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Investigation of Fluid Flow and Aerodynamic Performance of a Corrugated Dragonfly Wing section: A Review

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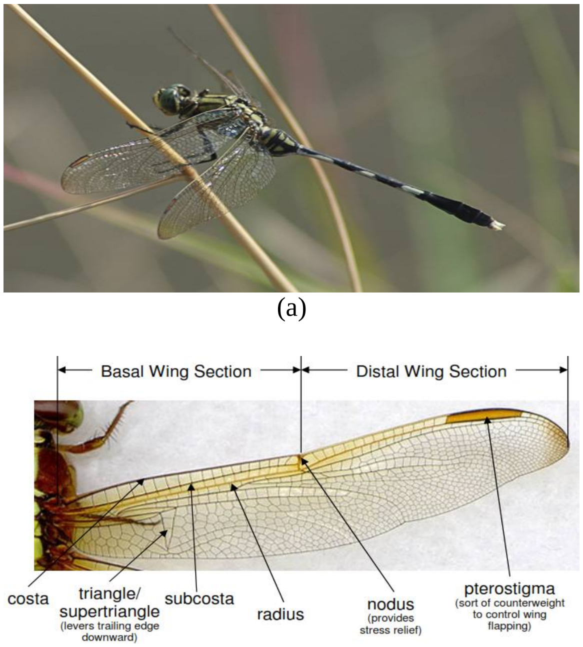
Abstract

This review paper describes the aerodynamic performance of dragonfly wing during flapping flight and gliding flight for micro air vehicle. Scientist have been intrigued by them and have carried out research for biomimetic application. Relative to the large number of works on its flight aerodynamics, few researchers have focused on the insect wing structure and its aerodynamics performance. Dragonfly demonstrate unique and superior flight performance than most of the other insect species. They are equipped with two pairs of independently controlled wings. The high level of dexterity in wing motion of the dragonfly allows it to hover, fly fast forward make turn rapidly, fly sideways and even glide. This review paper explain the past worked related to aerodynamic performance, mechanical properties and morphology of dragon fly.

1. Introduction

A number of insect species including locusts, dragonflies, and damselflies employ wings that are pleated along the chord. These ultra-light membranous insect wings support a variety of aerodynamic and inertial forces during flight. The pleated framework provides stiffening against span wise bending [1] [2]. The dragonfly has a flapping frequency between 30 Hz and 50 Hz [3] and typically flies with its forewings and hind wings beating out of phase [4]. Gliding flight is also observed frequently in dragonflies; for instance Pantala flavescens can sustain glides of 10–15 s at a flight speed of about 15 m s^{-1} [5].The dragonfly of the genus Aeschna is capable of gliding for up to 30 s without any appreciable loss in altitude It has also been hypothesized that dragonflies adopt this gliding mode to take advantage of convective cooling during hot weather. In gliding flight, the dragonfly elevates into the air using powered (flapping) flight and makes use of potential energy to move horizontally above the ground [6]. Smaller dragonflies had gliding periods lasting 0.5 s, covering a distance of approximately 1m and achieving maximum gliding speeds of up to 2.6 m s^{-1}. The typical Reynolds number of dragonflies can range from 100 to 10 000 which can be categorized as being in the ultra-low Reynolds number flow regime [7].The pleated wing is structurally stabilized primarily by the folded configurations, which increases flexural rigidity[8].

Gliding flight is an advantageous flight mode as it requires virtually no effort from the dragonfly [9].At high temperatures, large dragonflies run the risk of overheating during active flapping flight, and can avoid this by sustaining longer glides per wing beat [10]. Fluid Structure Interaction of uniform flow past a two dimensional pleated airfoil is carried out. When the wing interact with the air, it is subjected to both aerodynamic forces acting on the surface of the wing and the inertial force due to the acceleration of deceleration of the wing mass. The interaction between these inertial and aerodynamic forces resulted in wing deformation. In the first phase of the work, fluid flow simulation at Reynolds Number-100, 200, 500, and 1000 will be performed with angle of attack 0^0 to 15^0, it was found that for all the simulations performed flow always remained steady at Re 100 and 200. First unsteady flow was obtained at Re 500 and AOA 10^0. But flow always remained steady at AOA 0^0 and 5^0 for all the Reynolds numbers [11-14]. The primary overall structure property of wing is span wise stiffness and chord wise flexibility. The leading edge of the wing is compromised of a very stiff structure with three dimensional relief in order to provide high rigidity to the span of the wing. It is obvious that this quality contributes greatly to the wing's aerodynamic properties. There are number of key structures in the wing, shown below in figure 1, which contribute to the manner in which the wing bends in flight and therefore help to facilitate the wing's aerodynamic properties [15].



