Aerodynamic analysis of Dragonfly wings

BTP - 1 Report

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Contents

1 Abstract

This study investigates the aerodynamic optimization of dragonfly wings, focusing on their distinctive corrugated structure, which contrasts with the smooth profiles of conventional airfoils. Although prior research has compared the aerodynamic performance of corrugated profiles with smooth airfoils and flat plates, the aim was to determine whether the dragonfly wing geometry itself is evolutionarily optimized for aerodynamic efficiency. We began by analyzing the aerodynamic behavior of crane wing cross-sections using potential flow theory and thin airfoil theory implemented in MATLAB. These results were compared with CFD simulations to assess their accuracy. Deviations between theoretical and CFD results across various angles of attack (AoA) highlighted the need to define a suitable range of AoAs for accurate modeling. Five cross-sectional profiles along the span of the dragonfly Anax parthenope julius were obtained from Okamoto (1995) and 2D flow simulation was done over these sections, recording lift coefficient (Cl), drag coefficient (Cd), and Cl/Cd ratios across AoAs ranging from -10° to 50°. The AoA yielding maximum Cl/Cd for each section was identified. The study aimed to assess whether positioning each wing section at its respective optimal angle of attack would reconstruct the actual dragonfly wing geometry during gliding.

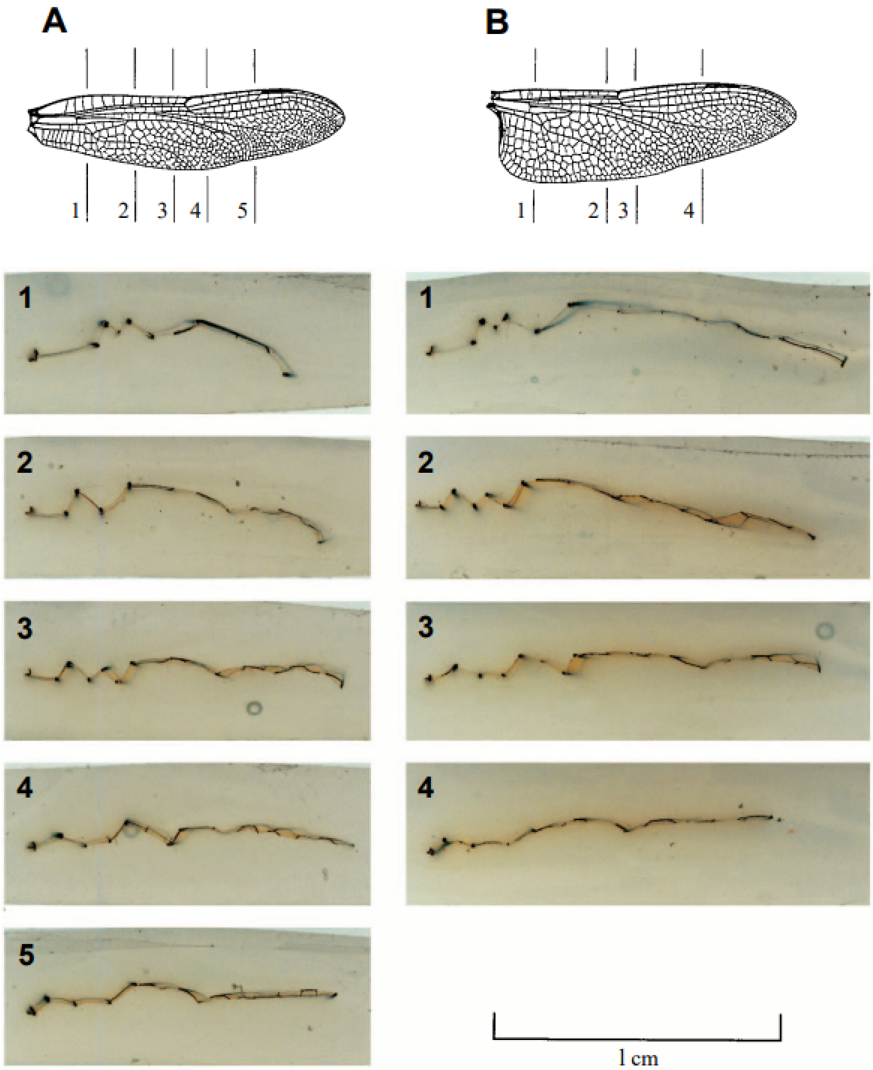

Figure 1: Corrugated wing structure of forewing and hindwing in dragonfly *Anax parthenope julius*

2 Introduction

Biomimetics holds immense promise for solving complex engineering challenges by mimicking nature's time-tested designs. In aerodynamics, the exceptional flight capabilities of insects, especially in terms of maneuverability and energy efficiency, have drawn significant attention. This is particularly relevant in the development of micro air vehicles (MAVs), where energy constraints pose a serious challenge. Dragonflies, ancient insects dating back 300 million years, exhibit both flapping and gliding flight. Notably, gliding allows them to conserve energy, consuming roughly 10–20 W/kg compared to 80–120 W/kg during flapping. For comparison, humans use around 5–7 W/kg during moderate activity. Mimicking this energy-saving gliding behavior has the potential to significantly enhance MAV endurance.

