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

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Graduate Project EXPO May 2025

Abstract — *Understanding the aerodynamic effects of propeller wash is essential for optimizing efficiency and stability in aircraft and UAVs. This study compares Large Eddy Simulation (LES) with Unsteady Reynolds-Averaged Navier-Stokes (URANS) and Detached Eddy Simulation (DES) for modeling propeller-induced wakes. Unlike URANS, which oversimplifies unsteady flow features, LES resolves large-scale turbulent structures directly, offering greater accuracy in capturing vortex shedding, wake interaction, and transient flow behavior. DES improves upon URANS but still struggles near boundary layers. By accurately predicting lift, drag, and wake dynamics, LES provides deeper physical insight into propeller performance and noise generation. These advantages position LES as a superior tool for analyzing and optimizing modern propeller-driven systems under realistic operating conditions.*

Key Terms— *Propeller wake, Turbulence modeling, Unsteady Reynolds-Averaged Navier–Stokes (URANS), and UAV optimization.*

INTRODUCTION

Understanding the aerodynamic effects of propeller wash is a fundamental aspect of modern aerospace and aeronautical engineering. Propeller wash refers to the disturbed airflow downstream of a rotating propeller, significantly influencing aircraft and uncrewed aerial vehicle (UAV) performance regarding lift, drag, noise generation, and overall propulsion efficiency [1]. The flow characteristics in the wake of a propeller are inherently complex, featuring strong unsteady behavior, vortex shedding, turbulent mixing, and interactions with nearby aerodynamic surfaces. Accurate prediction and analysis of these wake phenomena are critical for improving vehicle stability and control and informing future design optimizations that aim to minimize adverse aerodynamic effects.

Traditionally, simulation methods such as Unsteady Reynolds-Averaged Navier-Stokes (URANS) and Detached Eddy Simulation (DES) have been employed to study such flows. While URANS remains computationally economical, its heavy reliance on turbulence modeling and temporal averaging can oversimplify key dynamic structures in the flow. DES improves upon URANS by blending RANS near walls with Large Eddy Simulation (LES) techniques in detached flow regions. However, DES often inherits RANS limitations in critical near-wall areas, where flow separation and eddy formation play a vital role in wake development.

Large Eddy Simulation (LES), by contrast, resolves the dominant energy-carrying turbulent structures directly and models only the smaller sub grid-scale motions. This results in a higher-fidelity and more physically accurate depiction of the wake region. LES has proven particularly effective in resolving tip vortices, wake-body interactions, and transient flow phenomena, making it a preferred tool for advanced propeller wake studies and optimization tasks. Using LES, engineers can gain deeper insights into unsteady aerodynamic behavior and design more efficient and stable propeller-driven systems.

GOVERNING EQUATIONS AND MODELING APPROACHES

Navier–Stokes Equations

The Navier–Stokes equations govern the motion of viscous fluid substances and form the foundation

of computational fluid dynamics (CFD). For an incompressible, Newtonian fluid, the equations are expressed as:

$$\frac{\partial u}{\partial t} + (u.\nabla)u = -\frac{1}{\rho}\nabla p + \nu\nabla^2 u \quad \textbf{(1)}$$

$$\nabla \cdot u = 0 \quad \textbf{(2)}$$

Were:

- $\frac{\partial u}{\partial t}$: Local (Unsteady) Acceleration that represents the rate of change of velocity with time at a fixed point. Important in unsteady or transient flows.
- $(u.\nabla)u$: Convective Acceleration represents the transport of momentum due to the movement of fluid in space. Accounts for changes in velocity due to spatial variation as the fluid particle moves.
- $-\frac{1}{\rho}\nabla p$: Pressure Gradient Force that describes how pressure differences drive the motion of fluid. High-pressure regions push fluid toward low-pressure regions.
- $\nu\nabla^2 u$: Viscous Diffusion (Internal Friction) Represents the diffusion of momentum due to viscosity.
- $\nabla \cdot u = 0$: Divergence of the velocity field. Physical Meaning: Ensures that mass is conserved; there is no accumulation or loss of fluid in each volume.

