

Aerodynamic Characteristics of Dragonfly Wing Sections

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ABSTRACT: Nature has bestowed us with inexpugnable mysteries which when seen in the dimension of engineering will give cognitive ideas for many high-tech systems. The careful observation to capture the clues hidden in nature and successfully incorporating it with multi-disciplinary fields can lead to scientific breakthroughs. Dragonfly wings which have well-defined cross-sectional corrugations can be interpreted as the ultra-light airfoils during gliding. The cross-sectional configuration diversifies largely along the longitudinal axis of the wing. Due to the diversity, the local aerodynamic characteristics are also different. A numerical investigation was performed to study the local aerodynamic characteristics of different cross-sectional sections. The orientation of the leading edge is considered to obtain accurate results. These results exhibit the significance of detailed geometrical temporal relation as a solution to the static and aerodynamic requirements placed upon the ultra-light airfoils of a dragonfly.

KEYWORDS: Bio fluid dynamics; Biomimicry; Computational fluid Dynamics; Corrugated airfoil; Dragonfly ; Glider ; Insect flight.

I. INTRODUCTION

Nature has bestowed us with inexpugnable mysteries which when seen in the dimension of engineering will give cognitive ideas for many high-tech systems. A handful number of insects encompassing dragonfly, damselflies, and locusts implement wings with corrugated surfaces. By observing and grasping how nature surmounts quandaries correlated with insect flights, considerable enhancements have been successfully accomplished in engineering.

Unlike other four-winged insects, dragonfly's fore- and hind-wings are not connected, they function independently. Even gliding flight, which is rarely found in Pterygota, is part of their aggregation. This spankling and thermoregulated primal flight behavior endues one to treat wings of these insects as airfoils [1,2,3]. The aerodynamic characteristics of an aerofoil can be ascertained using simple steady-state analyses by ignoring unsteady effects. The air encompassing a wing is accelerated to produce the aerodynamic forces Lift and Drag, and the resultant force Thrust, that empowers the insect to fly.

The superior flight characteristics of dragonflies can be explained by the following reasons: New [4] suggested that significant lift is produced due to the low pressure leading edge vortices above their wings. Rees [5] suggested that the corrugated structures act as a trap for the airflow and thus the flow becomes stagnant and rotates slowly in the valleys, which aids in the reduction of flow separation events. Newman et al. [6] suggested that the increased aerodynamic performance is due to the earlier reattachment of the flow separation on the corrugated cross-sections. Kesel [1] observed that the negative pressure would be produced at the valleys of corrugations, which contributes to increased lift. Vargas and Mittal [7] conducted a numerical study to investigate the flow behavior around the corrugated dragonfly aerofoil and confirmed the presence of small vortex structures in the valleys of corrugated aerofoil.

One might expect to determine varying aerodynamic characteristics along the wing axis, since the corrugations vary along the longitudinal axis, and also due to the changing orientation of the leading edge. The scope of this study is to examine the various cross-sections of the dragonfly wing along the longitudinal axis.

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II. DRAGONFLY WING

Dragonflies appese astonishing flight maneuvers. They are capable of being stationary in the same position in the air and to vary the flight direction instantly. This extraordinary aerodynamic property is because of the two chief components: the wing geometry and the musculature. This paper focuses on the various cross-sections of the wing geometry, which are highly modified by nature. One wing weighs only about 3% of the total weight of the dragonfly [8], but at the same time is very sturdy and strong.

Dragonfly wings which have well-defined cross-sectional corrugations can be interpreted as the ultra-light airfoils during gliding. These corrugations form section valleys in which rotating vortices develop. The cross-sectional configuration diversifies largely along the longitudinal axis of the wing. Due to the diversity, the local aerodynamic characteristics are also different. However, the wing sections, reliant on their position along the span length, achieve high lift values. The detectable aerodynamic forces can be compared with those of technical wing sections at low Reynolds number. The original dragonfly wing section has better aerodynamic properties than the technical sections. Figure 1 below shows the position of cuttings of dragonfly wings and the resulting cross-sections.

