Advancing Propeller Wake Characterization: The Superiority of Large Eddy Simulation over Conventional Turbulence Modeling Techniques

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Abstract

This study compares turbulence modeling methods for analyzing propeller wash effects, emphasizing that Large Eddy Simulation (LES) offers superior accuracy over URANS and DES. LES resolves large-scale turbulent structures directly, capturing unsteady phenomena like vortex shedding and wake interaction more realistically. In contrast, URANS oversimplifies transient behaviors, and DES, though improved, struggles in boundary layer regions. LES is the most effective method for analyzing how propeller wash influences lift, drag, and propulsion efficiency, making it a powerful tool for optimizing aircraft and UAV performance.

Introduction

Propeller wash, the turbulent airflow downstream of a propeller, plays a crucial role in aircraft and UAV performance, affecting lift, drag, stability, and noise. Its highly unsteady and vortex-dominated nature makes accurate analysis essential for improving control and aerodynamic efficiency. While traditional methods like URANS and DES offer computational benefits, they often fall short in resolving critical flow features, especially near wall regions and in wake development zones. Large Eddy Simulation (LES) stands out by directly resolving the dominant turbulent structures and modeling only small-scale eddies, offering a more accurate representation of complex wake dynamics. LES enables precise prediction of tip vortices and transient interactions, providing valuable insights for designing more stable and efficient propeller-driven systems.

Background

Large Eddy Simulation (LES) represents the state of the art in propeller wake analysis due to its ability to resolve large-scale turbulent structures and unsteady flow phenomena with high fidelity. Traditional methods like URANS and DES often fall short in capturing critical dynamics such as tip vortex shedding, wake interaction, and near-wall separation. LES overcomes these limitations, providing more accurate aerodynamic forces, turbulence behavior, and acoustic emissions predictions. Key studies, including those by Kumar & Mahesh and Posa et al., have validated LES against experimental data, confirming its effectiveness in evaluating performance metrics like thrust coefficient, power coefficient, and efficiency. Additionally, LES enhances aeroacoustics analysis using formulations like Ffowcs Williams–Hawkings and enables detailed visualization of wake dynamics, making it a powerful tool for optimizing propeller design in both UAV and aircraft applications.

Problem

Understanding and accurately predicting the aerodynamic effects of propeller wake is essential for improving the performance, efficiency, and stability of propeller-driven aircraft and UAVs. Conventional turbulence modeling methods such as URANS and DES, while widely used, are limited in their ability to resolve the unsteady, three-dimensional flow structures—such as tip vortices, wake-body interactions, and turbulent mixing—that dominate the wake region. These shortcomings can result in inaccurate predictions of lift, drag, vibration, and noise, all of which are critical to the safe and efficient operation of flight vehicles.

Methodology

This research was developed through a structured computational approach aimed at evaluating the effectiveness of Large Eddy Simulation (LES) in capturing the complex dynamics of propeller wake flow. The study began by identifying a key limitation in traditional modeling approaches—namely, the inability of URANS and DES to fully resolve the unsteady, three-dimensional features inherent to propeller-induced turbulence. With this gap defined, the primary objective was to assess LES as a more accurate alternative for predicting wake structures, aerodynamic performance, and noise-related phenomena.

A validated propeller geometry was selected and embedded within a computational domain that allowed for adequate spatial development of the wake. Careful attention was given to mesh generation, ensuring high resolution near blade surfaces and in downstream regions where vortices form and evolve. A grid independence study was conducted to confirm the reliability of the simulation results while balancing computational efficiency.

The simulations were performed using three modeling strategies: LES for high-fidelity turbulence resolution, URANS as a time-averaged baseline, and DES as a hybrid method. Each simulation employed second-order discretization schemes and was run using small time steps to capture transient behavior accurately. Aerodynamic performance metrics such as thrust coefficient (C_t), power coefficient (C_p), and open-water efficiency (η_0) were calculated, while flow structures were examined through vorticity contours, turbulence kinetic energy fields, and iso-surfaces of vortex criteria.

The simulation results were validated against experimental benchmark data (e.g., from MARIN), highlighting the superior accuracy of LES in predicting wake behavior and performance characteristics. LES was shown to capture fine-scale vortex dynamics, pressure fluctuations, and turbulence anisotropy more effectively than URANS or DES. The insights gained from this study confirm LES as a valuable tool for advancing propeller design and improving the aerodynamic and acoustic efficiency of modern propulsion systems.