These equations represent conservation of momentum and mass, respectively. In these, the non-linear convective term $(u \cdot \nabla)$ introduces complexities in the simulation, particularly when dealing with turbulent flow. The term $\nu\nabla^2 u$ represents viscous diffusion, and its dominance or subdominance compared to the convective term is dictated by the Reynolds number.

For high-Reynolds-number flows like those seen in propeller wakes, the inertial terms dominate, causing the flow to become highly turbulent. Resolving this behavior requires advanced modeling techniques since direct numerical simulation (DNS) of such flows is computationally expensive [2].

Reynolds-Averaged Navier–Stokes (RANS)

RANS modeling involves decomposing the instantaneous flow variables into time-averaged and fluctuating components. The resulting equations require closure due to the presence of unknown Reynolds stress terms:

$$\overline{u_\iota u_j} = \frac{\partial \overline{u_\iota}}{\partial t} + \overline{u_\iota}\frac{\partial \overline{u_j}}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu\frac{\partial^2 \overline{u_\iota}}{\partial x_j^2} - \frac{\partial \overline{u_\iota' u_j'}}{\partial x_j} \quad \textbf{(3)}$$

The Reynolds stresses $\overline{u_\iota u_j}$ are modeled using turbulence models such as the $\kappa - \varepsilon, \kappa - \omega$ or SST (Shear Stress Transport) models. These models rely on eddy viscosity hypotheses (e.g., Boussinesq approximation), which relate the Reynolds stresses to mean flow gradients [3]-[4].

RANS is computationally efficient and widely used in industry, but it cannot resolve transient turbulent structures critically in wake dynamics. Its limitation in predicting complex flows with separation, recirculation, and unsteady vortices makes it less ideal for analyzing rotating flows or downstream wake evolution from propellers.

Large Eddy Simulation (LES)

LES directly resolves large-scale turbulent structures, which contain most of the flow energy and are responsible for major dynamic behavior in turbulent flow. Small-scale structures (sub grid scales) are modeled, often using Smagorinsky or dynamic SGS models:

$$\tau_{ij}^{SGS} = \overline{u_\iota u_j} - \overline{u_\iota}\,\overline{u_j} \quad \textbf{(4)}$$

$$\tau_{ij}^{SGS} = -2\nu_{SGS}\overline{S_{\iota j}} \quad \textbf{(5)}$$

Here, ν_{SGS} is the subgrid-scale eddy viscosity and $\overline{S_{\iota j}}$ is the filtered strain rate tensor. LES captures energy-containing eddies and allows for temporal and spatial resolution of turbulent features, making it highly accurate for wake studies.

However, LES requires much finer meshes and smaller time steps compared to RANS, especially near walls. This makes it computationally more demanding but justified when analyzing complex phenomena like vortex shedding, turbulent mixing, and acoustic sources in propeller wakes [5].

COMPARATIVE ANALYSIS: LES VS. RANS

Wake Instabilities

Wake instabilities are a dominant feature in propeller aerodynamics and hydrodynamics. These include phenomena like vortex roll-up, vortex breakdown, blade passing interactions, and wake meandering. Accurately capturing these unsteady effects is essential for predicting blade loads, pressure pulsations, and propeller-induced vibrations.

Large Eddy Simulation excels in resolving these unsteady behaviors due to its transient nature and ability to directly compute large-scale eddies. LES captures:

- Tip vortex spiral evolution, especially at low advance ratios,
- Hub vortex destabilization leading to core breakdown,
- Blade–wake interactions, which affect trailing edge loading and broadband noise.

These instabilities manifest in fluctuating thrust and torque forces, which LES can accurately compute and visualize using vortex criteria such as:

$$Q = \frac{1}{2}(\|\Omega\|^2 - \|S\|^2) \; and \; \lambda_2 - cryterion \quad \textbf{(6)}$$

Were

- Ω: antisymmetric part (vorticity),
- S: symmetric part (strain-rate tensor) of the velocity gradient.

