DEVELOPMENT OF NEXT-GENERATION BIO-INSPIRED MORPHING LEADING-EDGE TUBERCLES IN WINGS TO ENHANCE FUEL EFFICIENCY AND MANEUVERABILITY IN UNMANNED AERIAL VEHICLES

Project Reference No.: *49S_BE_6766*

College : Nitte Meenakshi Institute of Technology, Bengaluru
Branch : Department of Aeronautical Engineering
Guide(s) : Dr. Jini Raj R
Student(s) : Ms. Aditi Abhilasha
Ms. Chaithra K
Ms. H.R Ankitha

Keywords:

Humpback whale-inspired leading-edge tubercles, bio-inspired morphing wing, flow separation delay, stall control, drag reduction, maneuverability.

Introduction:

Aerodynamic flow control plays a vital role in enhancing the performance of unmanned aerial vehicles (UAVs), directly influencing fuel efficiency, manoeuvrability, and flight stability. UAVs typically operate under low-speed and low Reynolds number conditions, where flow separation and early stall can significantly degrade performance. Therefore, effective management of airflow over wing surfaces is essential to reduce drag and improve lift characteristics. With the rapid expansion of UAV applications in areas such as surveillance, environmental monitoring, and delivery systems, there is a growing need for advanced and adaptable aerodynamic technologies that can meet diverse operational demands while supporting sustainable aviation goals.

In recent years, bio-inspired design approaches have gained considerable attention for aerodynamic optimization. One of the most prominent examples is the humpback whale's flipper, which features leading-edge tubercles sinusoidal protrusions that generate streamwise vortices. These vortices energize the boundary layer, delay flow separation, and enhance lift while reducing drag. Although previous experimental and computational studies have demonstrated the aerodynamic advantages of tubercled wings over conventional smooth leading edges, most existing implementations are static and lack adaptability to changing flight conditions.

Addressing this limitation, the present project introduces a novel concept of morphing leading-edge tubercles capable of dynamic deployment and retraction during flight. By integrating passive flow control with active morphing mechanisms, the design enables UAV wings to continuously adapt to varying aerodynamic requirements, thereby optimizing performance. The study utilizes the NASA X-56 MUTT UAV as a reference platform and employs the NACA 64A210 airfoil for wing design. Morphing is achieved through servo-actuated alternate ribs, allowing smooth transition between conventional and tubercled configurations. This approach aims to improve boundary layer control, delay stall, and reduce drag, ultimately contributing to more efficient, versatile, and environmentally sustainable UAV systems.

Objectives:

1. Develop and validate a bio-inspired morphing leading-edge tubercled wing system inspired by humpback whale flippers.
2. Adaptive switching between smooth and tubercled configurations to improve performance.
3. Enhances fuel efficiency, maneuverability, and lift-to-drag ratio through delayed stall, counter-rotating vortices, and optimized boundary-layer control at low Reynolds numbers.

Methodology:

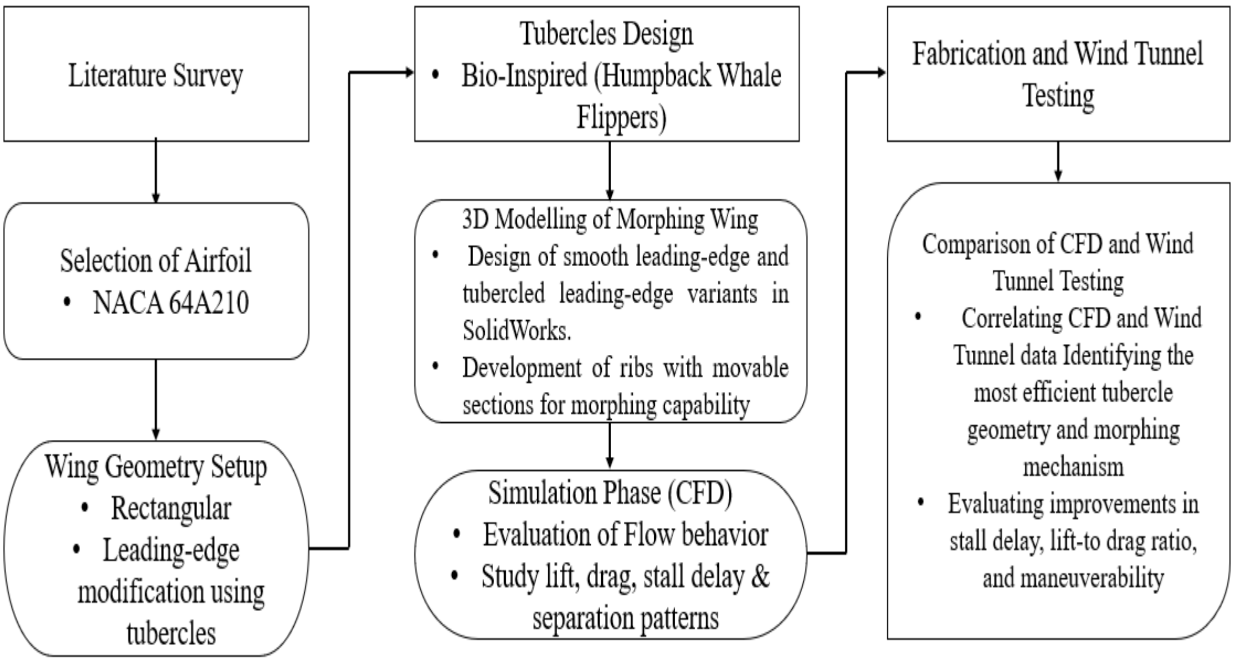

Figure 1: Block Diagram of the Morphing Leading-Edge Tubercle UAV Wing Project Workflow

Result and Conclusion:

The project successfully demonstrated the effectiveness of aerodynamic flow control using tubercled wings through detailed CFD analysis. A sufficiently large computational domain ensured that external boundary effects did not influence the flow behavior around the wing, enabling accurate prediction of aerodynamic parameters such as lift and drag. The applied boundary conditions and standard atmospheric properties provided realistic simulation conditions for UAV operation.
The use of an unstructured mesh with refined near-wall prism layers allowed precise capture of boundary layer behavior and complex flow features, particularly around curved leading

edges and separation regions. Grid independence validation confirmed the reliability of the numerical results.

For the conventional rectangular wing, flow remained fully attached at low angles of attack (0°- 6°), producing minimal lift at 0° and moderate lift at 6°. As the angle of attack increased further, strong adverse pressure gradients led to flow separation. At around 12°-16°, a large recirculation zone formed over the upper surface, causing a sharp drop in lift and a significant increase in drag, indicating stall.

