

Advanced Performance Analysis of Distributed Electric Propulsion Using a Meshless CFD Simulation Approach [†]

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Abstract

Achieving climate-neutral aviation requires propulsion systems capable of reducing emissions and noise while maintaining high aerodynamic efficiency. Distributed Electric Propulsion (DEP) represents a promising solution; however, accurately predicting the unsteady aerodynamic interactions between multiple propellers and lifting surfaces remains challenging. This work investigates the aerodynamic performance of two Distributed Propulsion (DP) configurations using FLOWUnsteady, a meshless Computational Fluid Dynamics (CFD) solver based on the reformulated Vortex Particle Method (rVPM) within a Large-Eddy Simulation (LES) framework. The Lagrangian particle formulation eliminates mesh generation and limits numerical dissipation. Two layouts—a twin wingtip-mounted arrangement and a four-propeller configuration including inboard units are analyzed and compared with a clean wing baseline as functions of propeller position, inflow speed (20 and 33 m/s), and angle of attack. Beyond global aerodynamic performance metrics, the rVPM–LES framework provides a time-resolved and spatially resolved characterization of local propeller–wing interference in multi-propulsor configurations, highlighting differences in loading and torque demand between inboard and wingtip propellers that are not typically captured by low- to mid-fidelity modeling approaches. The results show that distributed propulsion increases lift and reduces drag relative to the clean wing by accelerating the local flow, delaying separation, and enhancing wing circulation. Thrust and torque coefficients exhibit a clear dependence on rotational speed and angle of attack: inboard propellers experience stronger aerodynamic interference and higher torque demand, whereas wingtip propellers maintain more uniform loading. These findings confirm the capability of the meshless rVPM approach to accurately and efficiently capture unsteady interactions in distributed propulsion systems, supporting its application to the analysis and design of future DEP aircraft.



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1. Introduction

The aviation sector is currently undergoing one of the most significant transitions in its history. Driven by the ambitious target of the European Union to achieve climate neutrality by 2050, the aerospace industry faces increasing pressure to reduce greenhouse gas emissions, improve energy efficiency, and mitigate noise pollution [1]. Conventional

propulsion architectures, based on a limited number of large turbofan or turboprop engines, are reaching their physical and technological limits in terms of sustainability. As a result, alternative concepts and disruptive technologies are actively being investigated to ensure the long-term viability of air transport.

Among the emerging solutions, Distributed Propulsion (DP) has gained considerable attention over the past decade. The basic principle of DP is the replacement of a single, centralized power plant with multiple propellers strategically distributed along the airframe. This configuration offers several potential advantages. First, distributing thrust generation can lead to higher aerodynamic efficiency, since propellers can be positioned to interact beneficially with wing or fuselage flow fields. Second, DP provides additional control authority, enabling novel flight control strategies and improved maneuverability. Several studies have investigated the aerodynamic interactions between wings and multiple propellers, focusing on both the influence of propeller placement on wing performance and the variation of propulsive efficiency along the span. Experimental investigations, such as those by Lee et al. [2], have shown that distributed propellers can enhance lift and delay flow separation by accelerating local flow over the wing surface. Also, Han et al. [3] have conducted a series of experiments concerning leading-edge mounted DP systems, comparing dual and triple propeller configurations. The potential benefits of DP have also been extensively investigated by NASA, from the conceptual design stage to the realization of flight demonstrators [4]. Moreover, modern Computational Fluid Dynamics (CFD) enables the accurate prediction of increasingly complex aerodynamic phenomena, facilitating its employment during the preliminary design stage, e.g., [5]. Additional research efforts have been conducted within major European programs, such as DISPROP [6], which addressed distributed propulsion architectures and propeller–wing aerodynamic interactions, as well as in several studies led by DLR and CIRA [7], where coordinated experimental and numerical investigation campaigns were performed. Despite these promising works, implementing DP remains challenging. In fact, the aerodynamic environment generated by multiple propulsors operating in close proximity to lifting surfaces is characterized by strong unsteady interactions, wake–wake coupling, and complex vortex dynamics. Accurate prediction of these effects is essential for developing reliable design methodologies and ensuring that DP configurations can deliver their expected benefits. Traditional computational approaches often rely on simplified models of propellers, such as actuator disk representations based on momentum theory [8]. Although computationally efficient, these models inherently smooth out the fine-scale vortex structures shed by rotating blades, neglecting important three-dimensional and unsteady phenomena. As a result, they tend to underestimate or misrepresent the aerodynamic coupling between propellers and lifting surfaces. To overcome these limitations, more advanced modeling techniques are required. In recent years, meshless methods have gained increasing attention for their flexibility and ability to handle complex flow fields without the need for mesh generation. These approaches are particularly effective in simulating vortex-dominated or rapidly evolving flow phenomena, which are often addressed using alternative techniques such as dynamic meshing, e.g., [9].