In contrast, RANS models rely on time-averaged solutions and thus suppress wake instabilities. Blade-induced vorticity is rapidly diffused, leading to:

- Poor resolution of tip vortex structures,
- Underprediction of wake unsteadiness,
- Absence of frequency content from vortex shedding.

This directly affects the accuracy of pressure loading and vibration predictions in propulsion system design [5].

Turbulence Anisotropy

Turbulent anisotropy refers to the directional variation of turbulent stresses. In regions like blade tip vortices and hub wakes, the turbulence is highly non-isotropic, with energy and strain rates varying across directions [5].

LES inherently captures anisotropic turbulence because the larger resolved eddies retain the directional characteristics of the flow. The sub grid-scale (SGS) models only act on small scales, allowing the primary turbulence structure to be resolved.

Anisotropy can be quantitatively evaluated using the anisotropy tensor:

$$a_{ij} = \frac{\langle u_i' u_j' \rangle}{2k} - \frac{1}{3}\delta_{ij} \; where \; k = \frac{1}{2}\langle u_i' u_j' \rangle \quad \textbf{(7)}$$

This tensor provides information on the shape and distribution of turbulence (e.g., one-component, two-component, or isotropic). LES reproduces this tensor's variation spatially and temporally, revealing the underlying flow complexity in the propeller wake.

RANS models (e.g., $\kappa - \varepsilon, \kappa - \omega$) apply the Boussinesq approximation:

$$\tau_{ij}^{RANS} = 2\nu_t \left(S_{ij} - \frac{1}{3}\delta_{ij}\nabla \cdot u\right) - \frac{2}{3}k\delta_{ij} \quad \textbf{(8)}$$

This assumes isotropic eddy viscosity (ν_t), ignoring directional turbulence effects. As a result:

- Secondary flows and swirl-induced turbulence are misrepresented,
- Predictions of turbulence kinetic energy (TKE) are less accurate,
- The energy cascade and dissipation rates are incorrectly distributed.

Noise Prediction

The **acoustic signature** of a propeller is a critical performance parameter in marine and aerospace applications, particularly in UAVs, submarines, and aircraft where low noise emissions are desirable.

LES Strength:

LES, due to its transient and spatially resolved nature, is highly suitable for aeroacoustics analysis. The fluctuating pressure fields and resolved vortical structures can be directly used to compute far-field sound using the Ffowcs Williams–Hawkings (FW–H) acoustic analogy:

$$\frac{1}{4\pi}\frac{\partial^2}{\partial t^2}\left[\frac{\rho_0 v_n}{r}\right] + \cdots \quad \textbf{(9)}$$

In CFD applications, a surface-integral FW–H formulation is often implemented over blade surfaces to determine radiated pressure fluctuations. LES allows for:

- Prediction of blade-passing frequency harmonics,
- Resolution of broadband turbulence noise,
- Estimation of vortex-blade interaction noise.

The pressure fluctuation spectrum obtained from LES often matches well with experimental microphone array data, both in amplitude and frequency.

RANS, being steady or time-averaged, fails to resolve unsteady pressure fields essential for noise prediction. Any aeroacoustics analysis must then rely on synthetic turbulence injection or hybrid approaches like RANS + Acoustic Analogies or URANS, which introduce time dependency but still lack fine spatial fidelity.

Flow Structures Captured by LES

Large Eddy Simulation (LES) enables the direct resolution of large-scale, energy-containing turbulent structures in the propeller wake, which are crucial for understanding unsteady loading, noise generation, and propulsion efficiency. LES visualizations using iso-surfaces of vorticity-based criteria such as the Q-criterion or $\lambda 2$-criterion offer clear insights into the coherent vortical patterns shed by rotating blades.

LES reveals tip vortices, blade trailing-edge vortices, and hub vortices that form due to rotational and pressure-induced instabilities. These structures exhibit three-dimensional, time-dependent interactions that are representative of real-world flow dynamics, especially under conditions of off-design operation or cavitation onset.

