International Journal of Innovation and Scientific Research
ISSN 2351-8014 Vol. 9 No. 2 Sep. 2014, pp. 285-292

http://www.ijisr.issr-journals.org/

Numerical Investigation of Fluid Flow and Aerodynamic Performance of a Dragonfly Wing Section for Micro Air Vehicles (MAVs) Applications

Shwetanshu Gaurav[1] and Kamal Kumar Jain[2]

[1]Post Graduate Student, Department of Mechanical Engineering,
Sri Ram Institute of Technology,
Jabalpur, Madhya Pradesh, India

[2]Professor, Department of Mechanical Engineering,
Sri Ram Institute of Technology,
Jabalpur, Madhya Pradesh, India

ABSTRACT: A comprehensive numerical simulation of fluid dynamics based study of a pleated wing section based on the wing of Aeshna Cyanea has been performed at ultra-low Reynolds number corresponding to the gliding flight of these dragonflies in order to explore the potential applications of pleated airfoils for micro air vehicle applications. The simulation employs an unstructured triangular mesh based on finite volume discretization done in the ANSYS-14.0 using WorkBench14.0.Whenever, dragonfly wing interacts with the fluid (air taken), several forces and vibrations results out. These forces and vibrations cause certain changes over the dimensional structure over the wing and also influence the flows characteristics. A critical assessment of the computed results was performed.

In this work, 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 analysed. The simulations demonstrate that pleated airfoil produces higher lift and moderate drag that lead to an aerodynamic performance and hence pleated airfoil is an excellent choice for a fixed wing micro-air vehicle application.

KEYWORDS: Lift Coefficient, Drag Coefficient, Angle of Attack, Reynolds Number, MAVs.

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, *Pantalaflavescen s*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[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[7].

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]. 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]. 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 [11]. For particular *Aeschna juncea,* Ellington calculated aspect ratios of 11.63 and 8.4 for the forewing and hind wing respectively. 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 [12] [13]. 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 [14] [15] [2] [16]. 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 [17]. The pleated wing is structurally stabilized primarily by the folded configurations, which increases flexural rigidity [8]. 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 [17].

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, Rees [8a] and Rudolph [18] suggested that 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.

Newman et al. [15] suggested that 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. Rudolph [18] 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.

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, Okamoto et al [19] 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.

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 Kesel [20] 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. Based on detailed experimental work Buckholz [21] concluded that at Reynolds number 1500 pleats help in increasing lift.

Wakeling and Ellington [7] also come to 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. Wakeling and Ellington [7] stated that 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.

More recently, Luo and Sun [22] and Vargas et al [23] conducted numerical studies to investigate the flow behaviors around corrugated dragonfly wings. Their 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 [24].

Despite different explanations about the fundamental mechanism for the improved aerodynamic performance, most of the studies agree that corrugated dragonfly airfoils or wings work well in low Reynolds number regimes, which naturally point to the potential applications of employing such corrugated airfoils or wings for MAV designs.

A large number of studies conducted on pleated wing have concluded that pleated wing provides a structural benefit, allowing for a low mass yet stiff structure, but the question remains as to what precisely is the effect of the pleated structure on the wing aerodynamics. With the advent of micro-aerial vehicles (MAVs), it has become clear that there is much that can be learned from insect flight that could be translated into engineered systems. For fixed wing MAVs, wings that simultaneously provide a superior aerodynamic performance and structural robustness are critical.

Thus, if it is found that the pleats have an aerodynamic benefit, then such wings could be excellent choice for micro-aerial vehicles and this is the primary motivation for this work.

