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Aerodynamic Characteristics Calculation of Aircraft Propellers Using the Blade Element Method

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Abstract- This paper presents the application of the Blade Element Method (BEM) to calculate the aerodynamic characteristics of aircraft propellers. In this method, the propeller is divided into blade elements, each treated as an airfoil section of an aircraft wing. To determine the aerodynamic characteristics of the entire propeller, it is necessary to compute the aerodynamic forces on each element based on local geometric parameters and flow conditions at the section. The integration over all blade elements yields the total thrust and its coefficient.

Keywords: Blade Element Method, Aerodynamics, Propeller, Lift and Drag, Aircraft Design.

I. INTRODUCTION

In aerodynamic research and design, the precise determination of propeller characteristics is crucial, as it directly dictates the thrust, drag torque, energy efficiency, and the safe and stable operation of the vehicle. These characteristics are not only the basis for optimizing the propeller's shape and geometric parameters but also contribute to improving operational efficiency in practice. Therefore, a variety of methods have been developed for this calculation and evaluation process, ranging from classical theories to modern computational tools. Among these, seven typical groups of methods include: Blade Element Method (BEM), Momentum Method, Discrete Vortex Method, Panel Method, Small Disturbance Method, Experimental Methods, and Aerodynamic Simulation Software. Each method possesses unique advantages and limitations, making them suitable for different research purposes or design stages. Notably, the Blade Element Method (BEM) is considered the most basic and widely used foundation in the preliminary design stage. This method is based on dividing the blade into small elements along the radius, calculating the lift and drag on each element, and subsequently synthesizing the thrust and total torque. The outstanding advantage of BEM lies in its simple, intuitive computational formulation and its ability to yield reliable results under a variety of operating conditions. Furthermore, BEM serves as a reference benchmark for calibrating, verifying, and developing more modern approaches, such as numerical simulations and physical experiments. Through the synergistic combination of the aforementioned methods, the process of calculating the propeller's aerodynamic characteristics continuously improves in accuracy, contributing to enhanced efficiency in design and practical application.

II. METHODOLOGY

The essence of this method is to discretize the propeller into blade elements, where each element is modeled as an airfoil cross-section. This implies that to calculate the aerodynamic characteristics of the entire propeller blade, one must first determine the aerodynamic characteristics of each element, considering the local geometric parameters and flow conditions at its cross-section. Subsequently, integrating the contributions from all blade elements will yield the total thrust, drag force, and the associated coefficients (e.g., thrust coefficient and torque coefficient).

Assume a blade element has a chord length b, an infinitesimal radial width dr and is located at a radius r (Figure 1). The blade pitch angle is ▪, the axial flow velocity component is Uy, and the local induced velocity is V. Consequently, the inflow angle ▪ of the airflow relative to the cross-section is defined by:
tg▪=(Uy+V)/ωr,
Because the angle ▪ is small, the approximation ▪ ≈ tg▪=(Uy+V)/ωr is used.

Figure 1: Schematic diagram of the division of the leaf element

The differential lift force "dY" acting on the blade element (which is perpendicular to the relative velocity vector "W" is determined as follows:

$$dY = \frac{1}{2}.\rho.W^2.C_y.S = \frac{1}{2}.\rho.W^2.C_y.b.dr \quad (1)$$

Where W is the relative velocity of the airflow compared to the blade element. Since ▪ is small, the approximation W≈ω.R is often utilized. Furthermore, the dependence of the lift coefficient "C" _y on the angle of attack ▪ is assumed to be linear:

$$C_y = C_Y^{\alpha}.\alpha = C_Y^{\alpha}.(\varphi - \beta)$$

Therefore, the differential lift is:

$$dY = \frac{1}{2}.\rho.(\omega r)^2.C_Y^{\alpha}.(\varphi - \beta).b.dr \qquad (2)$$

