqrt{V^2 + V'^2} \quad (3)$$

The forces acting on the rotor section can be expressed as:

$$dT = \sigma \, \pi \, \rho \, U^2 \, C_T \, r \, dr \tag{4}$$

$$dQ = \sigma \, \pi \, \rho \, U^2 \, C_Q \, r^2 \, dr \tag{5}$$

Here, σ = B_C / (2π r) represents the local solidity of the rotor. The thrust and torque coefficients are computed using the following expressions:

$$C_T = C_L \, cos \, cos \, \phi - c \, C_D \, sin \, sin \, \phi \tag{6}$$

$$C_Q = C_L \, sin \, sin \, \phi + c \, C_D \, cos \, cos \, \phi \tag{7}$$

CL and CD represent the lift and drag coefficients, respectively, which are obtained from airfoil tables using XFoil. The parameter 'c' serves as a specific constant used to transition between turbine mode (c = -1) and propeller mode (c = 1) based on the local angle of attack for the airfoil.

$$\alpha = c \, (pitch - \phi) \tag{8}$$

Equivalent expressions for the forces can also be derived from the principles of momentum theory:

$$dT = 4\pi \, \rho \, r \, V_\infty^2 \, (1 + c \, a) \, a \, dr \tag{9}$$

$$dQ = 4\pi \, \rho \, r^3 \, V_\infty \, \Omega \, (1 + c \, a) \, a' \, dr \tag{10}$$

By combining these equations, we can directly derive expressions for the induction factors as follows:

$$a = \frac{1}{k - c} \tag{11}$$

$$a' = \frac{1}{k' + c} \tag{12}$$

$$k = \frac{4\phi}{\sigma \, C_T} \tag{13}$$

$$k' = \frac{4 sinsin \, \phi coscos \, \phi}{\sigma \, C_Q} \tag{14}$$

3.1. Prandtl tip loss factor

The 'Prandtl tip loss factor' addresses a crucial aspect by rectifying the assumption of an infinite number of blades. When dealing with a rotor possessing a finite number of blades, the vortex system in the wake behaves differently compared to that of a rotor with an infinite number of blades. This distinction results in a non-axisymmetric flow through the rotor, disrupting the idealised stream tube concept depicted in Fig. 2 and rendering the use of momentum equations more complex.

Nonetheless, Prandtl devised a correction factor (F) to rectify the aerodynamic loads. This correction factor is applied so that when the adjusted loads are uniformly distributed azimuthally and integrated into the momentum equations, they yield results for blade induction very akin to those achieved for the scenario with a finite number of blades. Consequently, Equations 11 and 12 are adapted by incorporating the correction factor F as follows:

$$dT = 4\pi \, \rho \, r \, V_\infty^2 \, (1 + c \, a) \, a \, F \, dr \tag{16}$$

$$dQ = 4\pi \, \rho \, r^3 \, V_\infty \, \Omega \, (1 + c \, a) \, a' \, F \, dr \tag{17}$$

The value of F is calculated as follows:

$$F = \frac{2}{\pi} (e^{-f}) \tag{18}$$

Where:

$$f = \frac{Bc}{2} \frac{R - r}{r sinsin \, \phi} \tag{19}$$

Where B represents the number of blades, R denotes the total radius of the rotor, r signifies the local radius, and ϕ stands for the flow angle. Utilising Equations 16 and 17, instead of Equations 11 and 12, when deriving the equations for 'a' and 'a', the following results are obtained:

$$a = \frac{1}{\frac{4 F\phi}{\sigma \, C_T} - c} \tag{20}$$

$$a' = \frac{1}{\frac{4 \, F sinsin \, \phi coscos \, \phi}{\sigma \, C_Q} + c} \tag{21}$$

Equations 20 and 21 should be employed in place of Equations 11 and 12 within the BEMT algorithm. Additionally, an additional step is required to calculate the Prandtl's tip loss factor, denoted as F. It's worth noting that the derivation of Prandtl's tip loss factor is a complex process, and the details are not presented here. A comprehensive description can be found in [15].