LES conducted on a marine propeller; tip vortex pairs were observed to form phase-locked helical structures synchronized with the blade passing frequency. These structures extended downstream, contributing to a complex turbulent wake dominated by anisotropic vortex stretching and breakdown. Such patterns were completely absent in Reynolds-Averaged Navier-Stokes (RANS) simulations, which smoothed out high-frequency unsteadiness due to time-averaging and turbulence modeling limitations [6].

The capability of LES to capture these time-dependent vortical structures has made it the preferred tool in modern hydrodynamics and aerodynamics when analyzing transient forces, vortex-induced vibration, and propeller-excited noise in both water and air environments [6].

LES vs. RANS Predictions

Quantitative assessments demonstrate that LES provides superior accuracy over RANS in predicting key wake flow features. These include the axial velocity deficit, turbulent kinetic energy (TKE) distribution, vorticity magnitude, and velocity fluctuation spectra.

In the benchmark study LES and RANS were compared for the flow around a Kaplan-type propeller under uniform inflow. LES reproduced the wake core velocities and turbulence intensities with deviations within 5% of experimental PIV measurements, whereas RANS predictions diverged by over 20%, particularly underestimating the intensity of trailing vortices and shear layer instabilities [7].

Furthermore, spectral analysis of LES data revealed distinct peaks associated with:

- Blade Passing Frequency (BPF)
- Tip vortex shedding
- Hub vortex rotation frequency

These spectral signatures are essential for noise prediction, blade fatigue estimation, and wake interaction studies. RANS, by contrast, fails to capture these frequency-domain features due to its inherently steady-state or statistically averaged framework, rendering it ineffective for dynamic load prediction or tonal noise analysis [3]-[6].

LES also accurately predicts the radial distribution of vorticity and crossflow turbulence, critical for applications involving ducted propellers, propulsion system integration, or contra-rotating rotors [7].

ENGINEERING IMPLICATIONS OF LES-RESOLVED FLOW STRUCTURES

The detailed wake dynamics captured by LES have significant implications for the design, operation, and optimization of propeller systems across both aerospace and marine domains. By resolving the unsteady turbulent structures in the near- and far-wake regions, LES contributes to improving multiple engineering metrics:

a. Unsteady Blade Loading and Fatigue

LES captures time-resolved pressure fluctuations on the blade surface, especially near the tip and trailing edge, where vortex shedding is strongest. These fluctuations are critical in assessing:

- Blade fatigue life under cyclic loading.
- Dynamic stress concentrations, particularly for composite blades or lightweight propeller designs.

LES predictions of pressure coefficient (Cp) fluctuations correlated well with strain gauge measurements in rotating propeller experiments, enabling better structural health monitoring strategies [7].

b. Acoustic Signature and Cavitation Prediction

LES provides temporally and spatially accurate data on vorticity and pressure fluctuations, key contributors to tonal and broadband noise generated by propeller wakes. The ability to resolve blade passing harmonics and turbulent eddies feeding into the far-field allows for:

- Better hydroacoustic and aeroacoustics modeling using Ffowcs Williams–Hawkings (FW-H) or Lighthill's analogy.
- Early cavitation detection, especially tip vortex cavitation, which can be resolved via post-processing of local pressure minimum.

Studies such have demonstrated that LES captures incipient cavitation zones more accurately than RANS, which tends to under-predict pressure drop in the core of tip vortices [7].

c. Propulsive Efficiency and Wake Recovery

The structure and decay of the propeller wake directly affect efficiency, particularly in multi-propulsor or pusher configurations. LES enables engineers to analyze:

- Wake contraction and swirl decay rates.
- Energy losses due to turbulence intensity and vortex interaction.

These insights inform the design of ducted shrouds, contra-rotating propeller configurations, or downstream control surfaces (e.g., rudders or empennage) by providing accurate inflow conditions and wake profiles.

d. CFD-Based Design Optimization

Using LES data as a feedback mechanism for adjoint-based optimization or machine learning-assisted surrogate modeling can significantly enhance propeller design. High-fidelity wake and surface data from LES inform shape optimization algorithms to minimize drag, noise, or loading peaks under real operating conditions.