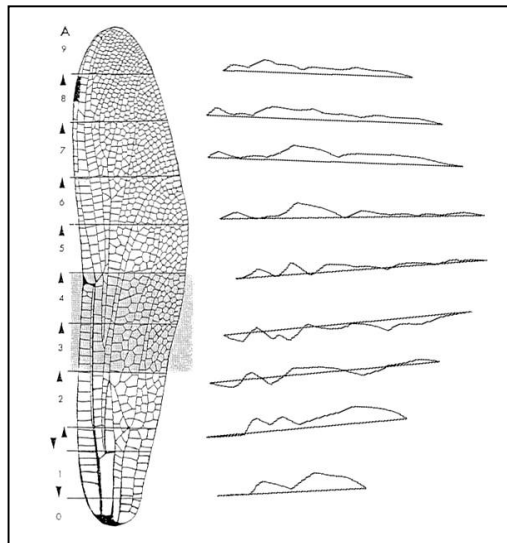


Figure 1: Position of the cuttings on the Dragonfly wing [9]

The prime reason behind the interest towards dragonfly wings is its high energy efficiency [10]. This high energy efficiency enables one to utilize this kind of wing geometry for possible technical applications. Future Unmanned Aerial Vehicles (UAVs) and Micro-Air-Vehicles (MAVs) could use the effect of rotating vortices to optimize their energy efficiency and flight dynamics. The corrugation makes it possible to construct an extremely light-weight wing.

