

Computational Flow-Field Analysis of a Bio-Inspired Corrugated Wing at Low Reynolds Numbers

Nagabhyru Naga Phaneendra^{1*}, Aayuman Amit Kumar¹, Umama Mahroz¹

¹Department of Aeronautical Engineering, Institute of Aeronautical Engineering, Hyderabad, India

Abstract: This paper presents a computational investigation of the aerodynamic performance of a bio-inspired corrugated airfoil at low Reynolds numbers and its comparison with a conventional flat plate. The corrugated geometry, inspired by dragonfly wings, enhances flow control through vortex formation and boundary layer stabilization. Numerical simulations were carried out using ANSYS Fluent at angles of attack of 4° and 8°. The results indicate that the corrugated airfoil generates strong leading-edge vortices, which delay flow separation and improve lift characteristics. A significant improvement in lift coefficient and lift-to-drag ratio is observed compared to the flat plate. The study demonstrates that corrugated airfoils are highly effective for low-speed aerodynamic applications such as UAVs and MAVs.

Keywords: Bio-inspired airfoil, Corrugated wing, Low Reynolds number, CFD analysis, Flow separation control, UAV aerodynamics.

1. Introduction

Low Reynolds number aerodynamics is an important area of study, especially for applications such as micro air vehicles (MAVs), unmanned aerial vehicles (UAVs), and other low-speed flight systems. In such conditions, conventional smooth airfoils often do not perform efficiently. They tend to experience early flow separation, which results in reduced lift and increased drag [1]. This directly affects the stability and overall performance of the aircraft.

In nature, however, flying insects such as dragonflies demonstrate efficient flight even at low Reynolds numbers. One of the key features of dragonfly wings is their corrugated structure, which consists of a series of peaks and valleys along the wing surface and enhances aerodynamic performance [1], which consists of a series of peaks and valleys along the wing surface. These corrugations are known to influence the airflow in a beneficial way by generating small vortices that help maintain attached flow over the wing surface.

Inspired by this natural mechanism, researchers have explored bio-inspired corrugated airfoils as an alternative to conventional designs. The presence of corrugations helps in energizing the boundary layer and delaying flow separation. As a result, these airfoils can produce higher lift and improved aerodynamic efficiency compared to smooth airfoils,

particularly at low speeds.

In this study, a computational flow-field analysis of a bio-inspired corrugated airfoil is carried out and compared with a flat plate model under similar conditions. The objective is to examine how the corrugated geometry affects flow behaviour, including vortex formation, pressure distribution, and boundary layer characteristics. The analysis is performed using ANSYS Fluent at different angles of attack to evaluate the aerodynamic performance of both configurations.

2. Literature Review

Several studies have investigated the aerodynamic performance of bio-inspired corrugated airfoils, particularly under low Reynolds number conditions. Kesel (2000) reported that dragonfly wing sections exhibit superior lift characteristics and delayed flow separation when compared to conventional smooth airfoils [1]. This improvement is mainly attributed to the presence of corrugations, which help in maintaining attached flow over the wing surface.

Further studies by Dwivedi (2020) demonstrated that the geometry of corrugations plays a significant role in determining aerodynamic performance [2]. Variations in peak shapes and spacing were found to influence vortex formation and boundary layer stability. Similarly, Khan et al. (2020) analysed the effect of corrugation angles and observed improvements in lift-to-drag ratio for optimized configurations [3].

Abdizadeh et al. (2021) investigated corrugated airfoils in ground effect conditions and concluded that such designs enhance aerodynamic efficiency and delay flow separation [4]. In addition, studies related to dragonfly flight mechanics have highlighted the importance of wing structure in achieving stable and efficient flight at low speeds [5]–[7].

More recent research has also confirmed that corrugated airfoils improve stall resistance and aerodynamic stability in low Reynolds number regimes [8]. Review studies further emphasize that bio-inspired airfoil designs provide significant advantages over conventional airfoils for small-scale aerial applications [9].

Overall, the existing literature confirms that corrugated airfoils offer improved aerodynamic performance due to

*Corresponding author: nagaphaneendra2004@gmail.com

enhanced vortex dynamics and delayed flow separation, making them suitable for UAV and MAV applications.