In this context, the reformulated Vortex Particle Method (rVPM) [10,11], as implemented in the FLOWUnsteady [12] framework, has demonstrated the ability to resolve complex wake structures over extended distances with minimal numerical dissipation. By solving the Navier–Stokes equations in the vorticity form within a Large-Eddy Simulation (LES) framework, the method combines physical fidelity with computational efficiency. Unlike mesh-based solvers, the Lagrangian particle formulation eliminates the need for mesh generation, significantly reducing pre-processing effort and avoiding mesh-induced artifacts in wake convection.

The objective of this work is to apply the FLOWUnsteady solver to analyze the aerodynamic characteristics of DP configurations and to assess the solver's capability in predicting unsteady propeller–wing interactions. The study focuses on understanding how the position of the propeller, their rotational speed, and the inflow conditions influence both the aerodynamic loads on the wing and the propulsive performance of the rotors. Two representative configurations were investigated: a two-propeller layout with wingtip-mounted propellers and a four-propeller configuration including additional inboard units, which were compared against a clean wing baseline. The analysis examines the evolution of the lift, drag, thrust, and torque coefficients under varying AOAs and freestream velocities. Through this investigation, the study aims to provide a comprehensive assessment of the aerodynamic coupling mechanisms that govern propeller–wing performance in multi-propulsor systems and to demonstrate the predictive capabilities of the meshless rVPM approach. Unlike steady or globally averaged approaches, the proposed methodology enables a detailed representation of propeller–wing interference and wake evolution, providing high-fidelity wake resolution with errors typically within 1–6% compared with URANS simulations and experimental data, at a substantially reduced computational cost relative to fully resolved mesh-based simulations [12].

This work is structured as follows: Section 2 presents the numerical methodology, including the meshless CFD framework, propeller and wing modeling, and the simulation setup. Section 3 discusses the main aerodynamic results, focusing on the influence of propeller configuration and operating conditions. Section 4 concludes the paper, highlighting key findings and future perspectives.

2. Methodology

This section provides a detailed discussion of the numerical framework employed in the present study.

2.1. Numerical Framework

The simulations were performed using FLOWUnsteady [12], a meshless CFD solver based on the reformulated Vortex Particle Method [10,11]. In this formulation, the incompressible Navier-Stokes equations are expressed in their vorticity form, with the vorticity field discretized into a collection of Lagrangian particles [11]. The Lagrangian nature of the solver avoids the need for mesh generation and reduces numerical dissipation, which is a common issue in grid-based solvers. The method is implemented within an LES framework. This particular approach ensures an accurate description of the main unsteady flow phenomena at a fraction of the computation cost of conventional grid-based LES [13].

2.2. Propeller and Wing Modeling

FLOWUnsteady uses the Actuator Line Method (ALM) to model the propellers, where each blade is represented by a lifting line discretized into radial elements. At each element, the aerodynamic forces are calculated from the tabulated lift and drag polars of the corresponding airfoil sections, then corrected for local inflow velocity and angle of attack [14]. Instead, the Actuator Surface Model (ASM) is used to model the wing: circulation is distributed throughout the wing surface to replicate its aerodynamic loading and trailing vortex system [14].

The propeller chosen for the simulations is the APC 10×7 propeller [15], a commonly used model in small-scale UAV applications. The wing employs a trapezoidal planform based on the NACA 64-2-015A airfoil along the entire span. It has a total span of 3.75 m and an aspect ratio of $AR = 5.33$, which yields a wing area of approximately 2.64 m² and a mean chord of 0.70 m. The wing taper ratio that is defined as $\lambda = c_{\text{tip}}/c_{\text{root}}$ is set

to $\lambda = 0.65$ in the present study. The wing has no sweep, dihedral, or geometric twist, providing a simplified but representative baseline.