(a)

(b)

Figure 1: (a) Dragonfly, (b) Dragonfly wing with structures of interest [15]

It is well known that high aspect ratio wings are advantageous in gliding flight and this is the reason why wings with high aspect ratios are employed in sail planes as well as by large soaring birds. Interestingly, dragonflies have some of the highest aspect ratio wings in the insect world which allow them to possess a better glide performance and consume less energy during gliding [16]. Various flow patterns and aerodynamic performance of pleated airfoil has been obtained at ultra-low Reynolds numbers (2000-3000) at different angle of attacks (AOA) ranging from 0° to15°. Also there effects on coefficient of Lift and Drag have been analyzed [17].

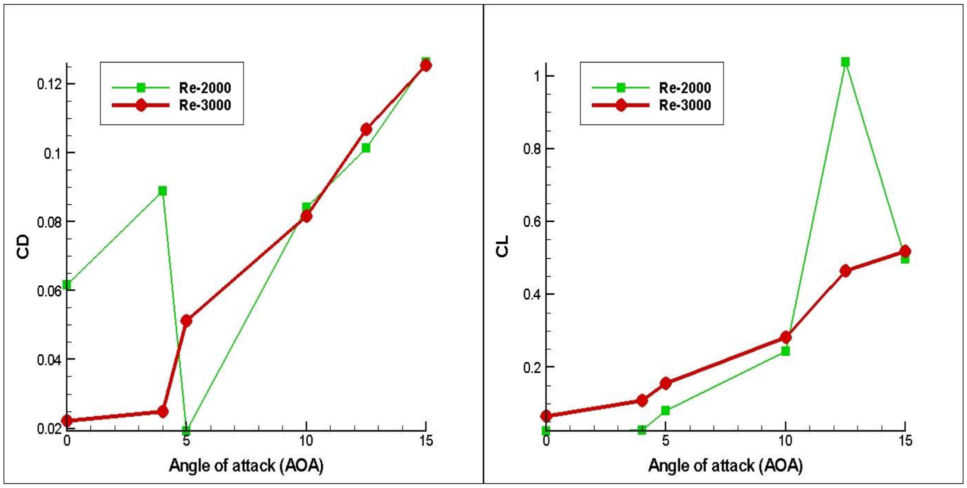


Figure 2: Variation in C_D and C_L with AOA for Re2000 and Re3000 [17]

The influence of aerodynamic performance on two dimensional NACA 4412 airfoil is investigated. The computational method consist of steady state, incompressible, finite volume method, spalart-allmaras turbulence model. The flow has been studied with the help of Navier-Stroke and continuity equations. Numerical simulations were performing at Reynolds number ($1x10^6$, $2x10^6$, $3x10^6$, and $4x10^6$) at different angle of attack (0^0, 3^0, 6^0, and 9^0). The results give the satisfactory measure of confidence of fidelity of the simulation [18].

2. Governing Equation

Fluid Flow

The equations governing the flow in the numerical solver are the time-dependent, viscous incompressible Navier–Stokes equations. The non-dimensional momentum and continuity equations are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j\,\partial x_j} \tag{2}$$

The equations are non-dimensionalized with the appropriate length and velocity scales, in this case the airfoil chord and free stream velocity. Here Re corresponds to the Reynolds number which is defined as below:

$$Re = \frac{\rho u_\infty c}{\mu} \tag{3}$$

The key quantities examined are the lift and drag coefficients which are defined as

$$C_L = \frac{F_L}{\frac{1}{2}\rho u_\infty^2 c}, \tag{4}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho u_\infty^2 c} \tag{5}$$

$$\text{Gliding Ratio} = \frac{C_L}{C_D} \tag{6}$$

3. Aerodynamic Performance

Figure 3 shows the time mean streamlines for all the airfoils at the various Reynolds numbers studied here. The plots show that at this angle of attack, large regions of separation exist over all the airfoils for Reynolds numbers greater than 5000. Below this Reynolds number, the flow over the airfoils is mostly attached and does not show large regions of separation. Furthermore, when *Re*= 5000 and 10 000 cases are compared, the separation is much more extensive at the lower Reynolds numbers. Thus, a further increase in the Reynolds number beyond this value tends to reduce the extent of separation.