3. Methodology

A. Geometry Creation

The corrugated airfoil geometry was designed using CATIA, incorporating multiple peaks and valleys inspired by dragonfly wing structures. A flat plate airfoil with the same chord length was also created to ensure a fair comparison under identical conditions.

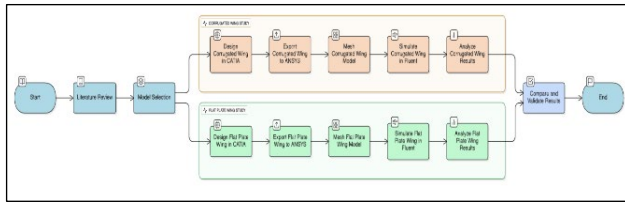


Fig. 1. Methodology flowchart for computational analysis of corrugated and flat plate airfoils

B. Governing Equations

The flow is assumed to be steady, incompressible, and Newtonian. The governing equations used in the simulation are the continuity and momentum equations.

Continuity equation:

$$\nabla \cdot \vec{V} = 0$$

Momentum equation:

$$\rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla p + \mu \nabla^2 \vec{V}$$

C. Reynolds Number

The flow regime is characterized using Reynolds number:

$$Re = \frac{\rho V c}{\mu}$$

D. Turbulence Model

The $k-\omega$ SST turbulence model was used due to its ability to accurately predict flow separation in low Reynolds number conditions [2]. This model combines the advantages of both $k-\epsilon$ and $k-\omega$ models, making it suitable for aerodynamic simulations involving boundary layer effects.

E. Boundary Conditions

The following boundary conditions were applied:

- Inlet: Uniform velocity inlet
- Outlet: Pressure outlet
- Airfoil surface: No-slip wall condition

F. Mesh Generation

A fine mesh was generated with higher refinement near the airfoil surface to accurately capture boundary layer effects. Inflation layers were applied near the wall region, and mesh

quality parameters such as skewness were maintained within acceptable limits.

G. Numerical Setup

The simulations were performed using a pressure-based solver. The SIMPLE algorithm was used for pressure–velocity coupling, and second-order discretization schemes were applied to improve accuracy. Convergence was achieved when residuals dropped below 10^{-5} .

H. Aerodynamic Coefficients

The aerodynamic performance was evaluated using lift and drag coefficients:

$$C_L = \frac{L}{\frac{1}{2} \rho V^2 A}$$

$$C_D = \frac{D}{\frac{1}{2} \rho V^2 A}$$

I. Mesh Independence Study

A mesh independence study was conducted using coarse, medium, and fine meshes. The variation in lift coefficient between medium and fine mesh was found to be less than 2%, indicating that the results are independent of mesh size.

J. Near-Wall Treatment

The y^+ values were maintained below 1 to ensure accurate resolution of the boundary layer and viscous sublayer effects.

K. Computational Domain

The computational domain was extended sufficiently to avoid boundary effects. The upstream distance was set to 5 times the chord length, while the downstream distance was set to 10 times the chord length.

4. Geometry Description

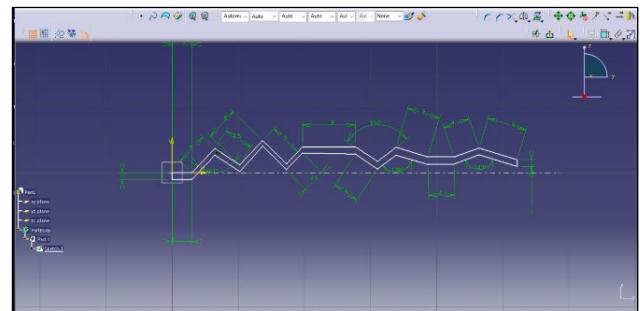


Fig. 2. Corrugated airfoil dimensions



Fig. 3. Flat plate dimensions

The corrugated airfoil used in this study was designed to replicate the structural features of dragonfly wings, consisting of a series of peaks and valleys along the chord. These corrugations are intended to influence the airflow by generating localized vortices that enhance boundary layer stability.