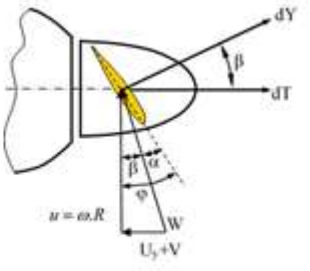

Figure 2. Vector Diagram of Forces on the Blade Element

For propellers with relatively large spans, the lift curve slope is typically approximated as C_Y^α≈5,7. Since ▪ is small, dY≈dT. Assuming rt=0, the drag force of the blade with m blades will be:

$$T = m.\int_0^R dT \approx m.\int_0^R dY = \frac{1}{2}\rho.C_Y^{\alpha}.\omega^2.m.\int_0^R (\varphi - \beta).b.r^2.dr \quad (3)$$

Using the dimensionless parameters $u_y = \frac{U_y}{\omega.R}$; $v_y = \frac{V}{\omega.R}$; $\bar{r} = \frac{r}{R}$ to calculate angle ▪, we will get the following expression for calculating the traction force:

$$T = \frac{1}{2}\rho.C_Y^{\alpha}.\omega^2.m.R^3 \int_0^1 \left[\varphi.\bar{r}^2 - \left(u_y + v\right).\bar{r}\right].b.dr \quad (4)$$

If we consider the induced speed V and the mounting angle φ to be constant along the length of the fan blade, then

$$T = \frac{1}{2}\rho.C_Y^{\alpha}.b.\omega^2.m.R^3 \left[\frac{1}{2}.\varphi - \frac{1}{2}.\left(u_y + v\right)\right] \quad (5)$$

Khi đó, hệ số lực kéo của cánh quạt tính theo công thức $C_T = \frac{T}{q.F}$ (F là diện tích mặt quét của cánh quạt)

At that time, the drag coefficient of the fan blade is calculated according to the formula $C_T = \frac{T}{q.F}$ (F is the swept surface area of the fan blade)

$$C_T = \frac{2.T}{q.F.(\omega.R)^2} \qquad (6)$$

In the case where the chord length b changes along the blade span, substituting the function describing the chord distribution into (4) will determine the total thrust. Suppose the chord length varies according to the linear rule:

$$b = b_0 - \Delta b_0.\bar{r} \quad (7)$$

Where: b0 is the chord length at the blade root; Δb_0 is the linear variation of the chord length along the blade span. Substituting (7) into (4) yields the total thrust of the propeller:

$$T = \frac{1}{2}\rho.C_Y^{\alpha}.\omega^2.m.R^3.\left\{b_0.\left[\frac{1}{3}\varphi - \frac{1}{2}\left(u_y + v\right)\right] - \Delta b_0\left[\frac{1}{4}\varphi - \frac{1}{3}\left(u_y + v\right)\right]\right\} \quad (8)$$

The Blade Element Method enables the determination of the drag coefficient and the power required for propeller rotation. This method offers the advantage of intuitive comprehension and direct evaluation of the drag force. However, a key limitation of this analytical approach is that calculating the drag force typically necessitates that airfoil geometry and blade shape information be expressed in an analytical form. Furthermore, analytical computations are generally restricted to linear problems, as accurately solving complex aerodynamic problems using analytical expressions becomes extremely challenging when considering nonlinear effects. The following outlines some typical applications of the Blade Element Method.

III. REPRESENTATIVE APPLICATIONS OF THE BLADE ELEMENT METHOD

Application in Aircraft Propeller Design and Optimization

One of the most significant applications of the Blade Element Method (BEM) lies in the design and performance analysis of aircraft propellers.

Historically, NASA incorporated BEM into several foundational studies, notably documented in the seminal work, "Propeller Design I: Practical Application of Blade Element Theory." The methodology involves segmenting the propeller into discrete blade elements, where the aerodynamic forces (lift and drag) at each radial station are computed. These elemental forces are subsequently integrated across the blade span to determine the overall thrust, torque, and propulsive efficiency.

This approach enables engineering teams to expeditiously estimate performance characteristics and power requirements across a comprehensive range of flight envelopes. Consequently, BEM facilitates the optimized selection of critical blade geometry and design parameters, including camber distribution, pitch angle setting, and blade count. The Blade Element Method has thus functioned as a fundamental analytical tool in the development of high-efficiency, fuel-optimized propulsion systems for both civil and military aviation platforms.