In this work, in order to investigate the steady flow, unsteady flow and aerodynamic performance for spatio- temporal dynamics of a cut section of dragonfly (*Aeshna cyanea*) numerical analysis has been performed at ultra-low Reynolds numbers (2000 to 3000) at different angle of attacks ranging from 0^0 to 15^0.These parameter ranges are relevant for both dragonflies and micro-aerial vehicles. Past experimental studies [19] [20] [21] have found no intrinsic three-dimensional effects at these low Reynolds numbers. Thus 2D simulations are implemented in this work to encompass a relatively wide range of the parameter space necessary to draw some general conclusions regarding pleated airfoils which can be further utilized for MAVs applications. The pleated airfoil implemented in the numerical simulation corresponds to a cross-section located at the midsection of the forewing of a dragonfly (*Aeshna cyanea*). The specific profile chosen for the numerical simulations corresponds to 'Profile 2', which was extracted from the paper of Vargas *et al* [23] (which is the same as Profile 2 from Kesel [20]. From the three pleated geometries to select from the paper of Kesel [20], 'Profile 2' was chosen due to its horizontal leading edge**,** thus eliminating the issue that the orientation of the leading edge has an influence on the aerodynamic performance [19] as shown in Figure 1(b).

(a) Profile 1 (b) Profile 2 (c) Profile 3

Fig. 1. Typical pleated cross-section found in dragonfly wings used by Kessel[20] and Vargas et al [23]

For the purposes of reducing the resolution requirements in the simulation, the sharp edges of the pleats were rounded out slightly without affecting the basic geometry of the pleats and the overall shape of the airfoil as shown in Figure 10.

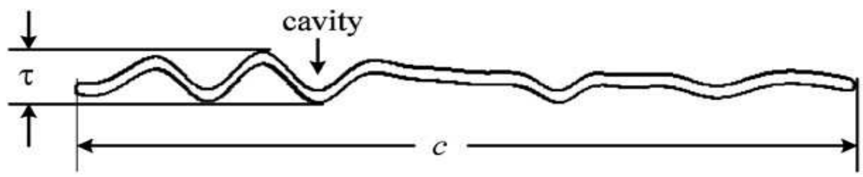


Fig. 2. Two dimensional Pleated airfoil representing a cross-section of the forewing of a dragonfly (Aeshna Cyanea) having τ/c =7.531 %

2 GOVERNING EQUATIONS

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

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial (p)}{\partial x_j} + \frac{1}{Re}\frac{\partial^2 (u_i)}{\partial x_j x_j} \qquad (2)$$

Where the indices, i = 1, 2, 3, represent the x, y and z-directions, respectively, and the velocity components u_1, $u_2$and u_3 correspond to u, v and w respectively.

Here, Re corresponds to Reynolds number which is defined as below:

$$Re = \frac{\rho u_0 c}{\mu} \qquad (3)$$

The key quantities that are to be examined here are Coefficient of Lift and Coefficient of Drag which can be defined as:

$$F_L = 1/2 C_L \rho A u^2 \qquad (4)$$

$$F_D = 1/2 C_D \rho A u^2 \qquad (5)$$

And Gliding Ratio=C_L / C_D (6)

3 VALIDATION CASE

In order to validate the current numerical solver, same flow parameters and geometrical dimensions as used by Kesel [20] and Vargas et al [23] have been used and simulations of flow past a pleated airfoil has been performed and compared to published results of Vargas et al [23] . Lift and Drag coefficients at Reynolds Number 2000 and angles of attack (AOA) 0^o and 4^o were the results of interest in this particular validation case. The numerical results displayed in the Table1 are time averaged Lift and Drag values at different time units and at particular time step size.

Table1 shows a near- zero Lift coefficient (C_L) obtained numerically in this present work as expected for airfoils.

Table 1. Comparison of C_L and C_D with the results from Vargas et al [23] at α = 0^0 and 4^0 at Re= 2000

Reynolds Number (Re)	AOA(α)	Lift Coefficient C_L Present	Drag Coefficient C_D Present	Lift Coefficient C_L [23]	Drag Coefficient C_D [23]
2000	0	0.025853	0.061631	0.0005	0.0785
	4	0.027964	0.088867	0.2732	0.0812

Also there were lesser difference in the present Drag coefficient (C_D) at different AOA (α) in comparison to that of Vergas et al. Overall, numerical results were in good agreement with those obtained by Vargas et al [23] for both angles of attack and chord Reynolds Number.

This validation case clearly demonstrates that current solver is capable of accurately simulating flow past airfoils at ultra-low Reynolds Number.

