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On the Aerodynamic Performance of Dragonfly Wing Section in Gliding Mode

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Abstract

A comprehensive numerical of fluid dynamic study of a pleated wing section based on the wing of Aeshna Cyanea has been performed at ultra low Reynolds numbers corresponding to the gliding flight of these dragon flies. The simulations employ an unstructured triangular mesh based on finite volume discritization. A critical assessment of the computed results was performed. In this work, we investigate the aerodynamic characteristics and spatio-temporal dynamics of a cut section of Aeshna Cyanea's wing. Numerical simulations were performed at ultra low Reynolds numbers (100 to 1000) at different angle of attacks ranging from 0^o to 15^o. The results give a satisfactory measure of confidence in the fidelity of the simulation. The effect of the Reynolds number on the gliding ratio is that at Re 1000 and at angle of attack (here after, AOA) 15^o. The largest gliding ratios are obtained. Flow invariably for all Reynolds number, minimum Drag coefficient is obtained at AOA 15^o.

Keywords: Gliding flight; pleated airfoil; Aeshna Cyanea; Gliding Airfoil; Ultra Low Reynolds number.

1. Introduction

There are two modes of flight in insects. First and the more dominating mode is the flapping mode while the second mode is the gliding flight. In a dragon fly, both modes are present. The dragon fly, for instance, Pantala Flavescens, can sustain 10-15s at a speed of about 15ms^{-1} (Hankin 1921). *Aeshna* genus dragon fly can glide up to 30s without any significant loss of altitude (Brodsky 1994). Wakeling and Ellington (1997) filmed a smaller dragon flies and found there gliding periods lasting 0.5s, covering a distance of approximately 1m and thus achieving gliding speed of 2.5ms^{-1}. Thus the typical range of Reynolds number in gliding flight can vary from 10^2 to 10^4 as suggested by Wakeling and Ellington (1997). This regime of flow can be thus termed as an ultra low Reynolds number regime.

Dragon flies have corrugated wings where the pleated configuration varies along the span-wise and chord-wise directions (Vargas *et al,* 2008). The rigidity varies throughout the wing and factors which cause this variation are the depth of pleats and rigidity of the longitudinal cross veins (Wotton 1991). Rees (1975a,b), Newman *et. al* (1977) and Rudolph (1977) conducted modelled wind tunnel experiments on modelled dragon fly. They concluded that pleats have no aerodynamic significance. Rudolph (1977) argued that the pleated airfoils have delayed flow separation at higher angle of attack and thus a delayed stall is experienced. Newman *et. al* (1977) concluded that microscopic hair like structures and serration on the leading edge are responsible for enhanced lift. Buckholz (1986) tested a pleated wing model at chord based Reynolds number of 1500 and concluded that pleats help in increasing lift. Wakeling and Ellington (1997) also had same conclusion after filming free gliding dragonflies and conducted their wind tunnel experiments at a Reynolds number range of 700 to 2400. Maximum coefficient of lift was recorded between 0.93 to 1.07. They further concluded that enhanced lift is neither due to Reynolds number or its aspect ratio but to the presence of pleats. Okamato *et al* (1996) conducted experiments for determining aerodynamic characteristics of dragonfly wings and model wings in the Reynolds number range of 11000 to 15000. Their experimental results focused on the effect of thickness, camber, pleats and leading edge sharpness. They concluded that, the thinner the flat plate with camber and sharper the leading edge, the better they performed. Further, they showed that the pleated plate outperformed the flat plate all angle of attacks at these Reynolds number. They also showed that the orientation of the leading edge has a great role in lift generated. They reported that downward facing leading edge has better performance that an upward facing leading edge airfoil. Kesel (2000) 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 a chord Reynolds number of 10 000, and the results showed that the pleated airfoils generated higher lift than the profiled airfoils. However, Okamoto et al (1996), Kesel (2000) revealed that the orientation of the leading edge does not have an effect in enhancing the lift production. As with the early flow visualization experiments, Kesel (2000) noticed trapped vortices present in the folds that serve to change the effective profile of the airfoil. Further, Kesel (2000) concluded that it is the camber found in dragonfly wings that is preserves even though trapped vortices in its folds. Kesel (2000) stated that an increase in lift did not arise due to uniform or randomly spaced corrugations along the chord of an airfoil (Buckholz