Unlike traditional aircraft wings, dragonfly wings are not smooth but corrugated. This unique morphology raises a compelling question: Is this corrugated structure evolutionarily optimized for aerodynamic efficiency, especially during gliding? Some species like Pantala flavescens can glide for 10–15 seconds at 15 m/s, while others like Aeschna can glide up to 30 seconds without significant altitude loss. These performance metrics, along with the ultra-low Reynolds number regime (100 to 10,000), make dragonflies an ideal subject for studying optimized natural flight.

The motivation for this study lies in the hypothesis that the geometry of dragonfly wings—specifically their twist and corrugation—is finely tuned for aerodynamic performance. The aim is to reverse engineer this optimization and translate it into design principles for engineered systems. Ultimately, this could facilitate the development of morphing wings that adjust their twist or corrugation based on flight requirements.

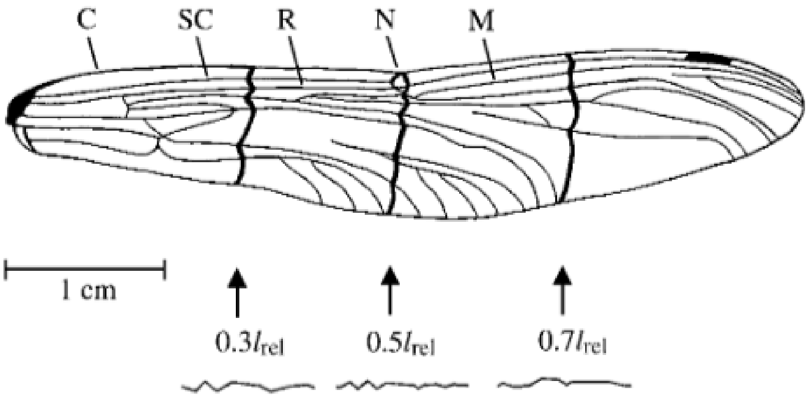

Figure 2: Corrugated wing structure of forewing in dragonfly *Aeshna cyanea*

3 Objectives

- To investigate whether dragonfly wing geometry is aerodynamically optimized for gliding
- To analyze 2D aerodynamic performance (Cl, Cd, Cl/Cd) of spanwise wing sections.
- To determine the AoA with maximum aerodynamic efficiency for each section.
- To infer the wing twist required to align each section with its optimal AoA.
- To explore the possibility of wing morphing by controlling the corrugation pattern or MAV design inspired by dragonfly wing structure

4 Literature Review

Previous studies have analyzed the 2D aerodynamic performance of corrugated airfoils. Some found corrugated profiles slightly outperform smooth ones, while others observed comparable performance. However, most studies focus only on 2D performance, overlooking crucial 3D effects. Only a few papers have explored 3D effects on hindwings, with scarce data on forewings. Experimental studies like those by Kesel (2000) and Okamoto et al. (1996) offer valuable insights.

Corrugation alters pressure distribution and can delay flow separation, making it beneficial in low Reynolds number regimes. Wing twist, on the other hand, allows each section to operate near its optimal AoA, enhancing lift-to-drag ratio across the span.

Computational Fluid Dynamics (CFD) plays a vital role in studying these complex flow phenomena. While potential flow theory offers quick approximations, CFD allows for detailed simulations of real-world conditions, especially where flow separation and turbulence are significant.

5 Methodology

5.1 Geometry Setup

Anax parthenope julius, a dragonfly subspecies was selected due to the availability of wing geometry data at five spanwise locations. Okamoto's corrugation profile was adopted instead of Kesel's (aeshna cyanea) because there is a clear match in geometry of both dragonflies and second, Okamoto's team also conducted 3D gliding experiments on actual wings, so we have some experimental data to compare with at the end of our simulations.

The images given below show how closely profiles at similar spanwise location resemble with each other. The l_{rel} written below means relative span length, to specify the spanwise loaction of that profile.

Figure 3: Profile 1 at $0.3l_{rel}$

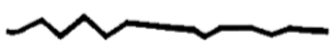

Figure 4: Profile 1 at $0.5l_{rel}$

Figure 5: Profile 1 at $0.7l_{rel}$

Figure 6: Profiles of *Aeshna Cynanea*

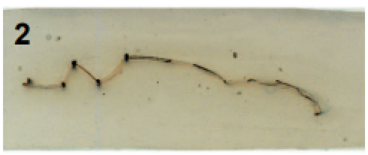

Figure 7: Profile 1 at $0.3l_{rel}$

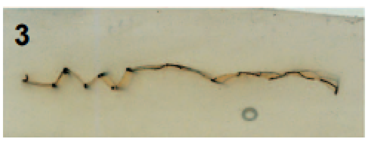

Figure 8: Profile 1 at $0.5l_{rel}$

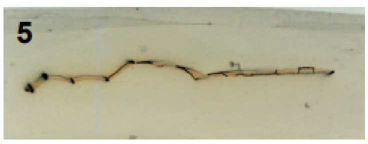

Figure 9: Profile 1 at $0.75l_{rel}$

Figure 10: Profiles of *Anax parthenope julius*

Using SolidWorks, the region between the two sections was interpolated to construct a 3D wing model using the `Boundary Surface` feature. Two configurations were designed:

1. **No twist:** All profiles set at 0° angle of attack (AoA).
2. **Twisted:** A linear twist of -15°, keeping the root profile fixed and rotating the tip.