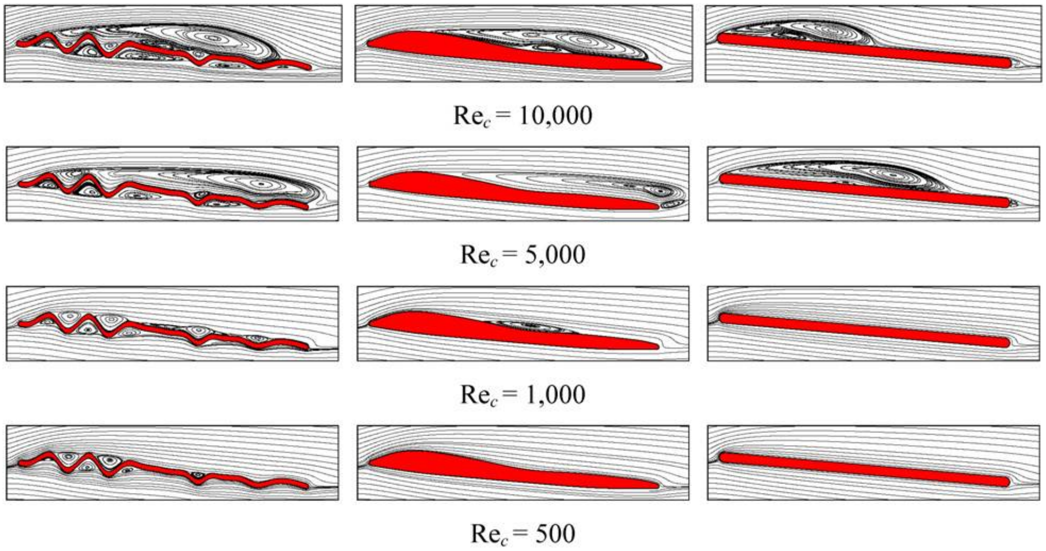


Figure: 3 Time-averaged streamlines of the pleated airfoil (left), profiled airfoil (middle) and flat plate (right) at α = 5◦ with Rec = 10 000, 5000, 1000 and 500 [19].

Figure 4 also shows that the pleated airfoil outperforms the profiled airfoil at all chord Reynolds numbers tested. Thus, the pleated airfoil has two key favorable properties: first, unlike the flat plate, its glide ratio increases monotonically over a large range of Reynolds numbers extending from 1000 to 10 000 and, second, it outperforms the profiled airfoil over this entire range of Reynolds numbers.