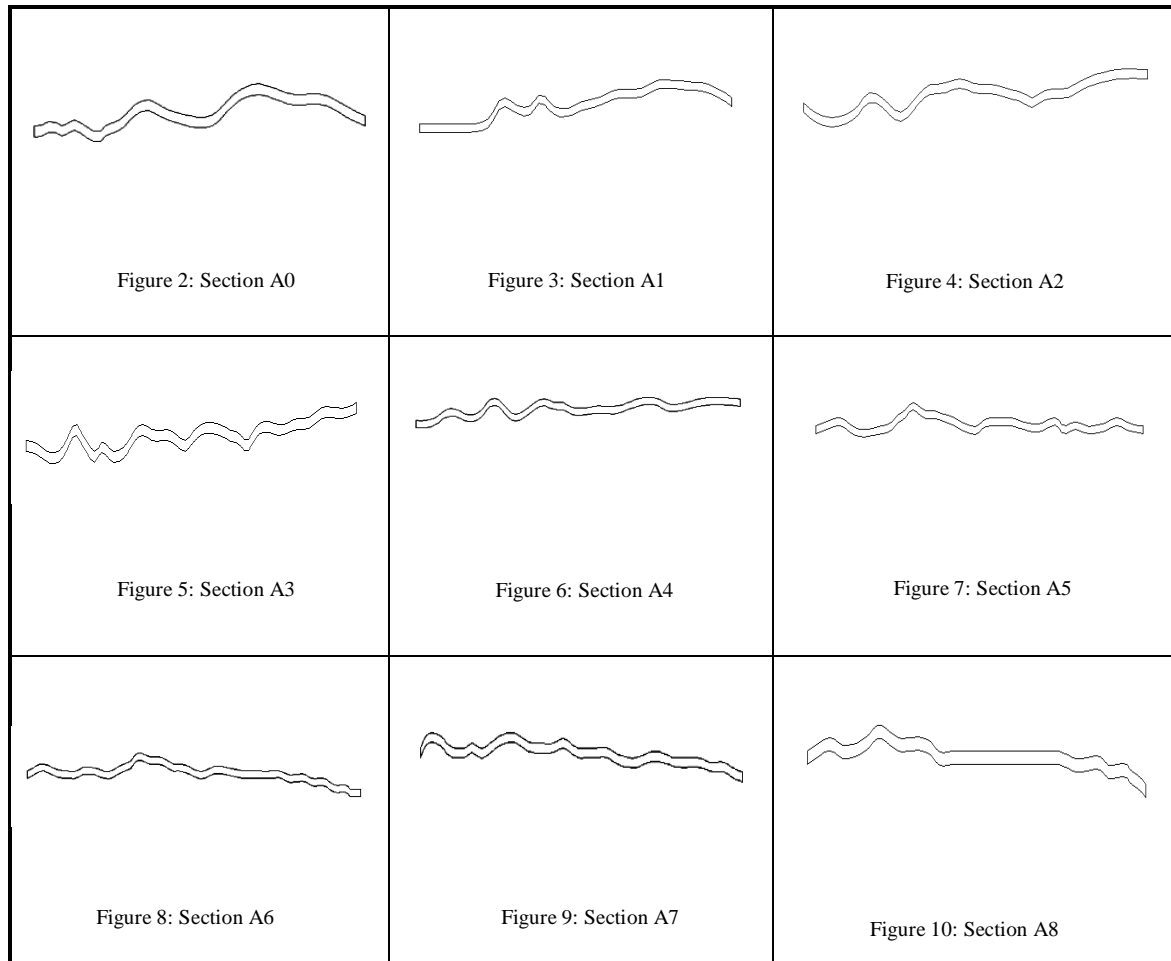
III. SECTIONS UNDER STUDY

Figure 2 to 10 below shows the various cross-sections of the wing geometry used in the study and are drawn by extracting vertex points from the respective sections shown in Figure 1. The sections based on dragonfly wing in the present study have irregular corrugations along the chord length.

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IV. METHODOLOGY

Two-dimensional CFD simulations were run and results analyzed for each of the sections shown in Figure 2 to 10. ANSYS Gambit 2.4 was used in the pre-processing stage and ANSYS Fluent 6.3 was used in the solving and post-processing stages. The flow field around the cross-sections consists of rectangular block upstream and downstream. Fig. 11 illustrates the flow field with boundary conditions around the Section A7. The geometry was meshed using Triangular/Prismatic elements with fine meshes in close proximity to the model and coarse mesh away from the model. Fig. 12 shows the mesh for the Section A7.

The models were solved using pressure-based incompressible solver. Turbulence was modelled with Realizable $k-\epsilon$ model with standard wall functions. $k-\epsilon$ is the commonly used model for turbulent flow conditions, wherein 'k' determines the energy in the turbulence and ' ϵ ' determines the rate of dissipation of turbulent kinetic energy. $k-\epsilon$ is used since it assumes turbulent viscosity is isotropic and also focuses on the mechanisms that influence turbulent kinetic energy. Realizable $k-\epsilon$ is used instead of Standard model since it satisfies certain mathematical constraints on Reynolds stress and also consistent with the flow physics of turbulent flows. Details about the implementation of the model in ANSYS Fluent guide [11]. The solution was initialized from the velocity inlet boundary. The velocity inlet uses the magnitude and direction specification method with X and Y component at constant value. The turbulent kinetic energy and the turbulent dissipation rate were set at the constant value.

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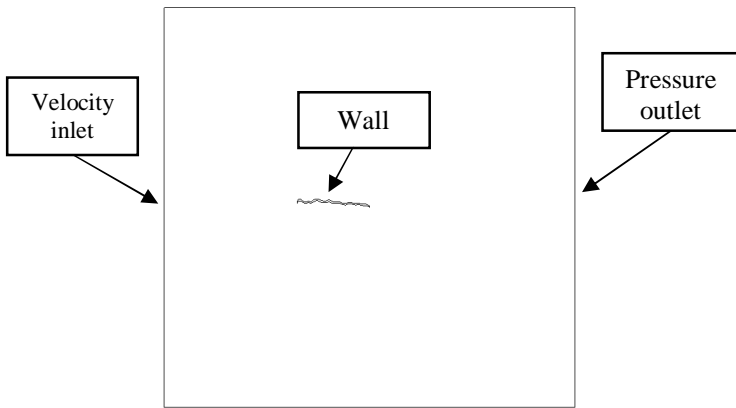


Figure 11: Flow domain of Section A7 with boundary conditions (also representative of other Sections)