Due to software constraints, the wing thickness was scaled up to 0.05 mm, approximately ten times thicker than the natural wing.

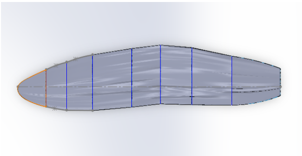

Figure 11: Top view

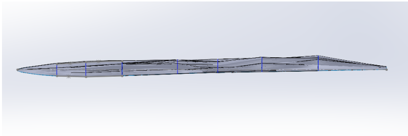

Figure 12: Front view

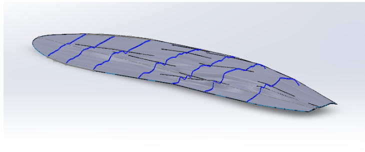

Figure 13: Isometric view

Figure 14: CAD of wing with $-15°$ twist

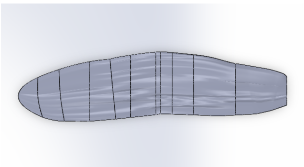

Figure 15: Top view

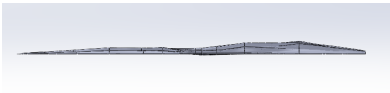

Figure 16: Front view

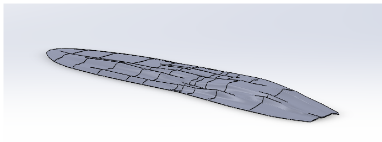

Figure 17: Isometric view

Figure 18: CAD of wing with 0° twist

The reason we are testing -15^o twist is due to results in Kesel (2000). In that study, the three profiles in the fig 3,4 and 5, of *Aeshna Cyanea* were simulated, results of which are shown below:

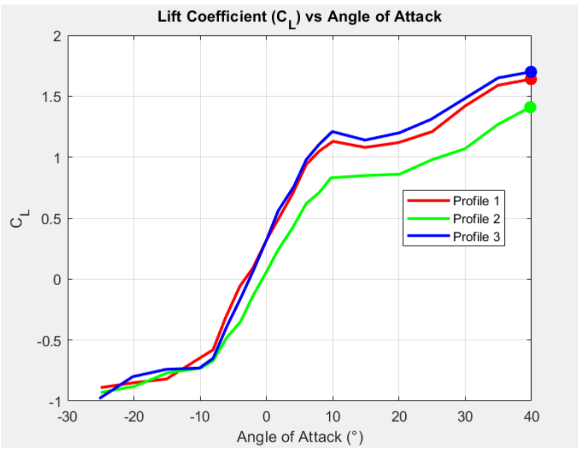

Figure 19: C_l vs α

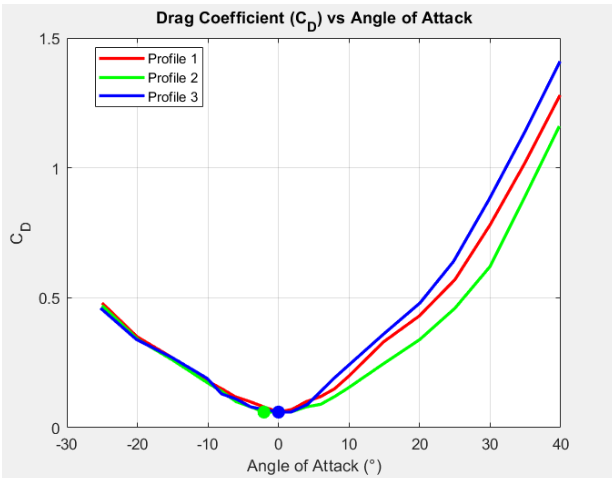

Figure 20: C_d vs α

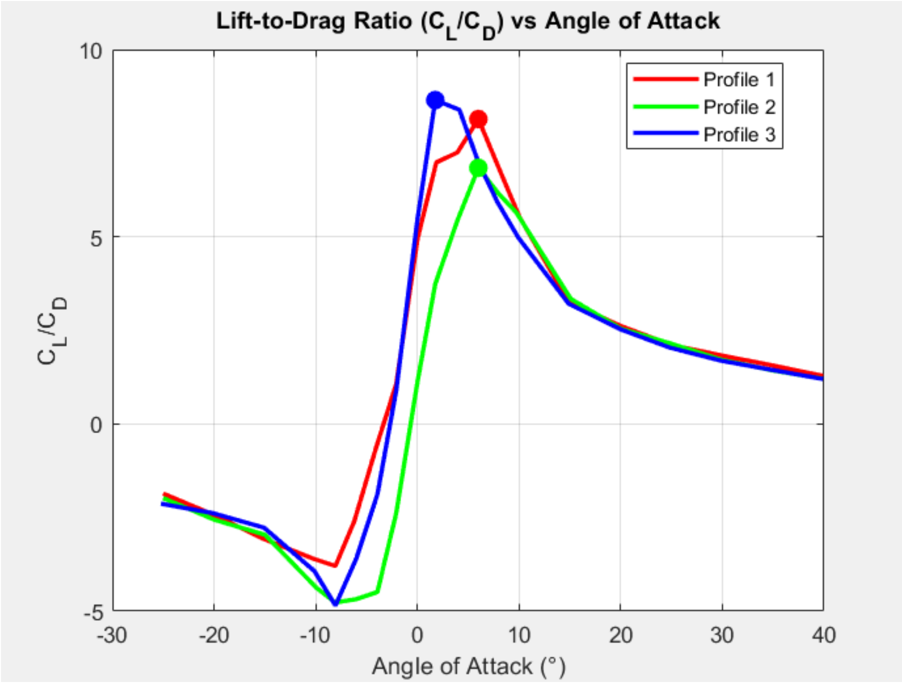

Figure 21: C_l/C_d vs α vs α

Table 1: AoA corresponding to maximum C_l/C_d for each profile of *Aeshna Cyanea*

Profile	**AoA for max C_l (degrees)**
1	6.00
2	6.00
3	1.76

The table indicates that negative twist might give a good aerodynamic performance. So to verify this, the 3D wing was made with -15^o twist. The results in the report ahead don't indicate the same thing, and it can be seen that there is need to check a wing with 15^o twist too.

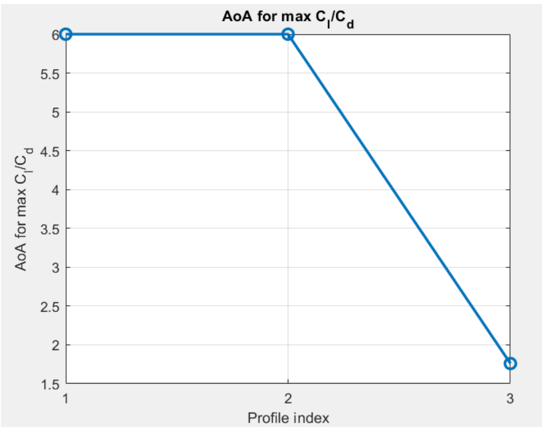

Figure 22: Profile wise AoA for max C_l/C_d

5.2 CFD Simulation Setup

Software: ANSYS Fluent

Boundary Conditions:

- Inlet: Curved surface
- Outlet: Opposite flat face
- Symmetry: All other faces

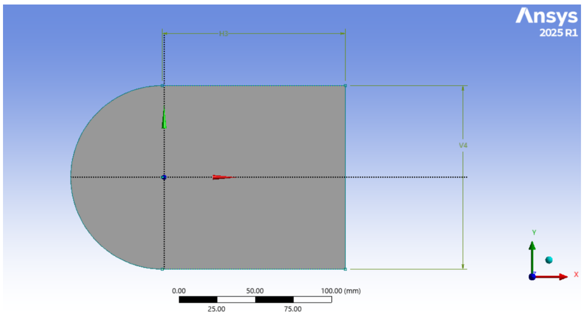

Figure 23: Front view of fluid domain showing H3 and V4

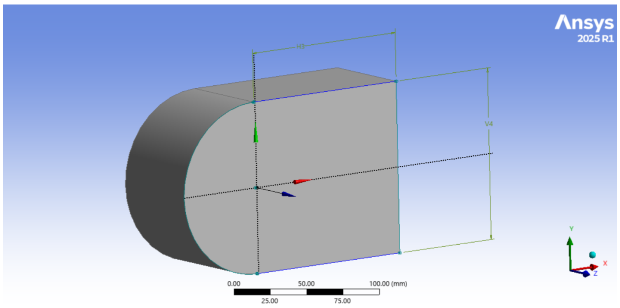

Figure 24: Isometric view of fluid domain

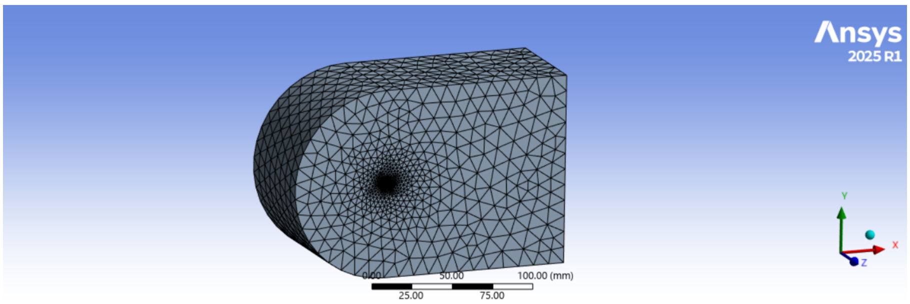

Figure 25: Mesh

5.2.1 3D Wing Simulation

- **Turbulence Model:** Spalart-Allmaras
- **Mesh:**
  - Elements: 859,756
  - Nodes: 157,327
- **Fluid Domain:**
  - Horizontal length (H3): 120 mm
  - Vertical height (V4): 120 mm
  - Extrusion depth: 70 mm

Due to hardware limitations, mesh convergence tests could not be performed.