To assess the benefits of DP, two configurations were considered: one with two wingtip-mounted propellers and another with an additional pair of propellers installed inboard along the wing. For comparison, a clean wing configuration without propellers was also simulated. Figure 1 presents schematic views of the two different DP configurations. Both geometries share the same reference wing planform.

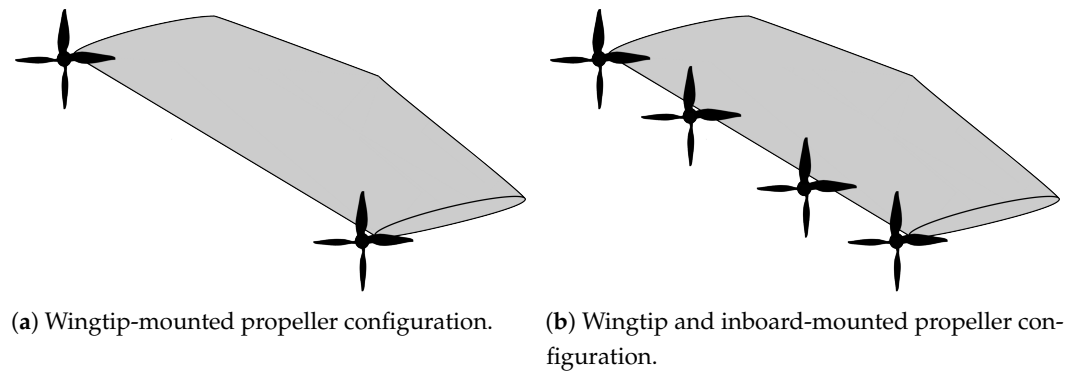


Figure 1. Distributed propulsion layouts considered in the present study.

2.3. Simulation Setup

The aerodynamic performance of the two DP configurations was analyzed using a mid-fidelity computational framework. The simulations were suitably designed to compare a wing-tip propeller layout and a tip-and-inboard configuration against a clean-wing baseline, under representative low-speed flight conditions. A first set of simulations was conducted at a freestream velocity of 33 m/s, corresponding to an advance ratio of $J = 0.85$, and a propeller rotational speed of approximately 4000 RPM. The flow was modeled as incompressible air with a density of $\rho = 1.06 \text{ kg/m}^3$ and a dynamic viscosity of $\mu = 1.79 \times 10^{-5} \text{ kg/(m} \cdot \text{s)}$, consistent with typical small-scale UAV operating regimes. The wing was discretized using 50 uniformly spaced panels per semispan, while each rotor blade was represented by 20 elements. Unsteady simulations were performed for eight complete propeller revolutions to ensure convergence of the time-averaged aerodynamic coefficients. Wind tunnel boundary effects such as floor, ceiling, and sidewalls were excluded, allowing the analysis to focus solely on propeller–wing aerodynamic interactions. To investigate the sensitivity of propulsive performance to operating conditions, additional simulations were carried out for the tip-and-inboard configuration at freestream velocities of 20 and 33 m/s, and at propeller speeds of 4000, 5000, and 6000 RPM. The resulting variations in thrust and torque coefficients (C_T and C_Q) were analyzed as functions of AoA and advance ratio. Other relevant simulation parameters, including the total physical time, the timestep size, and the number of iterations, are summarized in Table 1.

Table 1. Simulation parameters.

Configuration	Inflow Speed	RPMs	Total Revolutions	Simulation Time	Number of Timesteps
Wingtip mounted propellers	33 m/s	4000	8	0.12 s	288
Wingtip + inboard propellers	20 m/s, 33 m/s	4000, 5000, 6000	8	0.12 s	288

3. Results and Discussion

The aerodynamic performance of the different configurations was evaluated in terms of lift, drag, efficiency, and propulsive coefficients. Figure 2 shows the comparison of lift and drag for the clean wing and the two DP layouts. Both the wing-tip and the tip-and-inboard configurations exhibit a clear increase in lift coefficient compared against the clean wing, across the entire range of AoAs. This lift enhancement can be attributed to the propeller-induced acceleration of the flow over the wing surface, which strengthens local circulation and delays flow separation. The results are consistent with the experimental findings reported by Lee et al. [2]. A significant reduction in drag coefficient is observed for both DP configurations, particularly at moderate angles of attack, leading to an overall improvement in aerodynamic efficiency (C_L/C_D). The tip-and-inboard configuration provides the best performance, exhibiting the highest efficiency values across the investigated range. The numerical results show reasonable agreement with the experimental data reported by Dimchev [16] up to moderate angles of attack, confirming the reliability of the present meshless CFD approach in this regime. At larger angles of attack, however, the drag tendency observed in the experiments is not fully captured by the simulations, highlighting limitations of the current numerical model in representing flow separation effects. This provides a useful reference to assess the plausibility of the present numerical results.