4 RESULTS AND DISCUSSION

Results obtained at different conditions are shown in Table 2.The Flow patterns (steady flow '**S'** & unsteady flow **'U'**) so obtained and Gliding Ratio at these conditions are also described.

Table 2. Essential parameters required for aerodynamic performance at different Reynolds number and different AOA

Reynolds Number (Re)	AOA(α)	C_D	C_L	Gliding Ratio C_L/C_D	**S** or **US**
2000	0	0.061631	0.025853	0.419476	S
	4	0.088867	0.027964	0.31467	S
	5	0.019308	0.08116	4.203522	US
	10	0.084114	0.243084	2.889923	US
	12.5	0.101456	1.03869	10.23787	US
	15	0.126534	0.49659	3.924553	US
3000	0	0.022238	0.064985	2.922169	S
	4	0.024894	0.108852	4.372654	S
	5	0.05126	0.156658	3.056167	US
	10	0.081645	0.282252	3.457053	US
	12.5	0.107013	0.464502	4.340607	US
	15	0.125616	0.518605	4.128511	US

It was observed that for all the simulation performed flow always remained steady at Reynolds number 2000 and 3000 for angle of attacks 0^0 and 4^0 and a constant line was obtained for C_D and C_L at different time intervals. In order to represent the Steady flow (constant line), graph so obtained at Re2000 and AOA 0^0 is shown in figure3.

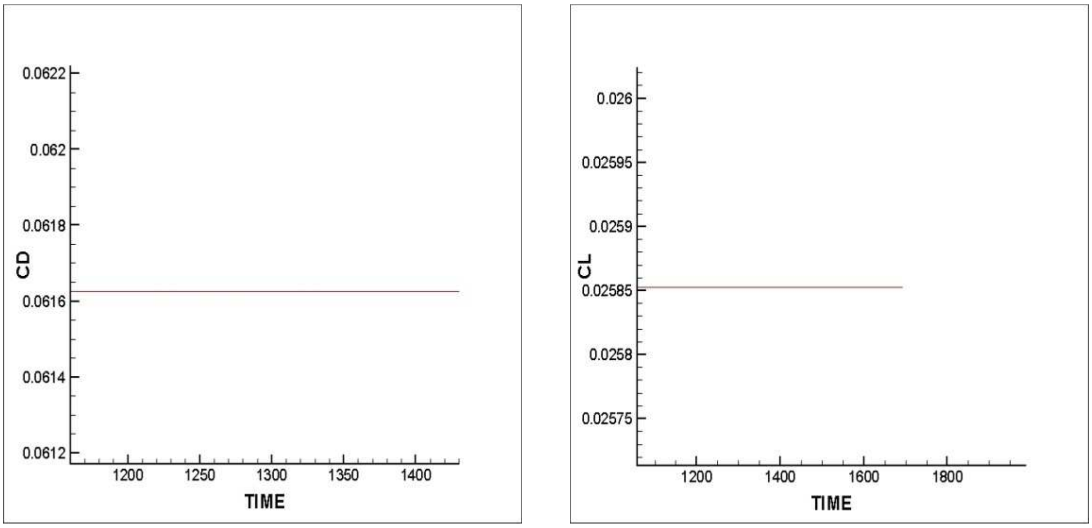


Fig. 3. Variation of C_D and C_L with time at Re 2000 and AOA 0^0

At rest of angle of attacks flow was Unsteady and inconsistent lines at different time intervals were obtained. In order to represent the unsteady flow (inconsistent line), graph so obtained at Re3000 and AOA 15^0 is shown in figure4