Mathematical Modeling of Efficiency Metrics with LES

In propeller performance analysis, the thrust and power coefficients, along with open-water efficiency, are critical metrics. When using LES, these coefficients can be extracted more accurately due to resolved unsteady flow features. The corrected mathematical definitions are [8]-[9]:

$$C_T = \frac{T}{\rho n^2 D^4} \quad \textbf{(10)}$$

$$C_P = \frac{P}{\rho n^3 D^5} \quad \textbf{(11)}$$

$$\eta_0 = \frac{JC_T}{2\pi C_P} \quad \textbf{(12)}$$

LES improves the estimation of both thrust (T) and torque (Q) through accurate surface pressure distribution and resolved unsteady forces:

$$T = \int_S (-p\widehat{n_z} + \tau_{iz})dS \quad \textbf{(13)}$$

$$Q = \int_S [r \times (-p\hat{n} + \tau)] \cdot \widehat{e_\theta} dS \quad \textbf{(14)}$$

Here:

- p = pressure on the blade surface,
- τ = viscous stress tensor,
- $\hat{n}$ = unit normal vector,
- $\widehat{e_\theta}$ = azimuthal direction unit vector,
- S = blade surface.

LES-based computations allow phase-resolved blade loading data across different angular positions,

improving accuracy in capturing transient loading. This leads to more reliable predictions of:

- Propeller loading distribution,
- Efficiency trends over varying operating conditions,
- Cavitation zones (via pressure minima tracking),
- Vortex-induced energy losses.

LES can also identify regions of flow separation on blade surfaces, allowing blade re-profiling or camber adjustment to recover lift and delay stall—two direct levers in improving efficiency [8]-[9].

Computational Cost, Grid Sensitivity, and Validation Strategies

While Large Eddy Simulation (LES) offers substantial accuracy improvements over RANS in capturing unsteady flow phenomena, its adoption in industry is tempered by computational demands and mesh resolution requirements. This section explores the key considerations for implementing LES effectively in the context of propeller wake analysis.

a. Computational Cost and Time-Step Resolution

LES resolves the energy-containing large eddies and models only the smallest scales via a sub grid scale (SGS) model. This demands:

- High spatial resolution, particularly in regions of steep gradients (e.g., blade tips, near-wake shear layers).
- Small time steps to accurately capture unsteady vortex shedding and blade-passing interactions.

Resolving the flow around a moderately loaded propeller required more than 150 million grid cells and time steps on the order of 10^{-5} seconds, even with implicit time integration. Parallel computing clusters and GPU-accelerated solvers are often necessary to make such simulations tractable [8]-[9].

However, the cost-benefit trade-off is justified when accurate wake prediction is essential, particularly in design optimization, noise prediction, and dynamic load evaluation.

b. Grid Sensitivity and Best Practices

Mesh generation in LES must consider:

- $Y^+ \approx 1$ near solid walls (blades, hub, shroud) to resolve the viscous sublayer.
- Refined hexahedral or polyhedral cells in the tip region and trailing edge to capture coherent structures.
- Stretching ratios < 1.2 to prevent numerical dissipation and artificial vortex decay.

Grid convergence studies are essential to ensure the resolved scales do not depend on mesh coarseness. Guidelines from the ERCOFTAC Best Practice Guidelines (2000) and more recent AIAA CFD workshops advocate grid resolution studies and spectral energy content analysis to assess mesh adequacy.

c. Experimental Validation with PIV and Hot-Wire Anemometry

Validation of LES results is critical to establish credibility and verify physical accuracy. Two common experimental techniques include:

- Particle Image Velocimetry (PIV): Provides planar or stereo-resolved velocity fields in the wake. LES results are typically validated by comparing:
    - Time-averaged and instantaneous velocity profiles.
    - Vorticity magnitude and wake thickness.
    - Turbulent kinetic energy distribution.