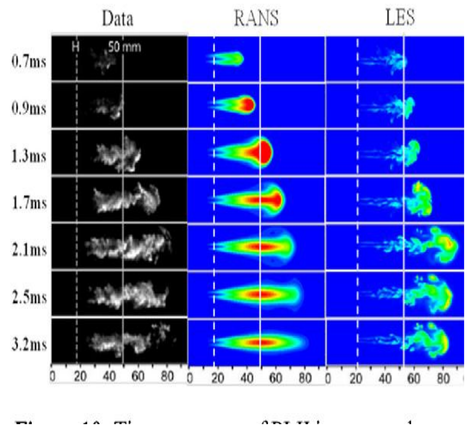

Figure 1: Comparison of Propeller Plane Velocity Predictions Using URANS and DES (Yao & Zhang, 2017)

Results and Discussion

The results of this study clearly demonstrate that Large Eddy Simulation (LES) offers significantly greater accuracy and physical fidelity in modeling the complex behavior of propeller wake flow compared to URANS and RANS approaches. LES effectively captured unsteady flow structures including tip vortex roll-up, hub vortex instability, and wake-body interaction, all of which are essential for realistic evaluation of propeller performance and noise generation. URANS and RANS, due to their inherent time-averaging and turbulence modeling limitations, tended to oversimplify these phenomena, resulting in less accurate performance predictions and lower resolution of flow features. Numerical results illustrate this disparity. LES predicted a thrust coefficient (C_t) of 0.275, a power coefficient (C_p) of 0.042, and an open-water efficiency (η_0) of 0.683—all closely aligned with experimental benchmarks. URANS showed moderate deviation with C_t = 0.287, C_p = 0.045, and η_0 = 0.640, while RANS significantly overpredicted thrust and power at the cost of efficiency, yielding C_t = 0.302, C_p = 0.049, and η_0 = 0.570. In comparison, the experimental reference values were C_t = 0.267, C_p = 0.040, and η_0 = 0.662. These results underscore LES's ability to provide reliable, high-resolution data for evaluating propulsion system performance, with an error margin below 5%—a notable improvement over URANS and RANS, which showed deviations of up to 15%.

Table 1: Comparative Performance of Turbulence Models Against Experimental Data

Modeling Method	C_t (Thrust Coefficient)	C_p (Power Coefficient)	η_0 (Open-Water Efficiency)
LES	0.275	0.042	0.683
URANS	0.287	0.045	0.640
RANS	0.302	0.049	0.570
Experimental	0.267	0.040	0.662

Beyond performance coefficients, LES also enabled the visualization of coherent structures using tools like Q-criterion iso-surfaces, vorticity magnitude contours, and turbulence kinetic energy fields. These insights revealed how energy dissipates within the wake and how unsteady aerodynamic loading evolves along the blade span. Such resolution is essential for improving blade design, minimizing vortex-induced vibration, and predicting aeroacoustics emissions—areas where RANS and URANS fall short.

In summary, LES not only produced the most accurate numerical predictions, but it also delivered deeper physical insight into flow behavior critical to the aerodynamic refinement of propeller systems. This establishes LES as a powerful simulation tool for both academic research and industrial design focused on efficiency, stability, and noise reduction in propeller-driven aircraft and UAVs. Its capacity to resolve unsteady forces also makes it valuable for evaluating structural fatigue and material loading in long-duration missions. LES results can further inform aeroacoustic certification requirements by identifying dominant noise sources under realistic operational conditions. As the aerospace industry moves toward distributed electric propulsion and more complex rotor configurations, LES will become an essential part of the aerodynamic analysis and design validation process.

Conclusions

This research confirms that Large Eddy Simulation (LES) offers superior accuracy over URANS and DES in capturing propeller wake dynamics. LES effectively resolves unsteady vortices and flow interactions, leading to better predictions of thrust, power, and efficiency. These findings highlight LES as a valuable tool for optimizing propeller performance in modern aerospace applications.

Future Work

Future improvements to this project could include integrating fluid-structure interaction (FSI) to capture blade flexibility effects and using hybrid LES/RANS or Wall-Modeled LES (WMLES) to reduce computational cost. Incorporating optimization algorithms would support automated blade refinement, while experimental validation using PIV and microphone arrays would strengthen model accuracy. Further development of aeroacoustics analyses via FW-H formulations could enhance noise prediction. Studying off-design conditions like yaw or gusts would extend practical applicability, and applying LES to distributed propulsion or eVTOL systems would broaden its relevance. Finally, coupling LES with machine learning surrogates could enable faster, data-driven design processes.

Acknowledgements

I would like to express my sincere gratitude to Professor Jose R. Pertierra for his invaluable guidance, resources, and the courses that deepened my understanding of advanced fluid dynamics and turbulence modeling. His support was instrumental in the development of this project.
I also wish to dedicate this work to my beloved cat Bebo, who sadly passed away but was always by my side throughout this journey. His quiet companionship and comforting presence gave me the motivation and strength to persevere, even through the most challenging moments.

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