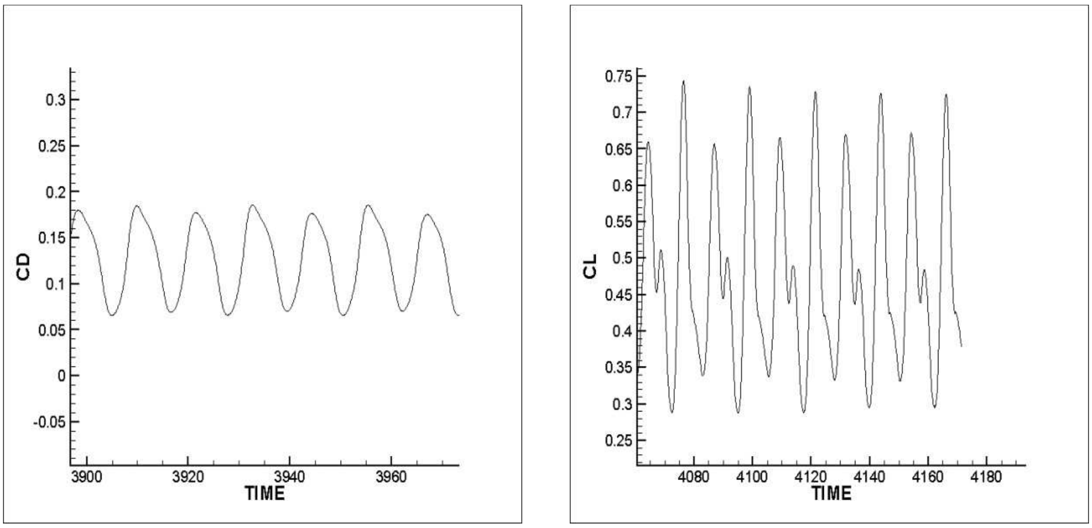


Fig. 4. Variation of C_D and C_L with time at Re 3000 and AOA 15^0

4.1 EFFECT OF ANGLE OF ATTACK AND REYNOLDS NUMBER

It was observed that pleated airfoil reached maximum C_L =1.03689 (which is almost similar to that suggested by Wakeling J M and Ellington [7] at Re2000 with angle of attack12.5^0 and minimum C_L = 0.025853 at Re2000 with angle of attack 0^0. Further, it was noted that pleated airfoil reached maximum C_D=0.088867 at Re2000 with angle of attack 4^0 and minimum C_D=0.019308 at Re2000 with angle of attack 5^0 as shown in figure5.It was also found that value of lift coefficients at Re 3000 with angle of attacks 0^0, 4^0, 5^0, 12.5 ^{0} and 15 ^{0} was maximum compared to that of drag coefficients at same conditions. The basic steps in understanding the aerodynamic performance at all Reynolds numbers were to analyze the flow at 0^0 and 4^0 angle of attack.

Gliding Ratio which is most important parameter in analyzing the aerodynamic performance of pleated airfoils was found maximum at Re2000 with angle of attack 12.5 ^{0} as shown in figure6(a). Its value is 10.23787 which is very much appreciable and can be explored for MAVs applications.

For AOA=0^0, 4^0, 10^0 and 15^0 gliding ratio increases with increasing Re, while it is decreases for AOA=12.5^0 and 5^0 as shown in figure 6(b).