3.2. Solution method

From the rotor force diagram, it becomes evident that the local inflow angle can be determined based on the local velocities, as follows:

$$tan \, \phi = \frac{(1 + a) \, \Omega R}{(1 - a') \, V_\infty^2} \tag{22}$$

In order to solve this system of equations, the pyBEMT software, an open-source Python tool for BEMT problemsolving, was utilised. The SciPy library was employed to solve Equation 20 and determine ϕ. The induction factors were calculated using Equations 18 and 19. Subsequently, the forces were derived from the blade element equations (Equations 9 and 10) and integrated along the rotor to obtain the total forces, applying the Newton-Cotes formula. The solution algorithm can be summarized as follows (keep in mind that the functions listed are intended to illustrate the steps and may not necessarily correspond to the actual method names in the solver class):

```
# Algorithm for Blade Element Momentum Theory
(BEMT) Analysis
# Step 1: Initialise induction factors 'a' and 'a`', typically
setting them to 0.
a = 0
a_prime = 0
# Step 2: Compute the flow angle ϕ using Equation 20.
phi = calculate_phi()
# Step 3: Calculate the local angle of attack using Equation
8.
alpha_local = calculate_alpha_local()
# Step 4: Retrieve lift coefficient CL(α) and drag
coefficient CD(α) from the airfoil data table.
CL_alpha, CD_alpha = lookup_coefficients(alpha_local)
# Step 5: Compute thrust coefficient CT and torque
coefficient CQ using Equations 6 and 7.
CT, CQ = calculate_CT_CQ(CL_alpha, CD_alpha)
# Step 6: Calculate updated values of 'a' and 'a' using
Equations 18 and 19.
a, a_prime = update_induction_factors(CT, CQ)
# Step 7: Check if 'a' and 'a' have changed beyond a certain
tolerance.
while check_tolerance(a, a_prime):
   # If yes, return to Step 2 for further iteration.
   phi = calculate_phi()
   alpha_local = calculate_alpha_local()
   CL_alpha, CD_alpha = lookup_coefficients(alpha_local)
   CT, CQ = calculate_CT_CQ(CL_alpha, CD_alpha)
   a, a_prime = update_induction_factors(CT, CQ)
# Step 8: Compute the local loads on the segment of the
blades.
compute_local_loads()
# Step 9: Finish the BEMT analysis.
finish_analysis()
```

3.3. PyBEMT

In this section, we introduce pyBEMT, a Python-based implementation of the Blade Element Momentum Theory (BEMT). pyBEMT offers a versatile set of capabilities, primarily focusing on the estimation of two crucial parameters:

1. **Thrust:** pyBEMT can accurately determine the thrust generated by a propeller. This capability is essential for assessing and comprehending the performance of propellers in various applications.
2. **Power:** Additionally, pyBEMT can calculate the power generated by a turbine. This feature is instrumental in evaluating the efficiency and effectiveness of turbines across different scenarios.

pyBEMT boasts several notable features that make it a valuable tool for propeller and turbine analysis:

- Unified Implementation: It provides a cohesive and unified implementation for both propellers and turbines, streamlining the analysis process.
- Coaxial Rotor Model: pyBEMT includes a model for coaxial rotors, allowing for a comprehensive assessment of such rotor configurations.
- Rotor Parameter Optimization: The tool supports the optimization of rotor parameters, enabling users to fine-tune designs for optimal performance.

The source code of pyBEMT follows an object-oriented structure, comprising four primary files in the main folder. Each file contains objects and methods dedicated to specific aspects of the BEMT analysis:

- **solver.py**: This file loads the configuration file and houses functions for executing single simulations, conducting parameter sweeps, and performing optimization tasks.
- **rotor.py**: Responsible for storing rotor properties, this file calculates induction factors and forces for the airfoil sections, a crucial step in BEMT analysis.
- **fluid.py**: This module handles fluid properties, including viscosity and density calculations, which are essential for accurate simulations. Currently, it primarily focuses on these two properties.
- **airfoil.py**: This file manages airfoil data and provides drag and lift coefficients to the solver, facilitating the computation of forces and other critical parameters in the analysis.

By adopting an object-oriented approach and structuring the code around these key components, pyBEMT offers a user-friendly and adaptable platform for propeller and turbine analysis based on the principles of BEMT.