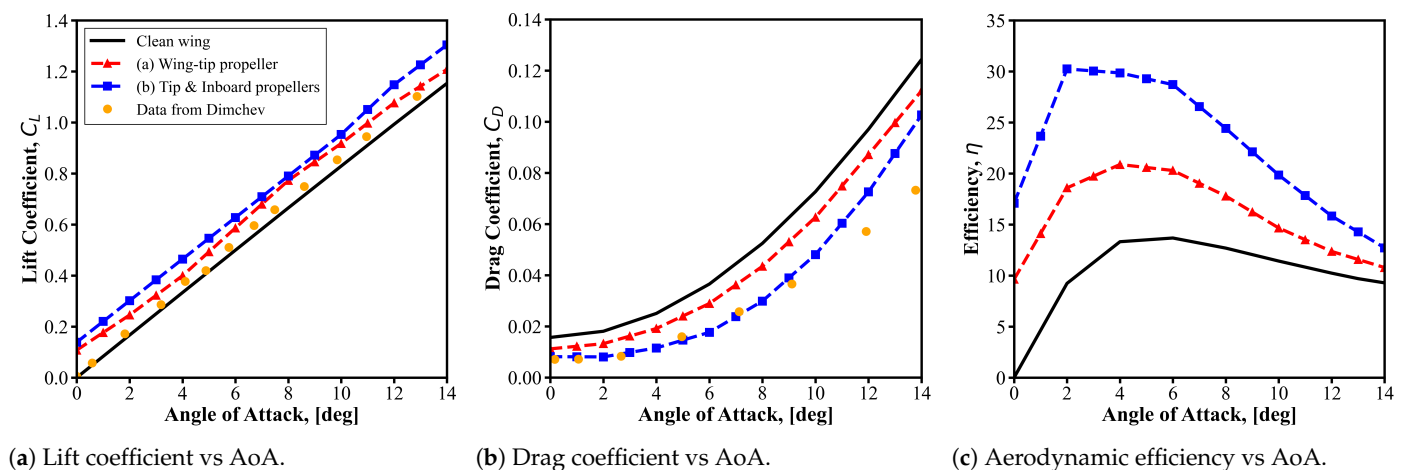


Figure 2. Comparison of aerodynamic performance for the clean wing and distributed propulsion configurations.

Figure 3 shows the variation of the torque coefficient C_Q and thrust coefficient C_T as functions of AoA for the inboard and wingtip propellers at rotational speeds of 4000, 5000, and 6000 RPM, with an inflow velocity of 33 m/s. The thrust and torque coefficients are defined as $C_T = \frac{T}{\rho n^2 D^4}$, $C_Q = \frac{Q}{\rho n^2 D^5}$, where ρ is the air density, n the propeller rotational speed, and D the propeller diameter.

A general increase in C_Q with the angle of attack is observed for all operating conditions, reflecting the higher aerodynamic loading on the blades due to the altered inflow field. At low angles of attack, the torque difference between the inboard and wingtip propellers at 4000 RPM is negligible. However, as the rotational speed increases, a noticeable discrepancy develops: at 5000 RPM and higher angles of attack, the inboard propeller exhibits a higher torque coefficient than the wingtip propeller. This trend becomes even more pronounced at 6000 RPM, where the aerodynamic torque acting on the inboard propeller significantly exceeds that one on the wingtip propeller. A similar behavior was also reported by Han et al. [3] in their experimental study. The corresponding C_T distributions show a similar dependence on the angle of attack. The thrust coefficient increases gradually with AoA up to 14°, with the wingtip propeller consistently producing higher thrust than

the inboard propeller. The thrust difference between the two propellers is more evident at higher AoAs, but diminishes as the rotational speed increases. These results are in good agreement with the experimental observations by Han et al. [3], confirming the reliability of the present numerical predictions.