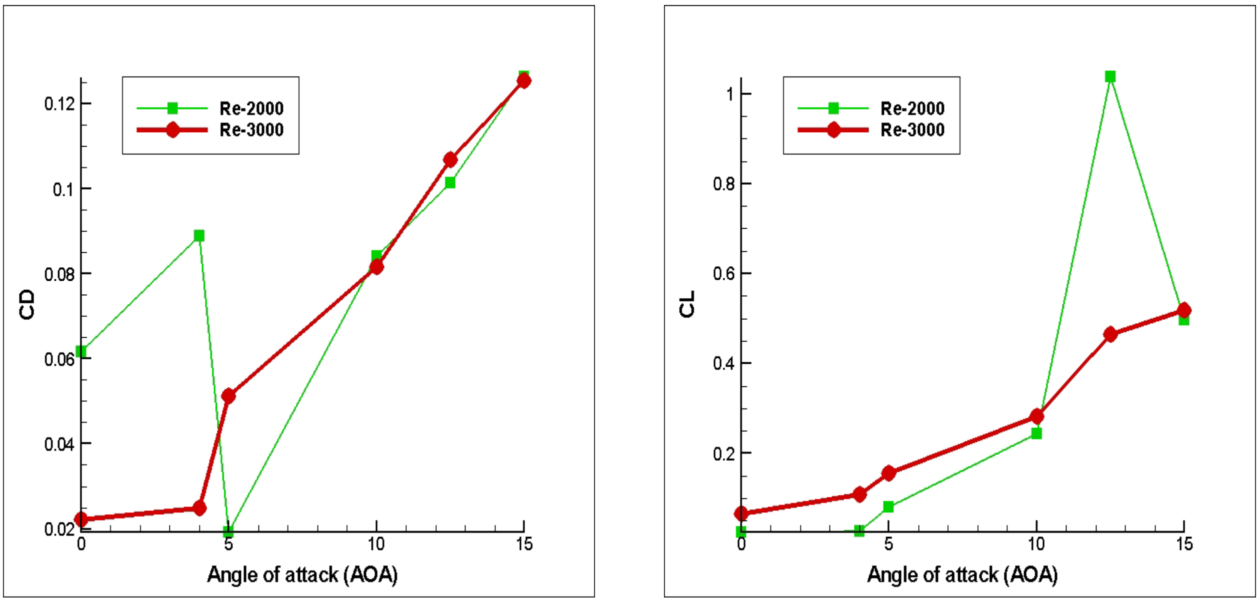
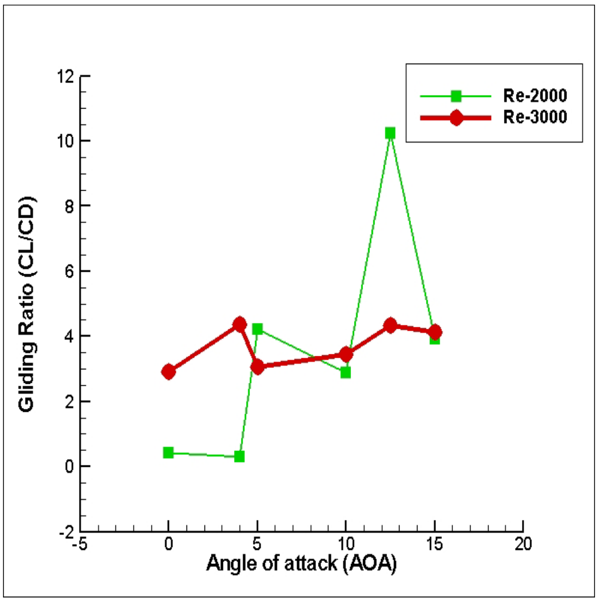
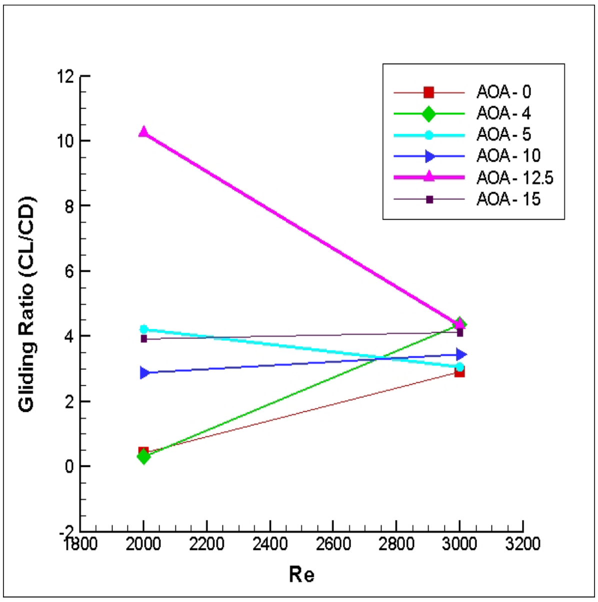


Fig. 5. Variation in C_D and C_L with AOA for Re2000 and Re3000



(a)



(b)

Fig. 6. Variation in Gliding Ratio with (a) AOA for Re2000 and Re3000 (b) Re for different angles of attack

5 CONCLUSIONS

In this work, numerical simulations were performed at Re 2000 and 3000 with different angle of attack ranging from 0^0 to 15^0 and further investigations were made. It was observed that coefficient of lift increase with increase in angle of attack and was maximum at Re2000 with angle of attack12.5^0

Further Gliding Ratio was found maximum at Re2000 with angle of attack 12.5 ^{0}. The simulations demonstrate that pleated airfoil produces higher lift and moderate drag in most of the cases that lead to an aerodynamic performance. These features could possibly be used for MAVs applications.