A flat plate airfoil with the same chord length was also modelled to serve as a reference case for comparison. Both geometries were analysed under identical flow conditions to evaluate the impact of corrugation on aerodynamic performance.

The geometric parameters were selected such that they represent typical low Reynolds number applications, ensuring relevance to small-scale UAV and MAV designs.

5. Results and Discussion

A. Velocity Analysis

The velocity vector plots illustrate the flow behaviour around both the corrugated airfoil and the flat plate.

At an angle of attack of 4° , the corrugated airfoil shows the formation of localized vortices within the corrugation valleys. These vortices help in maintaining attached flow by energizing the boundary layer. In contrast, the flat plate exhibits relatively uniform flow with initial signs of separation near the trailing edge.

The velocity distribution for both configurations is shown in Fig. 4 and Fig. 5.

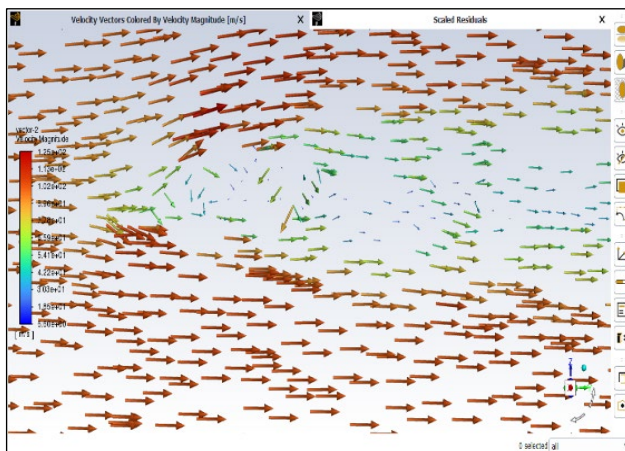


Fig. 4. Airfoil velocity vector at 4 degree of AoA

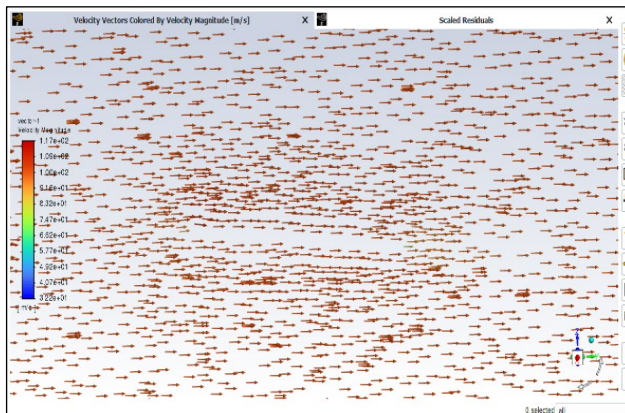


Fig. 5. Flat plate velocity vector at 4 degree of AoA

At 8° angle of attack, the corrugated airfoil continues to maintain attached flow due to stronger vortex formation, whereas the flat plate shows significant flow separation, indicating the onset of stall. This indicates that the corrugated airfoil maintains stronger flow attachment compared to the flat plate, particularly at higher angles of attack, due to sustained vortex activity.

The velocity behaviour at higher angle of attack is shown in Fig. 6 and Fig. 7.