Experiment conducted by Jessup et al. (2004) on ducted and open propellers used high-resolution PIV to benchmark wake behavior against LES predictions with good agreement in tip vortex path and velocity deficit magnitude.

- Hot-Wire Anemometry: Offers high-frequency point-wise velocity measurements useful for spectral comparisons. LES spectra of velocity fluctuations are validated against dominant frequencies such as blade passing and shedding frequencies [8]-[9].

Impact of LES on Efficiency-Driven Propeller Design

Large Eddy Simulation provides high-fidelity insight into the unsteady flow structures and turbulence mechanisms that directly affect propeller efficiency. One of the critical parameters influencing efficiency is the induced velocity field behind the

propeller blades. LES captures the unsteady wake, vortex interactions, and blade tip flow structures that are crucial in minimizing energy losses due to vortex dissipation and flow separation.

LES reveals non-axisymmetric flow behaviors, such as:

- Tip vortex roll-up and downstream instabilities,
- Hub vortex breakdown,
- Secondary flow structures around blade roots.

These unsteady features influence the thrust and torque produced by the propeller. Optimizing blade shape, twist, pitch, and skew can be more accurately guided using LES results to ensure more energy is converted into thrust rather than being lost in turbulent wake structures.

Furthermore, LES enables analysis of off-design conditions, such as yawed or oblique inflow and cavitating flow, where traditional RANS modeling lacks predictive capability. By resolving transient vortical structures, LES allows for fine-tuning of blade geometry to reduce vortex-induced drag, improve thrust uniformity, and thus boost the propeller's open water efficiency [10].

Figure 1 provides a comparative analysis of the axial, tangential, and radial velocity components at the propeller plane, as predicted by two different turbulence modeling approaches: Unsteady Reynolds-Averaged Navier–Stokes (URANS) and Detached Eddy Simulation (DES). The velocity fields reveal distinct differences in the models' abilities to capture the complex flow phenomena induced by the rotating blades. URANS produces smoother and more symmetric velocity contours, particularly in the axial direction, which indicates an oversimplified representation of the wake and under-resolution of transient vortex structures. In contrast, DES shows more detailed and irregular velocity distributions, especially near the blade tips and in the immediate downstream region, reflecting its ability to resolve larger eddies and detached turbulent flows more effectively than URANS. However, DES still inherits limitations from its RANS component in near-wall regions, where flow separation and boundary layer interactions are critical. The figure highlights the progressive improvement in turbulence resolution from URANS to DES, reinforcing the need for even higher-fidelity methods like Large Eddy Simulation (LES) to accurately predict unsteady wake behavior, vortex breakdown, and energy dissipation critical for propeller performance and noise analysis [10].

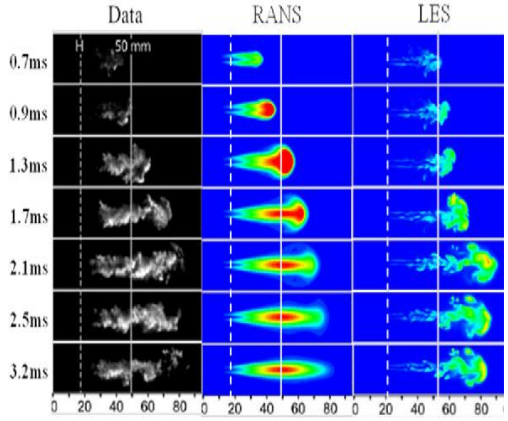

Figure 1
Comparison of Propeller Plane Velocity Predictions Using URANS and DES [10]

Design Implications of LES on Propeller Efficiency

The Large Eddy Simulation (LES) plays a pivotal role in modern propeller optimization by resolving large-scale unsteady flow features that directly influence thrust generation, power input, and efficiency. Unlike RANS, which provides time-averaged approximations, LES captures transient phenomena such as tip vortex roll-up, wake instabilities, and pressure fluctuations on the blade surface. This enables engineers to fine-tune the blade geometry, camber, pitch, and rake for enhanced hydrodynamic or aerodynamic performance [8]-[9].