5.2.2 2D Cross-Section Simulations

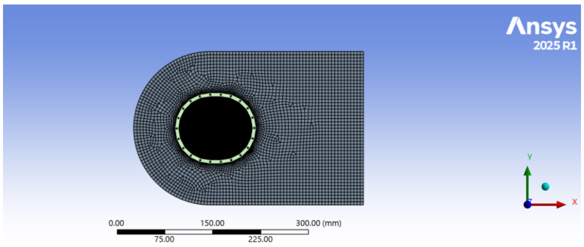

Figure 26: Front view of meshed fluid domain

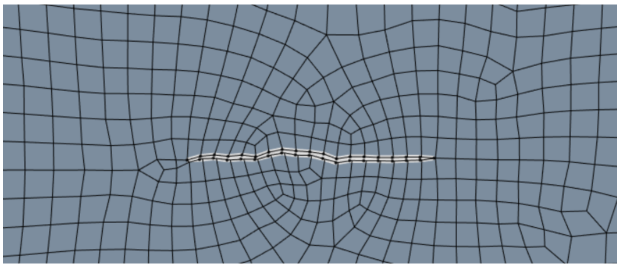

Figure 27: Close up view of profile 5 of *Anax parthenope julius*

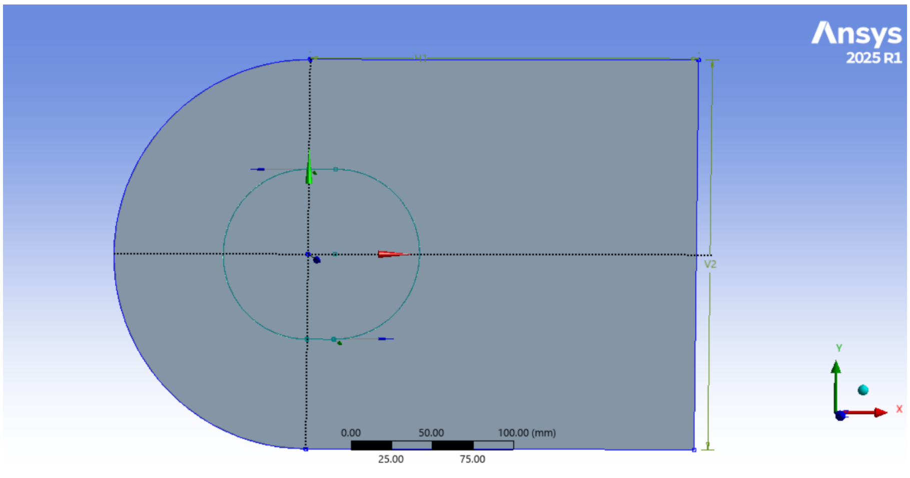

Figure 28: Fluid domain showing H1 and V2 dimensions

- **Turbulence Model:** k-ω
- **Mesh (Section 5):**
  - Elements: 50,099
  - Nodes: 50,189
- **Fluid Domain:**
  - Vertical Height(V2): 240 mm
  - Horizontal Width(H1): 240 mm

Each of the five cross-sections was simulated under angles of attack ranging from -10° to 50°. For each AoA, lift and drag coefficients were recorded. The lift-to-drag ratio (C_l/C_d) was used as the primary performance metric to identify the optimal AoA for each section.