Application in Wind Turbine Blade Analysis and Design

In the domain of renewable energy, the Blade Element Method (BEM) is regarded as the standard analytical tool for the aerodynamic design of Horizontal-Axis Wind Turbines (HAWTs). Leveraging its advantages of computational efficiency and a parsimonious modeling structure, BEM facilitates the determination of force distributions along the blade span, as well as the prediction of aerodynamic performance and power production across diverse operational wind regimes. This methodology is successfully applied to systems ranging from small-scale residential turbines to large utility-scale offshore installations.

In practical engineering design, BEM is frequently integrated with optimization algorithms to facilitate the selection of appropriate airfoil profiles and optimal pitch angle settings, thereby maximizing the efficiency of kinetic energy extraction from the wind. Consequently, the Blade Element Method has played a pivotal analytical role in the accelerated advancement of modern wind energy technology over the past decades.

Application in Marine Propeller Optimization

Beyond the fields of aeronautics and renewable energy, the Blade Element Method (BEM) is extensively applied within the maritime domain, specifically for the design and analysis of ship and submarine propellers. A representative case involves the analysis of the DTMB 4119 propeller—a widely recognized international reference geometry.

When BEM is utilized in conjunction with hydrodynamic corrections for cavitation effects and blade curvature, the computed thrust, torque, and propulsive efficiency exhibit strong correlation with empirical experimental data. This demonstrates BEM's efficacy in predicting hydrodynamic performance and supporting preliminary propeller design validation.

The methodology aids in mitigating costly experimental testing while simultaneously enabling configuration optimization to enhance efficiency, minimize flow-induced vibration, and reduce acoustic signatures. These factors are of critical operational importance for both modern naval platforms and large commercial vessels.

Application in Aerodynamic Flow Simulation

Currently, the Blade Element Method (BEM) is extensively utilized in aerodynamic flow simulation through its integration into simplified models, notably the Actuator Disk and Actuator Line methodologies. Within these frameworks, the aerodynamic forces computed via BEM are distributed across a representative disk or line corresponding to the rotor, thereby circumventing the need for direct modeling of the full geometric complexity of the blades. This approach allows researchers to effectively capture the momentum transfer and the induction effects of the rotor on the surrounding flow field and the downstream wake structure. This is particularly relevant in the analysis of complex systems such as multi-rotor wind farms or coaxial dual-rotor configurations.

This specific application yields a substantial reduction in computational expenditure compared to full-resolution Computational Fluid Dynamics (CFD) simulations, while concurrently providing quantitatively accurate results sufficient for preliminary analytical studies and the investigation of intricate flow phenomena.

IV. CONCLUSION

In summary, the Blade Element Method (BEM) remains one of the most fundamental and extensively utilized analytical tools for evaluating the aerodynamic characteristics of rotating propulsion systems. By systematically segmenting the blade into multiple discrete elements along the radial span, the method enables the direct determination of elemental lift and drag forces, which are subsequently integrated to yield the overall thrust and torque. Its foremost advantage lies in its computational parsimony—requiring minimal algorithmic complexity—while simultaneously providing reliable performance estimates under linear flow conditions and modest angles of attack.

Moreover, BEM facilitates the rapid preliminary estimation of essential performance metrics, including thrust, thrust coefficient (C_T), and power consumption, offering crucial support during the initial conceptual design phase of propulsion systems. In practice, BEM is broadly applied beyond aircraft propeller design, extending to critical areas such as wind turbine engineering, marine propulsion hydrodynamics, and industrial fluid machinery. It consistently serves as the initial foundational modeling approach before transitioning to advanced analyses, such as full-resolution Computational Fluid Dynamics (CFD) or empirical experimental validation. Due to its inherent simplicity and analytical versatility, the Blade Element Method continues to hold a pivotal and enduring role in modern aerodynamic research and engineering design.

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