4. XFoil

XFoil is a powerful and interactive software program, made available under the GNU GPL licence, designed primarily for the comprehensive analysis and design of subsonic isolated airfoils. This versatile tool serves a multitude of functions crucial to airfoil research and engineering. Key features and capabilities of XFoil include:

- **Lift and Drag Coefficients**: XFoil excels at calculating lift and drag coefficients for specific 2D airfoil shapes. By providing the program with coordinates of the airfoil, along with relevant parameters such as Reynolds and Mach numbers, users can obtain precise coefficients that are essential for aerodynamic analysis.
- **Pressure Distribution**: XFoil goes beyond basic coefficient calculations by providing insights into the pressure distribution across the airfoil. This data allows for a deeper understanding of airfoil performance and characteristics.
- **Power and Thrust Characteristics**: With XFoil, users can derive valuable information related to power and thrust characteristics of airfoils. This is invaluable for optimising airfoil designs for specific applications.
- **Inverse Design**: XFoil offers the capability of inverse design, enabling engineers and researchers to manipulate airfoil shapes to achieve desired parameters. This feature facilitates the iterative process of airfoil design and refinement.

5. Results and Discussion

In this section, we delve into the outcomes of our Blade Element Momentum Theory (BEMT) analysis, employing the pyBEMT tool in conjunction with XFoil for airfoil data. Our primary focus centres on the comparative evaluation between the simulated results and experimental data, particularly with regard to power and thrust coefficients, as well as propeller efficiency.

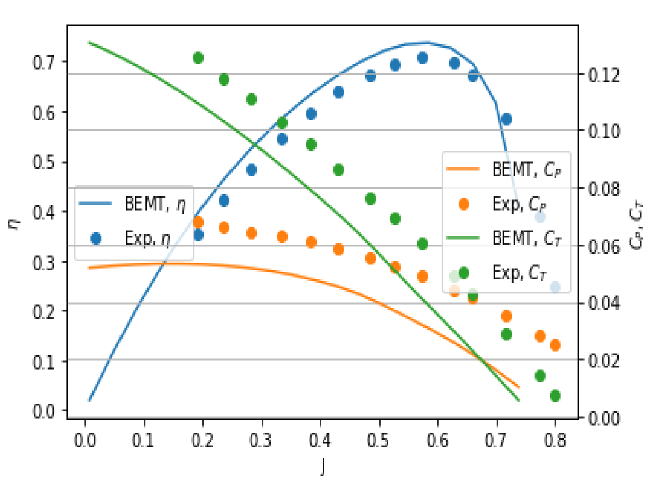

Fig 2. Comparison of Simulated and Experimental Results.

Upon close examination of Figure 2, which illustrates the alignment between simulated and experimental power and thrust coefficients, along with propeller efficiency, it becomes apparent that our approach yields promising results. However, a noteworthy observation is the presence of an error gap exceeding 5%, particularly noticeable in the CP (power coefficient) graph. This disparity can be attributed to certain factors inherent to the BEMT method.

One factor contributing to this error is the absence of a 3D correction factor and the simplifications inherent in the BEMT approach. These limitations result in minor discrepancies between the simulated and actual performance of the propeller, especially in scenarios where complex 3D effects come into play.

It's essential to highlight that our analysis employed 15 partitions for the propeller, each with specific airfoil characteristics. This deliberate choice, while contributing to the accuracy of our results, also justifies the acceptable error gap observed. This error gap tends to remain relatively stable even as the angular velocity (ω) exceeds 4000 rpm due to the heightened Reynold's stress at these levels. However, it's important to note that such high angular velocities are typically beyond the practical range of use for this type of propeller.

Another critical aspect contributing to the accuracy of our results is the implementation of the Prandtl loss correction factor. This factor plays a significant role in minimising errors and aligning our simulated data with experimental values.

In conclusion, while our BEMT analysis exhibits a remarkable degree of alignment with experimental data, it is essential to acknowledge the inherent limitations of the method, such as the steady-state assumption, 1D analysis of the fluid flow motion, ideal conditions, etc. The observed error gap, particularly in the CP graph, underscores the need for further refinement and the consideration of 3D correction factors in future analyses. Nonetheless, our results affirm the practical utility of pyBEMT and XFoil in predicting propeller performance, advancing our understanding of UAV propulsion systems and aerodynamic principles in real-world applications. Finally, exploring 3D effects is imperative for future research to overcome the limitations inherent in the current method.

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Conflict of Interest

The authors declare that they have no conflict of interest

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