6 Results and Inferences

6.1 Plots

6.1.1 2-D simulations at different spanwise locations

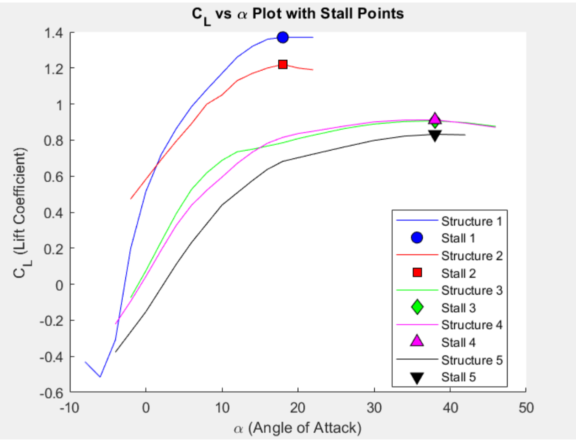

Figure 29: C_l vs α

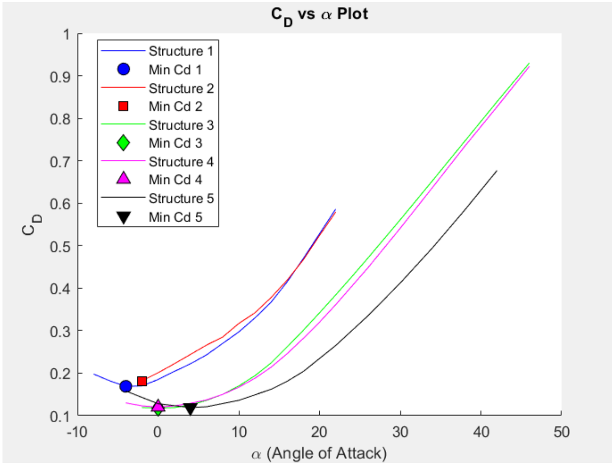

Figure 30: C_d vs α

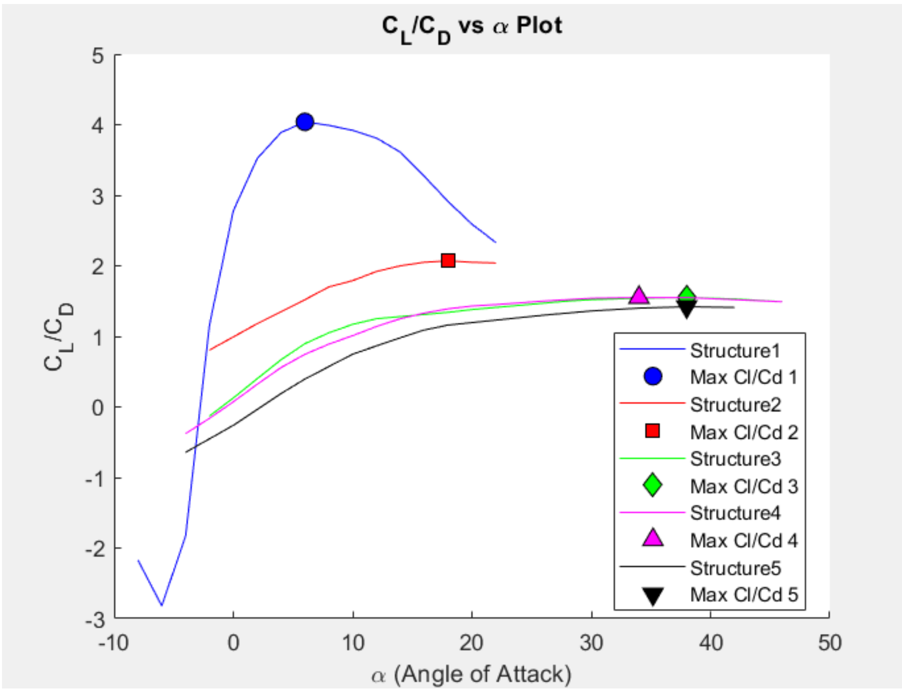

Figure 31: C_l/C_d vs α vs α

- It is observed that stall for the profiles is flat, mostly beacuse of low reynolds number.
- The drag is minimum near 0 angle of attack, since near that angle, we get the smallest projection of area of seen from the front (direction of incoming flow)
- One interesting finding is the flattening out of the C_l/C_d curve as we move outboard along the wing, while a distinct peak is observed for the section closer to the body. This is particularly noteworthy because the dragonfly exercises direct muscular control over the

basal regions of its wings, enabling it to manipulate those sections with greater authority. According to a study by Combes and Daniel (2003), spanwise flexural stiffness in insect wings scales strongly with the cube of the spanwise coordinate, while chordwise stiffness scales with the square of the chordwise coordinate. This indicates that aeroelastic deformations, such as passive twisting under aerodynamic loads—are more likely to occur at positions further from the wing root or near the trailing edge.

Consequently, while the dragonfly can actively control twist deformations near the body, its control diminishes outboard due to reduced stiffness and muscle influence. These outboard regions are thus more susceptible to passive, speed-dependent twist variations caused by aeroelastic effects. To maintain efficient aerodynamic performance across this varying range of passive twist-induced angles of attack, the wing profiles in the outboard region exhibit a flattened C_l/C_d curve. This ensures relatively consistent performance over a broad range of operating conditions during gliding.