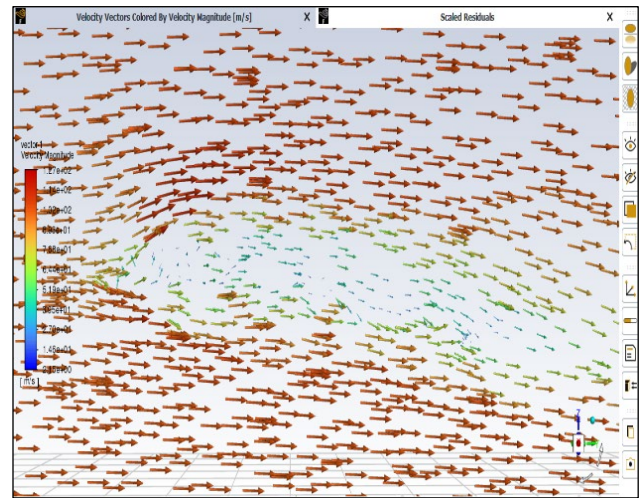


Fig. 6. Airfoil velocity vector at 8 degree of AoA

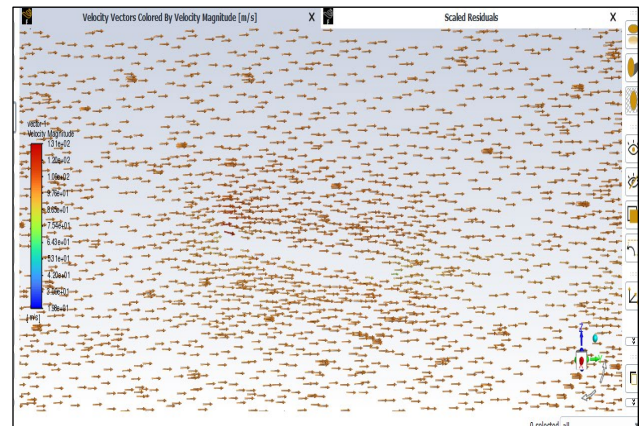


Fig. 7. Flat plate velocity vector at 8 degree of AoA

B. Pressure Distribution

The pressure contour plots reveal distinct aerodynamic characteristics for both models.

The corrugated airfoil exhibits multiple low-pressure regions along the corrugation valleys, which contribute to enhanced lift generation.

The pressure contours at 4° are shown in Fig. 8 and Fig. 9.

The flat plate, on the other hand, shows a smoother pressure distribution with weaker suction effects, resulting in lower lift. The stronger pressure gradients observed in the corrugated airfoil contribute significantly to enhanced lift generation and improved aerodynamic performance. The pressure distribution at 8° is shown in Fig. 10 and Fig. 11.