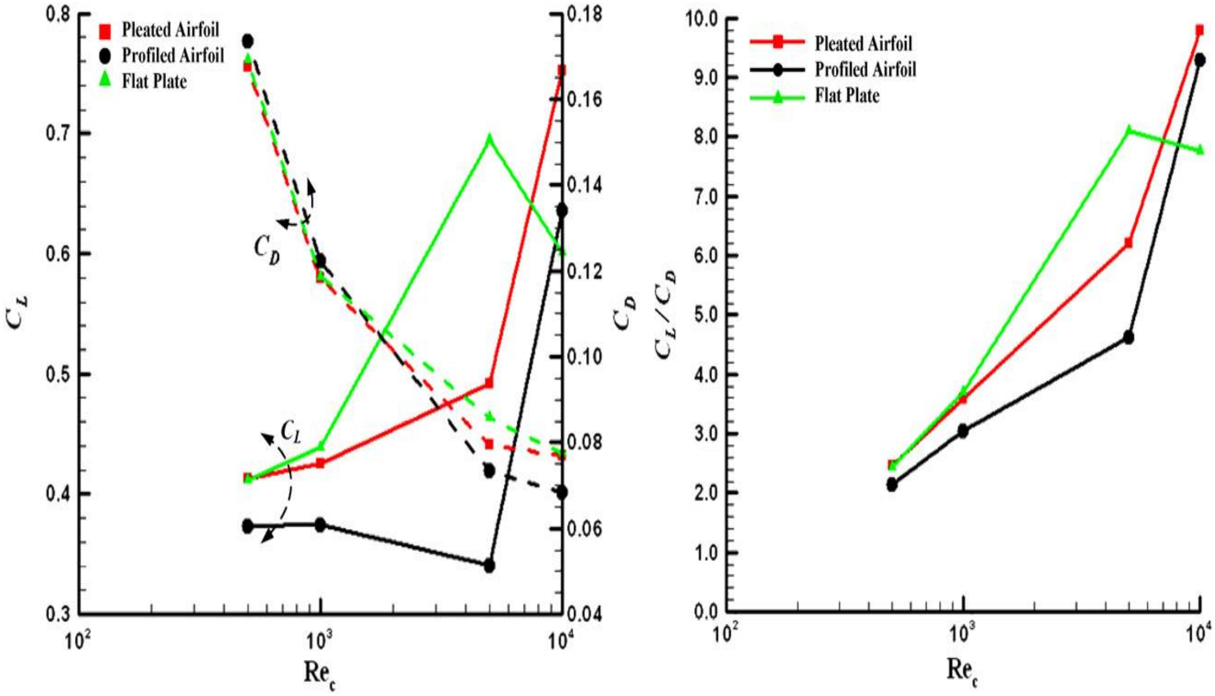
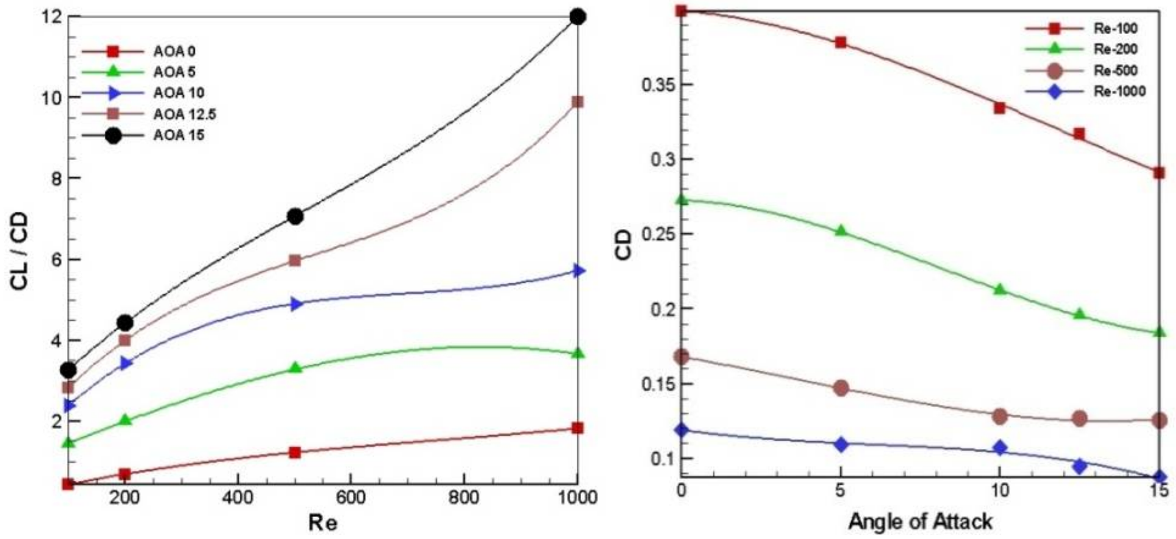


Figure 4. (*a*) The mean lift and drag coefficients of the three airfoils with varying chord Reynolds numbers. Solid and dashed lines represent C_L and C_D respectively. (*b*) Lift-to-drag ratio versus the chord Reynolds number for the airfoils at α =5^0 [19].

The aerodynamic characteristics of spatio temporal dynamics of a cut section of Aeshna Cyanea's wing has been performed at ultra-low Reynolds numbers (100 to 1000) at different angle of attacks ranging from 0^0 to 15^0. The effect of the Reynolds number on the gliding ratio is shown in figure 5a, at Re 1000 and angle of attack 15^0, the largest gliding ratios are obtained. Figure 5b shows that invariably at all Reynolds number, minimum Drag coefficient is obtained at AOA 15^0. The drag production leads to some interesting observations. As expected, the overall drag coefficient increases as Re is decreased .because the viscous effects are more dominant at lower Reynolds numbers which cause the skin friction to be the major contributor to the overall drag. As the angle of attack is increased, drag coefficient further decreases [11-14].



(a)

(b)

Figure 5:- (a) Comparison of Gliding Ratios for different Angle of Attacks (AOA), (b) Comparison of Average Drag Coefficient for different Angle of Attacks (AOA) [11]

For particular Aeschna cyanea, the aspect ratios of 11.63 and 8.4 for the forewing and hind wing respectively was calculated. The crane fly (Tipulapaludosa) is comparable to the dragonfly with an aspect ratio of about 11. The dragonfly's wing aspect ratio is quite high compared to other insects such as the fruit fly (Drosophila virilis) which has an aspect ratio of 2 and the bumblebee (Bombusterrestris) with an aspect ratio of 6.4 [19] [20].

Dragonflies have highly corrugated wings where the pleated configuration varies along the span wise and chord wise directions. The pleats provide stiffening against span wise bending, while allowing for torsion and the development of camber. The improved aerodynamic performance would be associated with the earlier reattachment of the flow separation on the corrugated wings. As the angle of attack increases, airflow would separate from the leading edge to form a separation bubble, and the separated flow would reattach sooner due to the corrugation compared with smooth airfoils [21] [22] [23].