Table 2: AoA for max C_l/C_d for each profile

Profile	**Value**
1	10.25
2	23.82
3	39.56
4	36.00
5	34.67

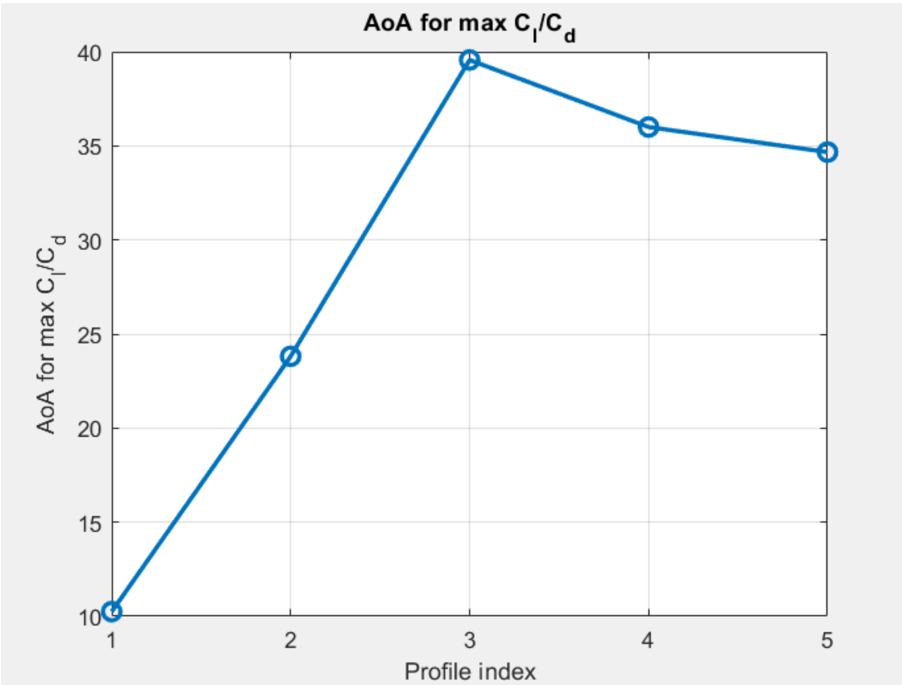

Figure 32: Profile wise AoA for max C_l/C_d

Here, a trend of positive twist can be observed, contrary to the negative twist from fig 32.

There was not much data on how the dragonfly wing looks like, or what twist does it have while gliding, but some images were obtained from "Flight of the dragonflies and damselflies

Richard J Bomphrey" (ref 3), which hints towards a more positive AoA as we go far from the body.