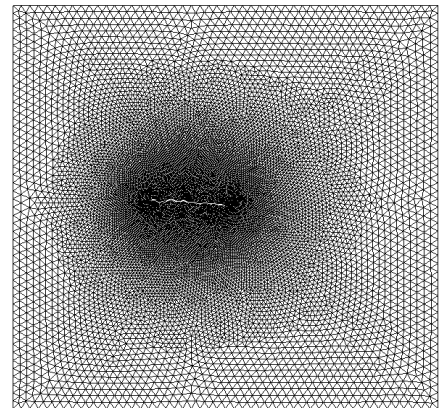


Figure 12: Final mesh used for Section A7 (also representative of other Sections)

The chord length of a real Dragonfly wing varies along its length and hence, each cross-section has different Reynolds number. Table I shows the Geometrical variables and Reynolds number of the each cross-section used in the study.

Table I

GEOMETRICAL VARIABLES AND REYNOLDS NUMBER OF THE CROSS-SECTIONS USED IN THE STUDY

Section	Chord Length (mm)	Thickness (mm)	Reynolds Number
A0	6.5	2	6023
A1	8.0	2	7413
A2	9.3	2	8617
A3	10.6	2	9822
A4	11.2	2	10378
A5	11.1	2	10285
A6	10.4	2	9636
A7	9.6	2	8895
A8	8.4	2	7783

The aerodynamic performance of a wing gliding can be determined by means of various C_L/C_D ratios. The gliding ratio (ϵ_R) gives the maximum gliding distance per unit length, where

The corresponding gliding angle γ can be calculated $\epsilon_R = (C_L/C_D)$ (1)

$$\gamma = \arctan (C_D/C_L) \quad (2)$$

The gliding ratio ϵ_S gives the minimum sinking from

$$\epsilon_S = (C_L^3/C_D^2) \quad (3)$$

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V. RESULTS AND DISCUSSION

A numerical study was conducted to investigate the aerodynamic characteristics of Dragonfly wing sections, with different Reynolds number since the chord length varies with its length. Computations show that the different cross-sectional geometries along the longitudinal axis of the wing are mutually related with different aerodynamic characteristics. Whilst sections A2 and A3 has upward facing leading edges, that of sections A5, A6, A7 and A8 faces downwards. Furthermore, the trailing edge always directed downwards except for the sections A2 and A3. Okamata et al. [10] used sections with symmetrical corrugations along the chord length and found that the aerodynamic characteristics of a section are dependent upon the emplacement of the leading edge. Table 2 shows the aerodynamic characteristics of the cross-sections.

Table II
AERODYNAMIC CHARACTERISTICS OF THE CROSS-SECTIONS

Section	Coefficient of Lift (C _L)	Coefficient of Drag (C _D)	Gliding Ratio (ε _R)	Gliding Angle (γ)	Minimum Sinking rate
A0	0.034	0.090	0.379	1.208	0.004
A1	-0.136	0.097	-	-	-
A2	-0.485	0.080	-	-	-
A3	-0.611	0.074	-	-	-
A4	-0.226	0.066	-	-	-
A5	0.181	0.071	0.253	1.322	0.011
A6	0.607	0.074	8.202	0.121	40.872
A7	0.736	0.056	13.035	0.076	125.164
A8	0.861	0.086	9.946	0.100	85.263

The values for Glide ratio, Glide angle and Minimum sinking rate for the cross-sections A1, A2, A3 and A4 are neglected since the results obtained are negative due to the negative lift coefficients. The cross-section A7 is proven to be the best optimized geometry to be emulated as a wing for technical applications in terms of Glide ratio, Glide angle and Minimum sinking rate; followed by sections A8 and A6.

Figure 13 to Figure 15 show the variation of aerodynamic characteristics of each section of the wing geometry.