REFERENCES

[1] Hertel, H., *Structure, Form, Movement,* Reinhold, New York, 1966, pp 78-87.

[2] Newman, D. J. S. and Wootton, R., J., "An Approach to the Mechanics of Pleating in Dragonfly Wings," *Journal of Experimental Biology*, Vol. 125, 1986, pp. 361-372.

[3] Ruppell G 1989 Kinematic analysis of symmetrical flightmaneuvers of odonata*J. Exp. Biol.* 144 13–42

[4] Alexander D E 1984 Unusual phase relationships between theforewing and hindwings in flying dragonflies *J. Exp. Biol.*109379–83

[5] Hankin M A 1921 The soaring flight of dragonflies *Proc. Camb.Phil. Soc.* 20 460–5

[6] Brodsky A K 1994 The aerodynamics of insect flight *The Evolutionof Insect Flight* (NewYork: Oxford University Press)

[7] Wakeling J M and Ellington C P 1997a Dragonfly flight: I. Gliding flight and steady-state aerodynamic forces *J. Exp. Biol.*200 543–56

[8] Rees, C. J. C., "Form and function in corrugated insect wings," *Nature,* Vol. 256, 1975a, pp.200-203

[9] Nachtigall W 1974 *Insects in Flight—A Glimpse Behind the Scenesin Biophysical Research* (London: Allen and Unwin)

[10] Miller P L 1987 *Dragonflies* (New York: Cambridge UniversityPress)

[11] Ennos A R 1989 The effect on the optimal shapes of gliding insectand seeds *J. Zool.* 219 61–9

[12] Ellington C P 1984b The aerodynamics of hovering insect flight: II.Morphological parameter *Phil. Trans. R. Soc.* 305 17–40

[13] Vogel S 1957 Flight in drosophila: III. Aerodynamic characteristicsof fly wing and wing models *J. Exp. Biol.* 46 431–43

[14] Hertel H 1966 *Structure, Form, Movement* (New York: Reinhold)pp 78–87

[15] Newman B G, Savage S B and Schouella D 1977 Model test on awing section of a Aeschna dragonfly *Scale Effects in AnimalLocomotion* ed T J Pedley (London: Academic) pp 445–77

[16] Sudo S and Tsuyuki K 2000 Wing morphology of some insects *JSME Int. J.* C 43 895–900

[17] Wootton R J 1981 Support and deformability in insect wings*J. Zool.* 193 447–68

[18] Rudolph R 1977 Aerodynamic properties of Libellulaquadrimaculata L. (Anisoptera: Libelludidea), and the flow around smooth and corrugated wing section models during gliding flight *Odonatologica*7 49–58

[19] Okamoto M, Yasuda K, Azuma A (1996) Aerodynamic characteristicsof the wings and body of a dragonfly. J ExpBiol 199:281– 294

[20] Kesel AB (2000) Aerodynamic characteristics of dragonfly wingsections compared with technicalaerofoil. J ExpBiol 203:3125– 3135

[21] Buckholz R H 1986 The functional role of wing corrugations in living systems *J. Fluids Eng.* 108 93–7 12

[22] Luo G, Sun M (2005) The effects of corrugation and wing planformon the aerodynamic force production of sweeping model insectwings. ActaMechSinica 21:531–541

[23] Vargas A, Mittal R, Dong H (2008) A computational study of the aerodynamic performance of a dragonfly wing section in gliding flight. BioinspirBiomim 3:026004. doi:10.1088/1748-3182/ 3/2/026004

[24] Kwok R, Mittal R (2005) Experimental investigation of the aerodynamics of a modeled dragonfly wing section. AIAA region I-MA student conference, Charlottesville, Virginia, 8–9 April 2005.