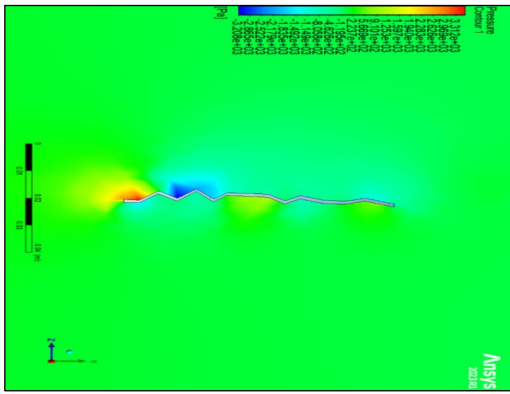


Fig. 8. Airfoil pressure contours at 4 degree of AoA

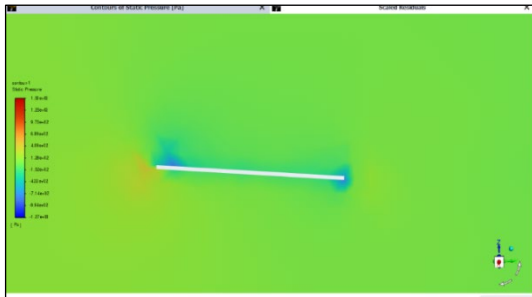


Fig. 9. Flat plate pressure contours at 4 degree of AoA

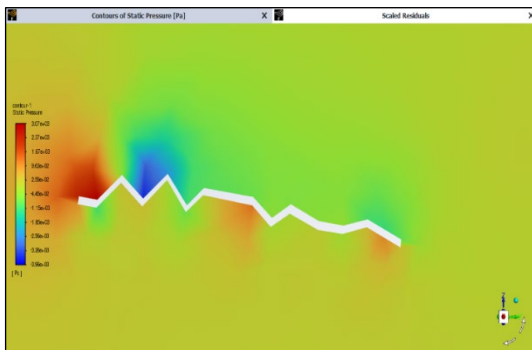


Fig. 10. Airfoil pressure contour at 8 degree of AoA

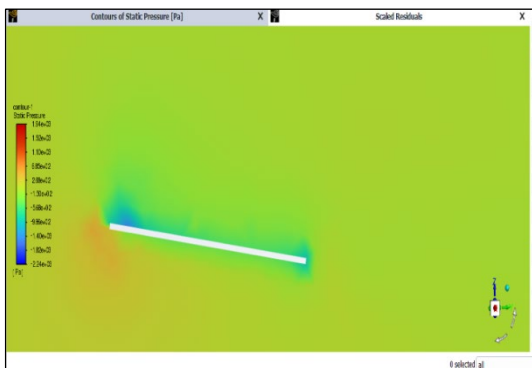


Fig. 11. Flat plate pressure contour at 8 degree of AoA

C. Residual Convergence

The residual plots indicate stable convergence for both models. The residual convergence plots are shown in Fig. 12 and Fig. 13.

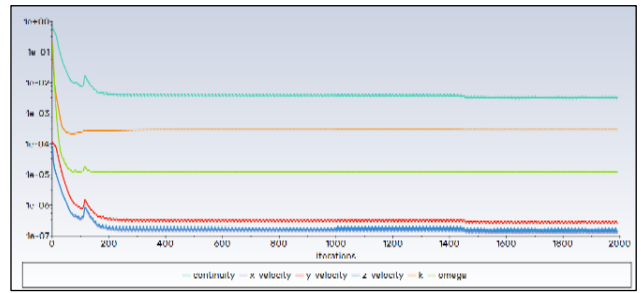


Fig. 12. Airfoil residual graph at 4 degree of AoA

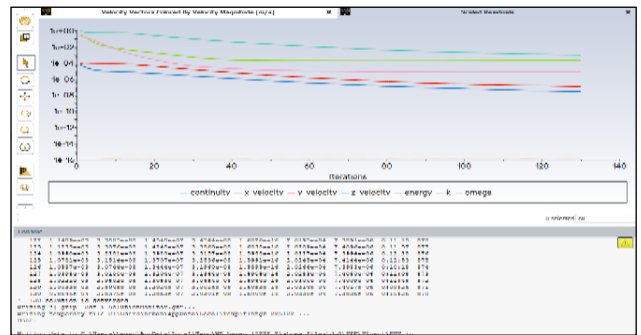


Fig. 13. Flat plate residual graph at 4 degree of AoA

However, the corrugated airfoil shows smoother convergence behaviour, suggesting more stable flow characteristics compared to the flat plate. This suggests that the corrugated airfoil exhibits more stable numerical behaviour due to organized flow structures and reduced flow separation.

The convergence behaviour at higher angle of attack is shown in Fig. 14 and Fig. 15.

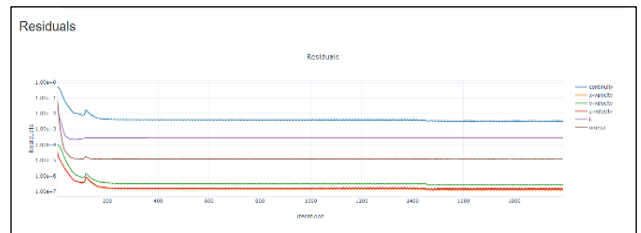


Fig. 14. Airfoil residual graph at 8 degree of AoA



Fig. 15. Flat plate residual graph at 8 Degree of AoA

D. Lift Coefficient (CL) vs Angle of Attack

Table 1
Lift coefficient comparison

AoA	Corrugated C_L	Flat Plate C_L
4°	0.62	0.48
8°	0.98	0.72

The corrugated airfoil exhibits higher lift coefficients at both angles of attack. This indicates improved aerodynamic performance due to vortex-induced boundary layer

stabilization. The corrugated airfoil shows approximately 25–30% higher lift compared to the flat plate.

The variation of lift coefficient of Corrugated airfoil (blue) and flat plate (orange) with angle of attack (in degrees) is illustrated in Fig. 16 below.