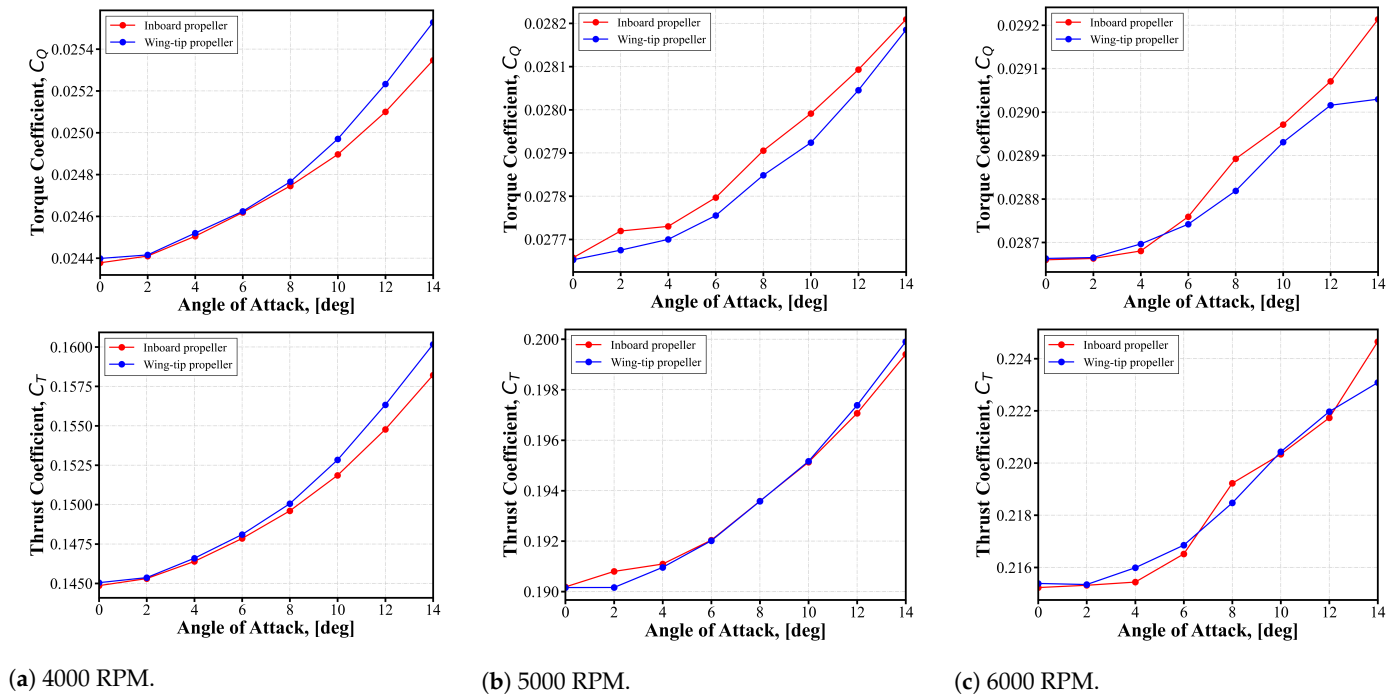
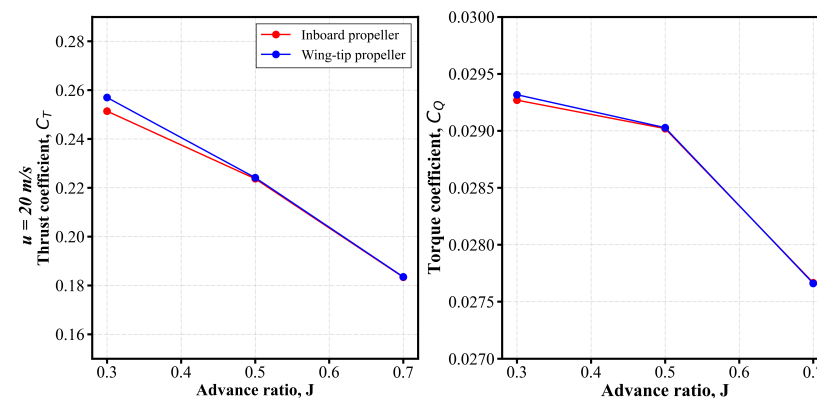


