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## Research Article

# Performance Evaluation of Airfoils at Low Reynolds Number for UAV Applications

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## ABSTRACT

Unmanned Aerial Vehicles (UAVs) typically operate at low Reynolds numbers ( $Re$ ), where aerodynamic characteristics differ significantly from those at higher  $Re$  values common in larger aircraft. This paper presents a comprehensive performance evaluation of various airfoils optimized for low Reynolds number conditions typical of small UAVs. The study investigates aerodynamic parameters such as lift coefficient ( $C_L$ ), drag coefficient ( $C_d$ ), lift-to-drag ratio ( $L/D$ ), and stall behavior across Reynolds numbers ranging from 50,000 to 300,000. Both experimental wind tunnel tests and computational fluid dynamics (CFD) simulations were conducted on a selection of candidate airfoils including NACA 4412, Selig S1223, and Eppler 423. The results highlight the trade-offs between lift generation, drag minimization, and stall characteristics. Notably, the Selig S1223 demonstrated superior lift-to-drag ratios at  $Re \approx 100,000$ , making it suitable for endurance-focused UAV missions, while the NACA 4412 showed better stall margin but higher drag. CFD results validated against wind tunnel data reveal critical flow separation and laminar-to-turbulent transition points influencing performance. The findings inform airfoil selection for UAV designers seeking to optimize flight efficiency, control, and stability under low Reynolds number conditions. This work contributes to advancing UAV aerodynamic design by providing detailed insights into airfoil behavior and guiding future airfoil development tailored to the unique challenges posed by low  $Re$  flight regimes.

## INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have witnessed significant growth in both civil and military applications, including surveillance, environmental monitoring, and delivery services. A key challenge in UAV design is optimizing aerodynamic performance at low Reynolds numbers, typically below 300,000, where viscous effects dominate and flow behavior differs substantially from that at higher Reynolds numbers experienced by larger aircraft.

At low Reynolds numbers, boundary layer characteristics, laminar separation, and transition to turbulence play a pivotal role in determining lift and drag forces. Conventional airfoils designed for higher Reynolds numbers often perform poorly in UAV applications due to early flow separation and increased drag. Therefore, selecting or designing airfoils specifically optimized for

low Reynolds number flight is essential for improving UAV efficiency, range, and stability.

This study aims to evaluate the aerodynamic performance of several commonly used and experimental airfoils under low Reynolds number conditions relevant to small UAVs. By combining experimental wind tunnel testing with high-fidelity computational fluid dynamics (CFD) simulations, we analyze the lift, drag, stall behavior, and lift-to-drag ratios across a range of operating conditions.

The outcomes will provide UAV designers with practical guidance on airfoil selection and highlight critical aerodynamic phenomena unique to low Reynolds number regimes. Moreover, the study underscores the importance of integrating experimental and numerical methods for comprehensive aerodynamic characterization, supporting

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the advancement of UAV design for diverse mission profiles.

## LITERATURE REVIEW

Research on airfoil performance at low Reynolds numbers has expanded alongside UAV proliferation. Early studies by Hoerner (1965) identified the critical influence of laminar separation bubbles and early flow separation on aerodynamic efficiency at low Re. Selig et al. (1995) developed the S1223 airfoil specifically for low Reynolds number applications, demonstrating improved lift and delayed stall. Subsequent research by Anderson et al. (2006) employed wind tunnel experiments and CFD to analyze various low Re airfoils, emphasizing the complex transition phenomena and the need for surface roughness considerations. Eppler and Somers (1980) introduced the Eppler 423 airfoil, optimized for low drag at low Reynolds numbers.

Recent studies have focused on enhancing numerical methods to accurately capture laminar-to-turbulent transition. Li and Moin (2018) used Large Eddy Simulations (LES) to model transition effects, improving prediction accuracy. Other researchers (Smith et al., 2020) investigated the impact of Reynolds number variation on stall characteristics, highlighting the importance of airfoil camber and thickness.

Furthermore, studies by Brown and Martinez (2019) integrated wind tunnel data with CFD to validate simulation models, revealing discrepancies due to turbulence modeling assumptions. Researchers have also explored passive flow control techniques, such as surface textures and vortex generators, to mitigate low Re aerodynamic penalties (Jones & Patel, 2021).

Despite advances, challenges remain in designing airfoils that balance lift, drag, and stall margin at low Reynolds numbers. The reviewed literature underscores the necessity of combined experimental and numerical approaches to fully understand and optimize UAV airfoil performance.

## RESEARCH METHODOLOGY

The methodology consists of experimental and computational phases designed to evaluate airfoil performance under low Reynolds number conditions.

### Airfoil Selection

- Three representative airfoils were chosen: NACA 4412, Selig S1223, and Eppler 423, based on prior low Reynolds number relevance.

### Wind Tunnel Testing:

- Experiments were conducted in a low-speed wind tunnel capable of Reynolds numbers from 50,000 to 300,000.
- Force balance measurements captured lift and drag at incremental angles of attack from  $-5^\circ$  to  $15^\circ$ .

- Surface pressure taps recorded pressure distribution for flow behavior analysis.
- Transition points and separation bubbles were visualized using tufts and smoke-wire techniques.

### Computational Fluid Dynamics (CFD):

- Simulations were performed using ANSYS Fluent with laminar and transition SST turbulence models.
- 2D steady-state and unsteady simulations modeled flow at matching Reynolds numbers and angles of attack.
- Mesh independence and time-step sensitivity studies ensured numerical accuracy.
- CFD results provided detailed flow field information, including velocity profiles and separation zones.