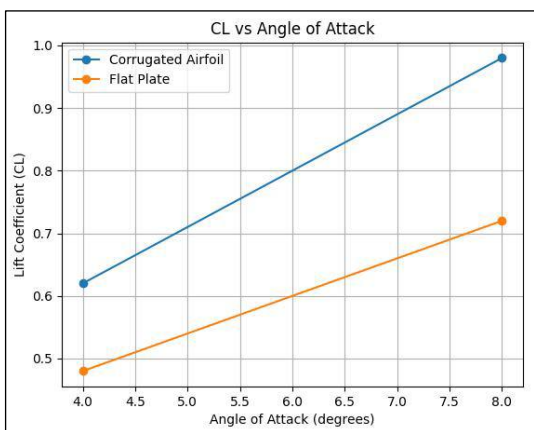


Fig. 16. Variation of lift coefficient with angle of attack

E. Streamline Analysis

The streamline plots show that the corrugated airfoil traps vortices within its valleys, which delays flow separation. In contrast, the flat plate exhibits early flow detachment, leading to reduced aerodynamic efficiency. This behaviour confirms that the corrugated geometry effectively traps vortices, which act to delay flow separation and maintain aerodynamic performance.

F. Pressure Coefficient (C_p)

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho V^2}$$

The corrugated airfoil shows strong suction regions (low C_p) along its surface, which contributes to higher lift. The flat plate exhibits weaker suction effects.

G. Lift-to-Drag Ratio

The corrugated airfoil demonstrates a higher lift-to-drag ratio compared to the flat plate, indicating better aerodynamic efficiency in low Reynolds number conditions.

H. Key Observation

The results clearly indicate that the corrugations act as passive flow control mechanisms by generating stable and localized vortices within the valleys of the airfoil surface. These vortices play a crucial role in energizing the boundary layer by continuously mixing high-momentum fluid from the outer flow with the near-wall region. As a result, the boundary layer gains additional energy, which helps it resist adverse pressure gradients more effectively. This behaviour is consistent with findings reported in previous studies on corrugated airfoils [2], [3].

This mechanism significantly delays flow separation, which is one of the major limitations in low Reynolds number

aerodynamics. In conventional flat plate airfoils, the boundary layer loses energy quickly, leading to early separation and reduced lift. However, in the corrugated airfoil, the trapped vortices act as energy reservoirs that sustain flow attachment over a larger portion of the surface.

Furthermore, the presence of multiple corrugation peaks creates several localized low-pressure regions, enhancing suction and contributing to higher lift generation. This distributed pressure effect improves the overall aerodynamic efficiency of the airfoil.

Another important observation is that the corrugated geometry reduces the sensitivity of the flow to changes in angle of attack. Even at higher angles, the airfoil maintains relatively stable flow characteristics, thereby delaying stall and ensuring better performance compared to the flat plate.

Overall, the corrugated airfoil demonstrates superior aerodynamic behaviour due to its ability to control flow separation through vortex-induced boundary layer stabilization, making it highly effective for low-speed and low Reynolds number applications.

6. Conclusion

The present study investigates the aerodynamic performance of a bio-inspired corrugated airfoil under low Reynolds number conditions using computational analysis. The results clearly demonstrate that the corrugated geometry significantly enhances aerodynamic behaviour when compared to a conventional flat plate.

The formation of stable vortices within the corrugation valleys plays a key role in energizing the boundary layer and delaying flow separation. This leads to improved lift generation, higher lift-to-drag ratio, and better overall aerodynamic efficiency. The corrugated airfoil maintains attached flow even at higher angles of attack, indicating delayed stall characteristics and improved flow stability.

The comparative analysis confirms that the corrugated airfoil consistently outperforms the flat plate at both 4° and 8° angles of attack. The presence of multiple low-pressure regions further contributes to enhanced suction and lift production.

The findings of this study highlight the potential of bio-inspired corrugated airfoils as an effective solution for improving aerodynamic performance in low-speed UAV and MAV applications.

A. Limitations and Future Work

Although the present study provides valuable insights, it is limited to steady-state simulations and does not capture unsteady aerodynamic phenomena such as vortex shedding and dynamic stall. Future work can focus on transient simulations, experimental validation, and optimization of corrugation geometry to further enhance aerodynamic performance.

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