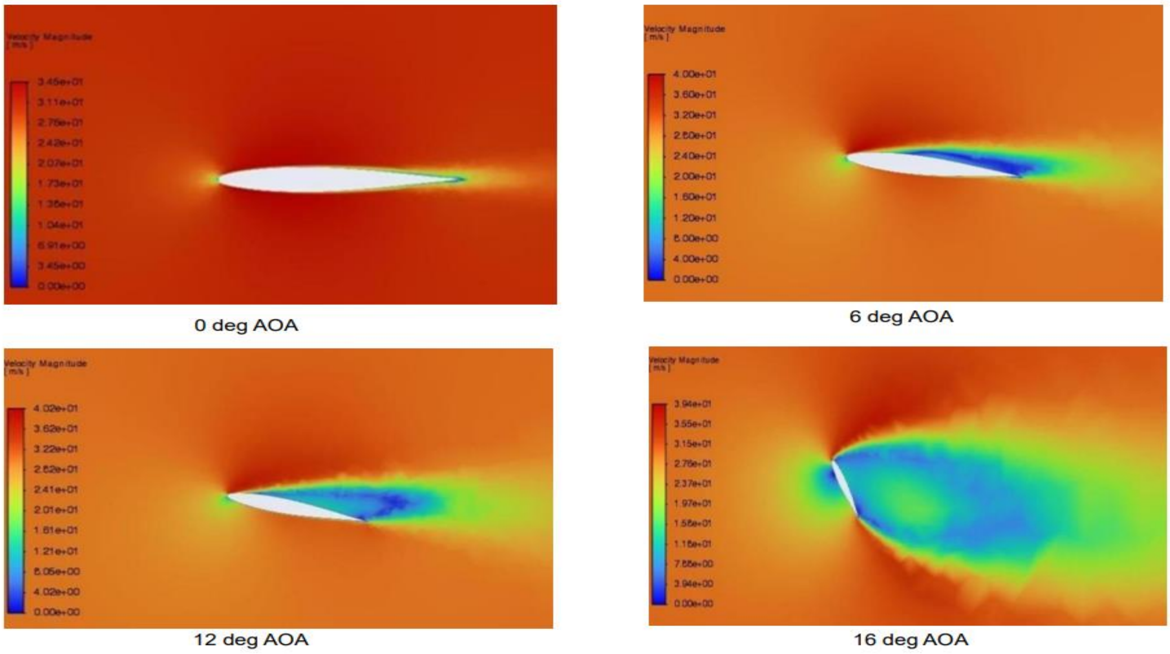

Figure 1: Rectangular Wing Contours

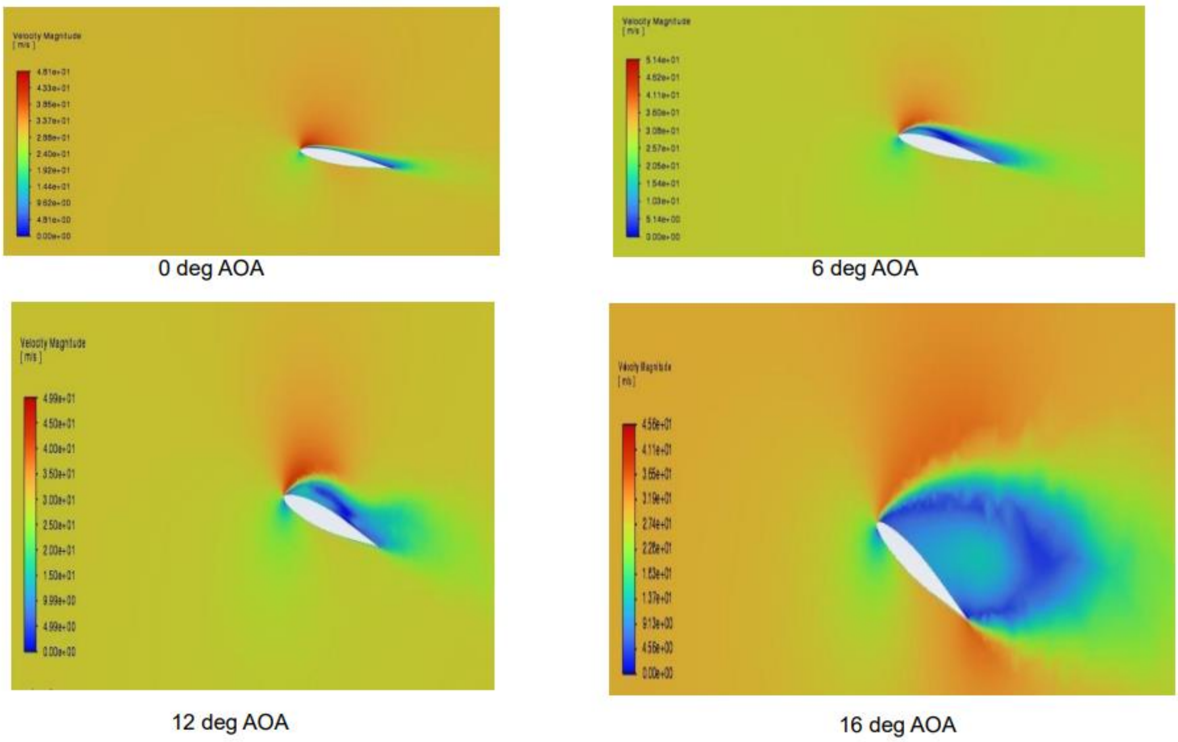

Figure 2: Tubercle Wing Contours

In contrast, the tubercled wing exhibited improved aerodynamic behavior across all angles of attack. The presence of leading-edge tubercles generated streamwise vortices that energized the boundary layer, helping to maintain attached flow even at higher angles. This resulted in higher lift coefficients and delayed stall compared to the rectangular wing.
Additionally, the tubercled wing showed a smoother and more gradual stall behavior, enhancing stability and controllability during high-angle flight conditions. The maximum lift coefficient was also higher, indicating better lift generation capability.