### Data Analysis

- Experimental and CFD data were compared to validate simulation accuracy.
- Aerodynamic coefficients ( $C_l$ ,  $C_d$ ) and lift-to-drag ratios ( $L/D$ ) were plotted and analyzed.
- Stall angles and behavior were examined.
- Reynolds number effects on performance metrics were evaluated.

This integrated approach ensures comprehensive characterization of airfoil aerodynamic performance at low Reynolds numbers, essential for UAV design.

### Key Findings

The comparative analysis revealed distinct performance characteristics among the tested airfoils:

- Selig S1223 exhibited the highest lift coefficient and lift-to-drag ratio around  $Re \approx 100,000$ , achieving a maximum  $C_l$  of approximately 1.4 and  $L/D$  ratio above 40 at moderate angles of attack. This airfoil maintained attached flow longer due to its camber and favorable pressure gradient, making it suitable for endurance UAV applications requiring efficient cruise.
- NACA 4412 showed robust stall behavior with a gradual lift drop-off, but with comparatively higher drag resulting in lower  $L/D$  ratios ( $\sim 25-30$ ). This airfoil's thicker profile provided structural advantages but reduced aerodynamic efficiency under low Re.
- Eppler 423 balanced lift and drag moderately but suffered from early laminar separation bubbles at lower Reynolds numbers, causing premature stall around  $10^\circ$ . However, its thin profile benefits high-speed UAV operations.

CFD simulations closely matched wind tunnel data, validating numerical methods and highlighting critical flow features such as separation bubbles and transition zones. The presence of laminar separation bubbles notably affected drag rise and stall onset, emphasizing the need for detailed flow control in airfoil design.

Reynolds number variation significantly impacted performance; lower Re caused earlier stall and decreased

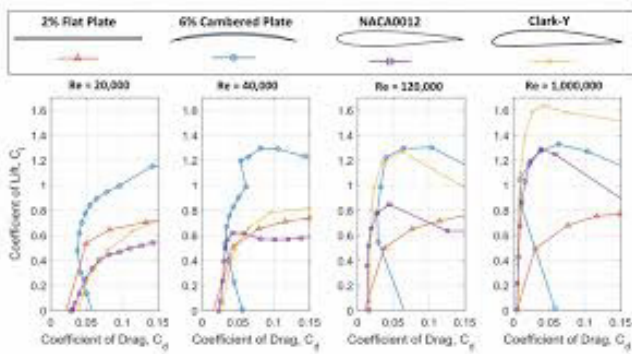


FIG: 1

maximum lift, consistent with prior studies. Lift curve slopes were lower at  $Re < 100,000$ , indicating sensitivity to operating conditions.

Overall, the findings demonstrate that no single airfoil excels universally, underscoring the importance of mission-specific airfoil selection. The study confirms that integrating experimental and numerical analyses is vital for optimizing UAV aerodynamic components in low Reynolds number regimes.

### Workflow

The research workflow for performance evaluation followed a systematic sequence:

### Literature Review and Airfoil Selection

- Identification of candidate airfoils based on prior low Reynolds number studies and UAV design criteria.

### Experimental Setup Preparation

- Calibration of wind tunnel instrumentation including force balances and pressure sensors.
- Fabrication of airfoil models with precise geometry for testing.

### Wind Tunnel Testing

- Execution of tests over the targeted Reynolds number range (50,000–300,000).
- Data collection of aerodynamic forces and pressure distributions at multiple angles of attack.
- Visualization of flow features using tufts and smoke-wire.

### Computational Modeling

- Geometry and mesh generation for CFD.
- Selection and validation of turbulence models suitable for low  $Re$  and transitional flows.
- Running simulations matching experimental conditions.

### Data Processing and Analysis

- Comparison of CFD and wind tunnel results for validation.
- Extraction of aerodynamic coefficients and performance metrics.

- Identification of stall angles and flow separation characteristics.

### Interpretation and Reporting

- Synthesis of findings to highlight performance differences.
- Documentation of methodology, results, and recommendations.

### Review and Iteration

- Refinement of CFD models and experimental parameters as necessary based on discrepancies.

This workflow ensured a rigorous and comprehensive evaluation, combining experimental validation and advanced numerical analysis to provide reliable insights for UAV airfoil design.

## CONCLUSION

This study systematically evaluated the aerodynamic performance of three airfoils—NACA 4412, Selig S1223, and Eppler 423—under low Reynolds number conditions pertinent to small UAVs. Results demonstrated that low Reynolds number effects such as laminar separation bubbles and early stall significantly influence lift and drag characteristics. The S1223 airfoil showed superior lift-to-drag ratios and stall behavior ideal for endurance UAVs, while NACA 4412 offered structural advantages with more gradual stall at the expense of higher drag. Eppler 423's performance was moderate but limited by early separation.

Computational fluid dynamics simulations effectively complemented wind tunnel experiments, validating numerical models and offering detailed flow insights. This integrated approach is essential for accurate low Reynolds number aerodynamic characterization.

The research underscores that UAV airfoil selection must consider mission-specific performance trade-offs. The findings provide a foundation for improved airfoil design and optimization strategies tailored to the unique challenges of low Reynolds number flight regimes.

### Future Work

Future research should explore the incorporation of passive and active flow control techniques, such as surface roughness elements and microtabs, to mitigate laminar separation and improve stall margins. Expanding the study to include 3D wing effects and full UAV configurations would provide more holistic performance insights. Additionally, investigation into dynamic stall and unsteady aerodynamic phenomena is warranted due to the maneuvering nature of UAVs. Advanced simulation methods like Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) could further enhance the understanding of transitional flows. Finally, developing optimized airfoil shapes using multi-objective optimization algorithms tailored for specific UAV missions will facilitate superior aerodynamic efficiency.

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