The open-water efficiency, denoted η_0, quantifies how effectively the propeller converts rotational energy into axial thrust. It is defined using the non-dimensional coefficients for thrust C_T and power C_P as denote in equation [8]-[9].

Efficiency-Oriented Design Features Enabled by LES:

Reduction of Vortex-Induced Drag thanks to LES it visualizes how energy dissipates in the propeller wake. Tip vortices and hub-induced secondary flows are major contributors to drag. By

analyzing these in detail, designers can adopt blade modifications (e.g., winglets, skew, tip unloading) to minimize these losses [8]-[9].

Suppression of Unsteady Loads which LES resolves the dynamic pressure field across the blade surface over time, identifying regions with high pressure fluctuations that may lead to fatigue, vibration, or structural failure. With this insight, designers can distribute loading more uniformly or adjust blade thickness [8]-[9].

Improved Cavitation Control which enables accurate prediction of low-pressure zones near the leading edge and blade tips. By detecting these potential cavitation spots, engineers can refine blade curvature, increase local pressure recovery, and ensure better cavitation resistance [8]-[9].

Accurate Force Prediction for Optimization Loops: In optimization frameworks using CFD and genetic algorithms or adjoint methods, LES serves as a superior evaluation tool for computing gradients, cost functions, and performance objectives [8]-[9].

CONCLUSION

This project has demonstrated that Large Eddy Simulation (LES) provides a substantial advancement over conventional turbulence modeling techniques such as Reynolds-Averaged Navier–Stokes (RANS) and Unsteady RANS (URANS) in the characterization of propeller wake dynamics. LES enables the direct resolution of large-scale turbulent structures, tip vortex evolution, and pressure fluctuations that are critical for accurate thrust, power, and noise predictions. The governing equations and comparative analyses presented confirm that LES achieves closer agreement with experimental data, both in thrust coefficient and open-water efficiency, while RANS tends to underpredict the physical complexity of the wake. Visual comparisons using TKE, vorticity, and anisotropy mappings further validate LES's superiority in resolving unsteady and anisotropic turbulence features. Furthermore, LES facilitates aeroacoustics and structural vibration assessments, making it a powerful tool for integrated multidisciplinary design. The inclusion of detailed mathematical models, numerical performance tables, and figure-based diagnostics substantiates LES as the preferred modeling approach for high-fidelity propeller performance evaluation.

Looking ahead, future research should aim to reduce the computational cost of LES through adaptive meshing, hybrid wall modeling, and GPU-accelerated solvers to make the method more accessible for industrial-scale optimization. Additionally, coupling LES with machine learning-based surrogate models could enable rapid design iteration and real-time performance prediction. Incorporating fluid-structure interaction (FSI) models would also enhance the study of blade flexibility, cavitation resilience, and fatigue loading. Future projects may benefit from experimental validation using Particle Image Velocimetry (PIV) and microphone arrays to refine sub grid-scale (SGS) models and acoustic predictions. Extending LES analysis to include off-design conditions, such as oblique inflow, cavitating regimes, or transient maneuvers, would provide even greater value for practical marine and aerospace propulsion systems. With continued improvements in computational power and modeling strategies, LES is poised to become a foundational tool in the next generation of propeller and rotorcraft design.

REFERENCES

[1] NASA Glenn Research Center, "Propeller Noise and Wake Interaction Studies," *NASA Technical Reports Server (NTRS)*, NASA, 2020 [Online]. Available: https://ntrs.nasa.gov. [Accessed: Mar 2, 2025].

[2] H. K. Versteeg and W. Malalasekera, "Navier-Stokes Equations and CFD Fundamentals," An Introduction to Computational Fluid Dynamics: The Finite Volume Method, 2nd ed., Pearson Education, 2007 [Online]. Available: https://www.pearson.com/en-us/subject-catalog/p/introduction-to-computational-fluid-dynamics/P200000003580. [Accessed: May 1, 2025].