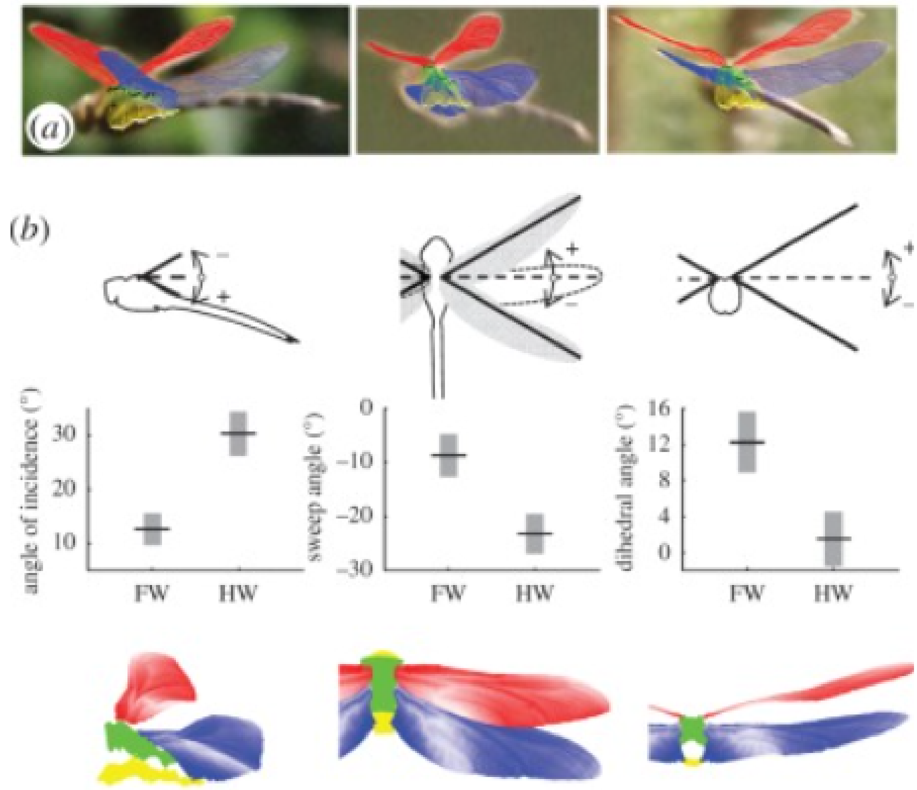

Figure 33: Images of a flying dragonfly

6.1.2 3-D wing simulations

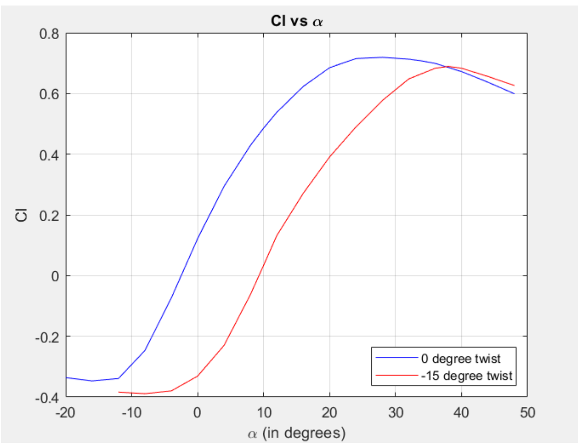

Figure 34: C_l vs α

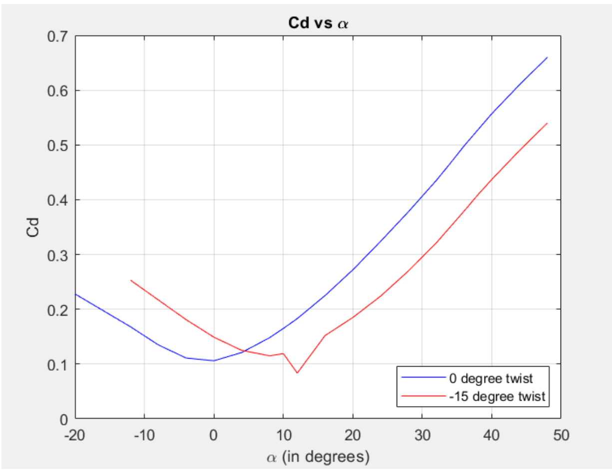

Figure 35: C_d vs α

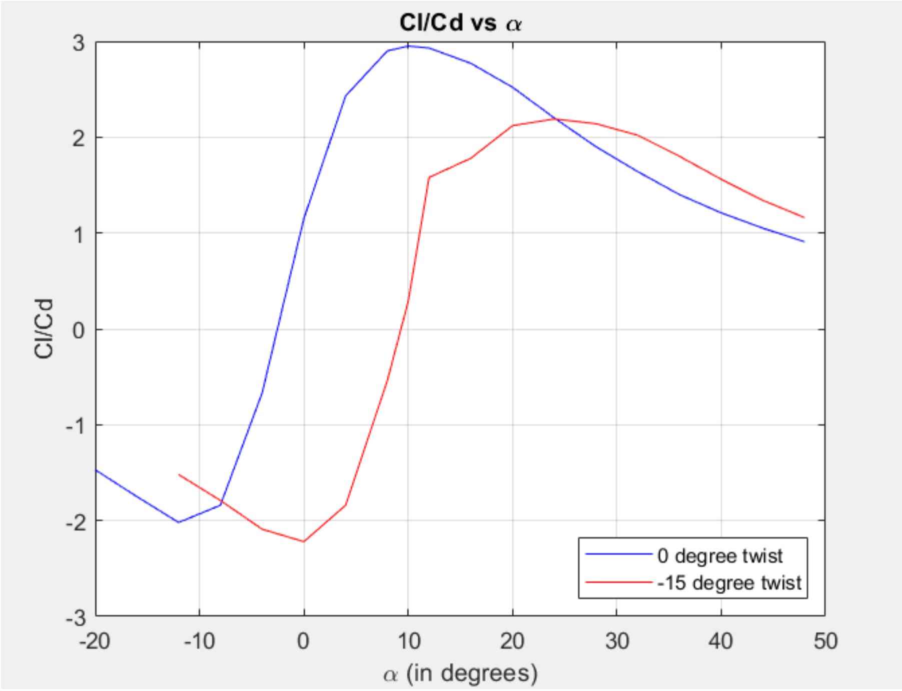

Figure 36: C_l/C_d vs α vs α

- It can bee seen that the curve just shifts towards the left, with slight increase in C_L max as we change the twist
- The same thing can be said for C_d curve too, it just shifts laterally
- The C_l/C_d curve is the one which is most import and that has a decent enough increase as go from -15^o to o^o twist. The location of maximum C_l/C_d also shifts towards left

So it is observed that results from the paper don't align with ours. It is also worth noting that 2D results alone are not sufficient in finding the ideal wing twist for optimal gliding, 3D effects are to be taken into account and can't be ignored.

7 Conclusion

In this report, a summary of the work done towards the aerodynamic performance of corrugated dragonfly wing is provided. The focus was to see if the dragonfly wing structure is optimized for aerodynamics. For that, first 2D analysis was done, followed by 3D analysis to get even better result. Results from other papers like Kesel (2000) were also analyzed while doing our analysis, and it was observed that the idea of wing having having negative twist giving better result did not align with our simulation results. In the future, more wings of different twist angles need to be studied to arrive at the optimal one. the future work also involves changing the corrugation pattern or twist to get mission specific optimal performance.

8 References

- Okamoto et al. (1995): https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e8ea731446505988ff557865b1740ed4533aaf21
- Kesel (2000) https://www.researchgate.net/publication/12319395_Aerodynamic_characteristics_of_dragonfly_wing_sections_compared_with_technical_airfoils

- Flight of the dragonflies and damselflies Richard J Bomphrey 1,, Toshiyuki Nakata 2, Per Henningsson 3, Huai-Ti Lin 4: https://pmc.ncbi.nlm.nih.gov/articles/PMC4992713/#RSTB20150389C26
- https://iopscience.iop.org/article/10.1088/1748-3182/3/2/026004/pdf
- https://www.sciencedirect.com/science/article/pii/S0889974616000098
- https://www.sciencedirect.com/science/article/pii/S0022519309003282
- https://iopscience.iop.org/article/10.1088/1742-6596/2879/1/012052/pdf
- https://www.sciencedirect.com/science/article/pii/S088997462400015X