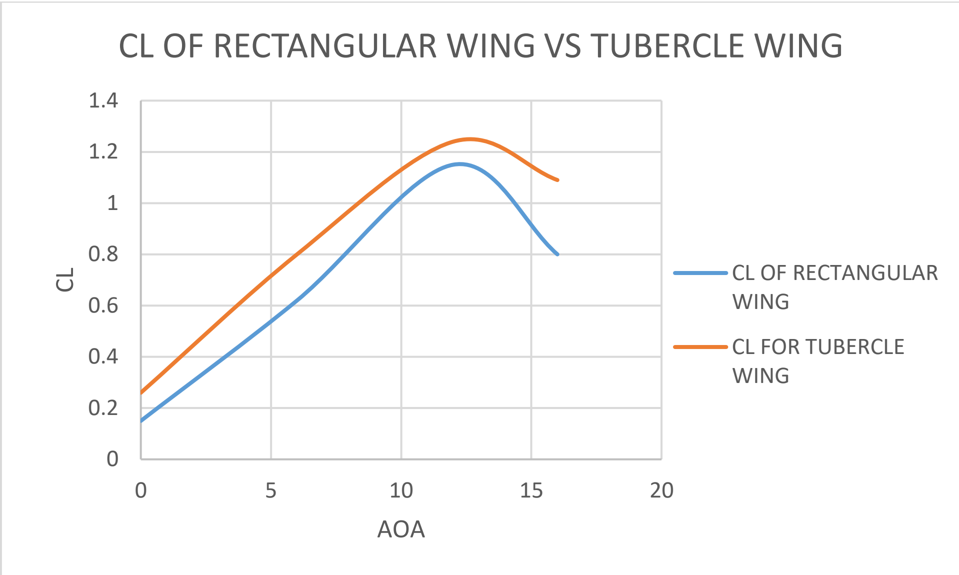

Figure 3: CL VS AOA

Figure 4: Cruise Mode

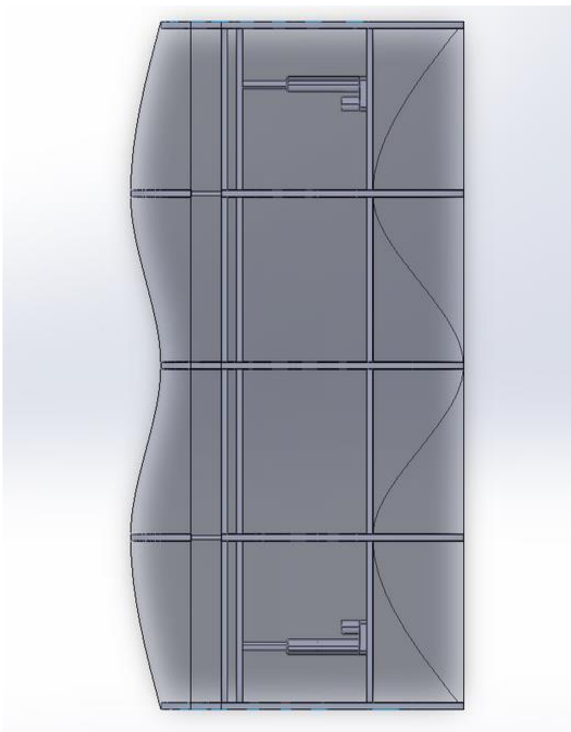

Figure 5: Maneuver Mode

References:

1. G. V. T. Gopinathan, "Numerical and Experimental Aerodynamic Investigation of Airplane Wings with Leading Edge Tubercles," Ph.D. dissertation, Dept. Aero. Eng., Anna Univ., Chennai, India, 2021.
2. W. Ke et al., "Influence of leading-edge tubercles on the aerodynamic performance of a horizontal-axis wind turbine: A numerical study," Energy, vol. 239, pt. B, Jan. 2022, Art. no. 122186.
3. Effect of leading edge tubercles on the aerodynamic performance of symmetrical airfoils at higher angles of attack, Phys. Fluids, vol. 37, no. 5, May 2025, Art. no. 055103.
4. F. E. Fish and G. V. Lauder, "The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology," *Integr. Comp. Biol.*, vol. 51, no. 1, pp. 203-214, Jul. 2011.
5. S. M. A. Aftab *et al.*, "CFD study on NACA 4415 airfoil implementing spherical and sinusoidal leading-edge tubercles," *PLoS ONE*, vol. 12, no. 8, Aug. 2017, Art. no. e0183456.
6. V. T. Gopinathan and J. B. R. Rose, "Aerodynamic performance characterization of bio-inspired wings with leading edge tubercles at low Reynolds number," *Proc. Inst. Mech. Eng. G J. Aerosp. Eng.*, vol. 237, no. 12, pp. 2775-2791, Sep. 2023.

Future Scope:

The future scope of this project includes:

1. Adaptive Morphing Tubercles for Real-Time Flight Conditions
2. Improved Fuel Efficiency and Aerodynamic Performance
3. Integration with Smart Materials and Actuators
4. Advanced Flow Control and Stall Management
5. Application in Micro-UAVs and Low Reynolds Number Flight
6. Noise Reduction and Environmental Benefits
7. AI-Based Aerodynamic Optimization
8. Integration with Variable-Geometry or Morphing Wings