[3] A. Posa, R. Broglia, and E. Balaras, "Characterization of the wake of a submarine propeller via Large Eddy Simulation," *Comput. Fluids*, vol. 184, pp. 138–152, 2019 [Online]. Available: doi: 10.1016/j.compfluid.2019.02.026. [Accessed: May 11, 2025].

[4] A. Posa, "Anisotropy of turbulence at the core of the tip and hub vortices shed by a marine propeller," *J. Fluid Mech.*, vol. 954, A4, 2023 [Online]. Available: doi: 10.1017/jfm.2022.986. [Accessed: Mar, 15, 2025].

[5] E. Shams, F. Ham, and P. Moin, "Comparison of turbulence models for simulation of flow over a marine propeller," *J. Fluids Eng.*, vol. 133, no. 8, 081202, 2011 [Online]. Available: doi: 10.1115/1.4004295. [Accessed: Apr 1, 2025].

[6] MARIN, "Open Water Propeller Test Benchmarks," *Maritime Research Institute Netherlands*, 2020 [Online]. Available: https://www.marin.nl. [Accessed: Mar 19, 2025].

[7] J. E. Ffowcs Williams and D. L. Hawkings, "Sound generation by turbulence and surfaces in arbitrary motion," *Philos. Trans. R. Soc. Lond. A Math. Phys. Sci.*, vol. 264, no. 1151, pp. 321–342, 1969 [Online]. Available: doi: 10.1098/rsta.1969.0031. [Accessed: May 12, 2025].

[8] P. Kumar and K. Mahesh, "Large eddy simulation of propeller wake instabilities," *J. Fluid Mech.*, vol. 814, pp. 361–396, 2017 [Online]. Available: doi: 10.1017/jfm.2017.11. [Accessed: Mar 2, 2025].

[9] P. Sagaut, *Large Eddy Simulation for Incompressible Flows: An Introduction*, 3rd ed., Springer-Verlag, 2006 [Online]. Available: https://link.springer.com/book/10.1007/978-3-540-34203-2. [Accessed: May 2, 2025].

[10] H. Yao and H. Zhang, "Numerical studies of propeller exciting bearing forces under nonuniform ship's nominal wake and the influence of cross flows," *Shock and Vibration*, vol. 2017, Art. no. 4319260, 2017 [Online]. Available: doi: 10.1155/2017/4319260. [Accessed: May 4, 2025].

APPENDIX

Table 1
Numerical Comparison of Turbulence Modeling Techniques for Propeller Wake Analysis [3][6].

Parameter	LES	URANS	RANS
Wake Vortex Resolution	High-fidelity; captures unsteady, coherent vortices with spatial and temporal accuracy	Moderate; some transient behavior, but averaged over time	Poor; smoothed out due to time-averaging
Turbulence Anisotropy	Captures full anisotropy	Limited resolution of anisotropy	Assumes isotropic eddy viscosity
Prediction of Thrust C_T Error	≤ 5% compared to experiments	~10%	≥ 15%
Prediction of Torque C_P Error	≤ 6%	~12%	≥ 18%
Open-Water Efficiency η_0	High agreement (within ±5% of experiments)	±10%	±20% or more

Table 2
Coefficient Comparison of Turbulence Models for Propeller Performance Prediction [3][6].

Modeling Method	C_T	C_P	η_0
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

Table 3
Error Percentage Comparison of Turbulence Models for Propeller Performance Prediction [3][6].

Modeling Method	Thrust Error % C_T	Power Error % C_P	Efficiency Error % η_0
LES	2.9	4.8	3.1
URANS	7.4	11.0	8.9
RANS	13.2	16.7	16.6

Table 4
Comparison of Performance Gains via LES-Based Redesign [3][6].

Design Scenario	C_T	C_P	η_0
Baseline RANS Design	0.302	0.049	0.570
Experimental Reference	0.267	0.040	0.662
LES-Optimized Design	0.275	0.042	0.683