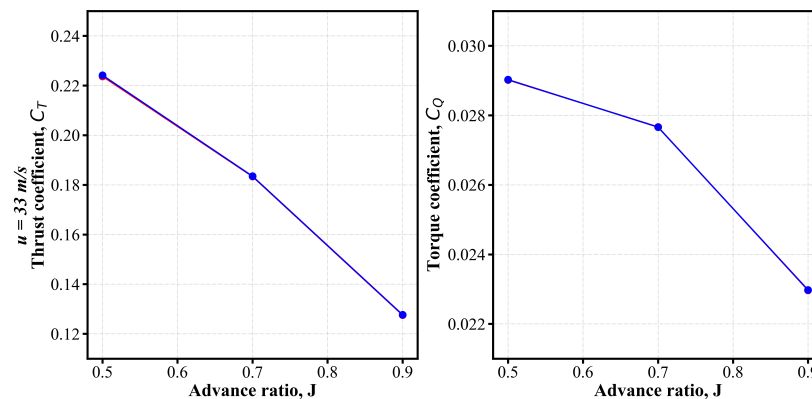
Figure 3. Variation of torque coefficient C_Q (top) and thrust coefficient C_T (bottom) with angle of attack for the inboard and wingtip propellers at different rotational speeds.

Figure 4 illustrates the variation of C_T and C_Q coefficients as functions of J for freestream velocities of 20 m/s and 33 m/s. At both flight speeds, C_T decreases with increasing J , which is consistent with classical propeller theory. A similar decreasing trend is observed for C_Q , indicating reduced aerodynamic loading as the advance ratio increases. Both coefficients exhibit higher values at 20 m/s than at 33 m/s, reflecting the stronger propulsive load generated at lower inflow velocity. The difference between the inboard and wingtip propellers remains negligible under both conditions. The present results are in good agreement with the experimental findings of Han et al. [3], thus confirming the consistency of the present numerical approach.



(a) Thrust and torque coefficient vs advance ratio at 20 m/s.

Figure 4. Cont.



(b) Thrust and torque coefficient vs advance ratio at 33 m/s.

Figure 4. Thrust and torque coefficient versus advance ratio for the two propellers mounted on the wing, evaluated at flight speeds of 20 m/s and 33 m/s. Results highlight the influence of operating conditions on propeller aerodynamic performance.

4. Conclusions

This study numerically investigated the aerodynamic characteristics of Distributed Propulsion systems using FLOWUnsteady, a meshless CFD solver based on the reformulated Vortex Particle Method. Two representative configurations were analyzed: a wingtip-mounted propeller layout and a tip-and-inboard arrangement, which were compared against a clean wing baseline configuration. The present results demonstrate that distributed propulsion significantly enhances aerodynamic performance by increasing lift and reducing drag, thereby improving overall efficiency. The propeller-induced acceleration of the flow delays separation and strengthens wing circulation, confirming the aerodynamic benefits of distributed thrust generation. Among the tested layouts, the tip-and-inboard configuration achieved the highest efficiency, particularly at moderate angles of attack, in good agreement with available experimental data. The current analysis also revealed distinct differences in propeller behavior. The inboard propellers experienced stronger aerodynamic interference and higher torque coefficients at elevated rotational speeds, whereas the wingtip propellers maintained more uniform loading. These findings highlight the importance of propeller placement and spacing in optimizing performance and minimizing power requirements. The rVPM-based meshless framework effectively captured the complex unsteady flow interactions between propellers and lifting surfaces while preserving wake coherence with minimal numerical dissipation. The method thus provides a robust and computationally efficient tool for analyzing and optimizing multi-propulsor configurations. Future work will extend this approach to explore broader flight conditions and include acoustic analysis and optimization strategies for performance–noise trade-offs in next-generation DP systems.

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Abbreviations

The following abbreviations are used in this manuscript:

ALM	Actuator Line Method
AOA	Angle of attack
AR	Aspect ratio
ASM	Actuator Surface Model
CFD	Computational fluid dynamics
DEP	Distributed electric propulsion
DP	Distributed propulsion
LES	Large Eddy Simulation
rVPM	Reformulated vortex particle method
UAV	Unmanned aerial vehicle

Nomenclature

The following symbols are used in this manuscript:

C_D	Drag coefficient
C_L	Lift coefficient
C_Q	Torque coefficient
C_T	Thrust coefficient
D	Propeller diameter
J	Advance ratio
λ	Taper ratio
η	Aerodynamic efficiency
μ	Viscosity
ρ	Density

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