Stiffness in the span wise direction arises from the construction of a pleated wing since the longitudinal veins are located at the maximum and minimum peaks and are connected by the cross veins . The pleated wing is structurally stabilized primarily by the folded configurations, which increases flexural rigidity. Rigidity varies throughout the wing, and the factors which cause this variation are the depth of the pleats and the rigidity of the longitudinal cross veins [24].

A number of hypotheses have been suggested to explain the fundamental mechanism of the rather unexpected aerodynamic performance improvement of corrugated dragonfly airfoils or wings over conventional smooth airfoils. By conducting wind tunnel experiments with scaled corrugated wing models, the fluid flowing over the corrugated airfoil would be trapped between the corrugation valleys where it either becomes stagnant or rotates slowly, resulting in the corrugated airfoil functioning as a streamlined airfoil. It also found that, compared with a streamlined technical airfoil, the tested corrugated airfoil would delay flow separation at higher angles of attack, and a stall did not occur abruptly [25]. Based on detailed experiments to investigate the aerodynamic characteristics of dragonfly wings and model wings at a Reynolds number ranging from 11,000 to 15,000 found that the corrugated wing model outperformed the flat plate at all angles of attack. The lift produced by a dragonfly wing was found to be higher than that produced by streamlined airfoils. Their experimental results focused on the effect of thickness, camber, pleats and leading edge sharpness [26]. The analysis of fluid flow around a 2 dimensional circular cylinder with Reynolds No of 150, 200, 500, and 1000 with different angle of attack 0^0, 5^0, and 10^0 has been studied. In this simulation an implicit pressure-based finite volume method and second order implicit scheme is used. Flow has been studied with the help of Navier-Stokes and continuity equations. The pressure, lift, & drag coefficients and vortex shedding for different Reynolds numbers and different angle of attack were computed [27]. Based on pressure measurements on the surfaces of a dragonfly wing model in addition to total lift and drag force measurements at a chord Reynolds number of 10,000, suggested that negative pressure would be produced at the valleys of the corrugated dragonfly wing models, which would contribute to the increased lift. He also compared aerodynamic performance of cross sections at different positions along the span of a wing of an Aeschna cyanea to develop the pleated models and its corresponding profiled airfoil at chord Reynolds number of 10,000 and results showed that the pleated airfoils generated higher lift than profiled airfoils. He also noticed trapped vortices present in the folds that serve to change the effective profile of the airfoil [28]. Based on detailed experimental work Buckholz [29] concluded that at Reynolds number 1500 pleats help in increasing lift. The same conclusion when filming free gliding dragonflies and conducting wind tunnel experiments on their wings at a Reynolds number ranging from 700 to 2400. C_L max recorded for free gliding dragonflies was 0.93 and 1.07 when tested in a wind tunnel environment. The enhanced lift produced by dragonflies is not attributed to the Reynolds number, the aspect ratio or the wing area, but rather a surface feature, mainly the corrugations found in dragonflies [7]. The simulation results confirmed that corrugated dragonfly wings would perform (in terms of the lift-to-drag ratio) as well and sometimes slightly better than smooth technical airfoils. The existence of small vortex structures in the valleys of the corrugated dragonfly airfoils were revealed clearly from the simulation results. The small vortex structures in the valleys of the corrugated cross-section were also revealed qualitatively in the flow visualization experiments of Kwok and Mittal [30-32].

4. Conclusion

The aerodynamic performance of dragonfly wing during flapping flight and gliding flight for micro air vehicle was reviewed. Scientist have been intrigued by them and have carried out research for biomimetic application. Relative to the large number of works on its flight aerodynamics, few researchers have focused on the insect wing structure and its aerodynamics performance. It has been reviewed that though the dragonfly wings have complex corrugations, it performs well in the ultra-low Reynolds number flow regime. The effect of the pleats on the flow is significant as it reduces the overall drag coefficient. With increase in angle of attack, although pleated airfoil experiences an increase in the pressure drag, it is compensated by a noticeable decrease in the shear drag. The reduction in the shear drag is due to the recirculating zones that exist inside the cavities that lead to negative shear drag contribution. Dragonfly demonstrate unique and superior flight performance than most of the other insect species. They are equipped with two pairs of independently controlled wings. The high level of dexterity in wing motion of the dragonfly allows it to hover, fly fast forward make turn rapidly, fly sideways and even glide.

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