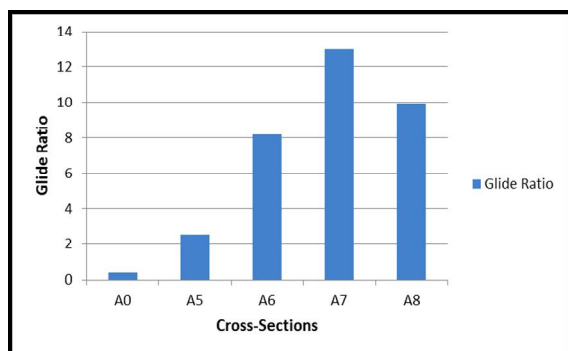


Figure 13: Glide Ratio

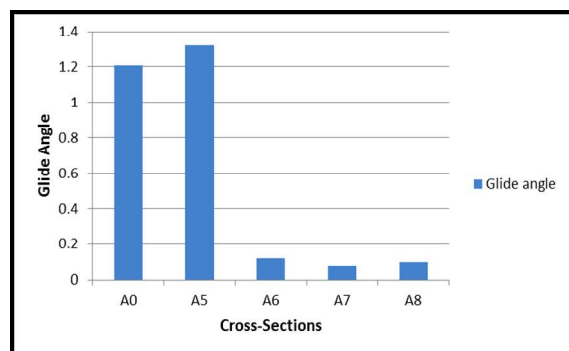


Figure 14: Glide Angle

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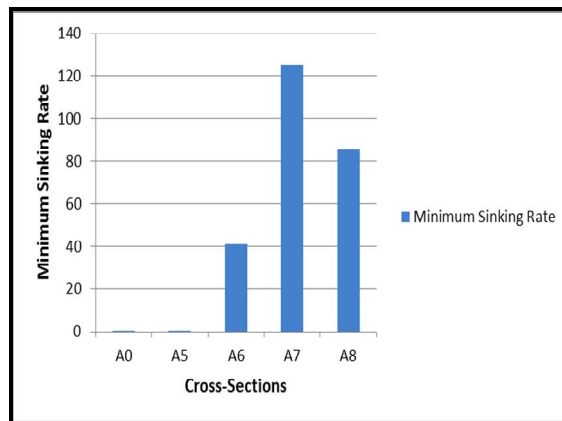


Figure 15: Minimum Sinking Rate

Wakeling and Ellington [12] explain in an explicit manner that the improvement in lift generation cannot be due to the Reynolds number, or to the aspect ratio. Therefore, other parameters must be amenable for the high lift generation in Dragonfly wings. Buckholz [13] exhibited that negative pressure is formed in the upper side of the wings, thus assisting in superior flight performance. The geometric assembly and in particular, the deformations and the arrangement of edges over the chord length, plays a significant role in the production of lift of the wing. An increase in lift due to the vortex system can only be reached if the geometry is optimized. Thus, the principally static demands of the cross-sectional topology will experience aerodynamically necessary fine tuning, over the chord length and also over the span length. This may elucidate the gradual widening of the wing from root to tip and peculiarly the reorientation of the leading edge at the mid-span. The leading edge geometry resulting from the requirements on the wing-root is, however, aerodynamically less favorable and should be aerodynamically optimized for better flight characteristics. Therefore, the dragonfly can be considered as a multi-criterion feedback to the counterinsurgency between static and dynamic demands.

At present, the study does not focus on the reason behind the negative lift coefficients. In future, the study will concentrate on filling the valleys to form profiled aerofoils which may lead to a distinct desolation in lift generation.

IV. CONCLUSION

In nature, we can find many evidences for highly optimized laws and methods; the Dragonfly wing is such a structure. In the era, where energy is becoming progressively high-priced remarkable optimizations in the shape of the airfoil would result in positive spiral effect. This helps in reduction of wing area, and thus materials, leads to overall reduction in aircraft structural weight. Fuel consumption is further reduced for a proposed flight section, due to the decrease in structural weight and hence reduced gross weight. The protruding corners of cross-sections act as “turbulators” to induce unsteady vortices to encourage the transition of boundary layer from laminar to turbulent speedily. These unsteady vortices trapped in the valleys of the corrugations could pump high-speed fluid from outside to adjacent wall regions to provide ample energy for the boundary layer flow to overrun the adverse pressure gradient, thus, discourage flow separations and airfoil stall.

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