1986). Vergas *et al (2008)* also studied the aerodynamic performance of a pleated wing section based on the wing of Aeshna cyanea has been performed at ultra-low Reynolds numbers (5000-10000) corresponding to the gliding flight of these dragonflies in two dimension using computational fluid dynamics. The simulations demonstrate that the pleated airfoil produces comparable and at times higher lift than the profiled airfoil, with a drag comparable to that of its profiled counterpart.

In this work, we investigate the aerodynamic characteristics and 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^o to 15^o. To the best of authors knowledge, the aerodynamic characteristics at such Reynolds number is not studied. These parameter ranges are relevant for both dragonflies and micro-aerial vehicles. Past experimental studies (Buckholz, 1986, Okamoto *et al,* 1996, Kesel, 2006) have found no intrinsic three-dimensional effects at these low Reynolds numbers. Thus, 2D simulations are implemented in this study to encompass a relatively wide range of the parameter space necessary to draw some general conclusions regarding pleated airfoils. The pleated airfoil implemented in the numerical simulation corresponds to a cross-section located at the mid-section of the forewing of a dragonfly (*Aeshna cyanea*). The specific profile chosen for the numerical simulations corresponds to ‘Profile 2’, which was digitally extracted from the paper of Vargas et al (2008) (which is the same as Profile 2 from Kesel (2000)) . From the three pleated geometries to select from the paper of Kesel (2000), ‘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 (Okamoto et al 1996) (Figure 1). 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 2.

2. Governing Equations and Numerical Method

2.1 Governing equations

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:

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

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

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:

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

Using the same flow parameters and geometrical dimensions as Kesel (2000), this allowed for validation and a critical analysis of the numerical results. The key quantities examined are the lift and drag coefficients which are defined as

$C_L = \frac{F_L}{1/2\rho u_\infty^2 c}$, $C_D = \frac{F_D}{1/2\rho u_\infty^2 c}$ and Gliding Ratio $= \frac{C_L}{C_D}$.

(a)Profile (b) Profile (c) Profile

Figure 1: An Illustration of different cut section profiles used by Kessel (2000) and Vargas et al (2008)

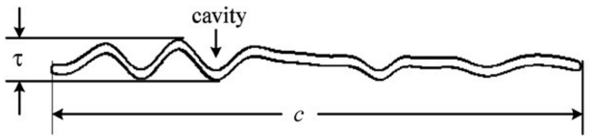

Figure 2: The two-dimensional airfoils used in the numerical simulation. Pleated airfoil representing a cross-section of the forewing of a dragon fly (Aeshna cyanea) having τ /c = 7.531%.

2.2 Numerical Methodology

Ansys Fluent 14.0 is used to solve the above equations. The solver used is based on collocated methodology and finite volume discretization technique is used. the gradients are calculated using Green-Gauss Cell-Based methodology proposed by Holmes and Connel (1989) and Rauch *et al.*(1991). Convection terms in the momentum equation are discretized using the second order upwind methodology given by In the second order upwind, quantities at cell faces are computed using a multidimensional linear reconstruction approach (Barth and Jespersen, 1989).

3. Result and Discussion

Validation study was carried for two profiles, Profile 1 and 2 as shown in figure 2. Simulations were carried out for chord based Reynolds number of Re =10000 and zero angle of attack (here after, AOA). for profile 1. These results are compared with Kesel (2000) which are experimental results. Similar simulations were also performed for Profile 2. The global parameters, C_D, C_L were calculated and were well in agreement with experimental results of Kesel (2000) and Vergas et al (2008). In all twenty simulations were performed to determine the aerodynamic characteristics and 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^o to 15^o. The global parameters are tabulated in table 1 for these simulations. The effect of the Reynolds number on the gliding ratio is shown in figure 3a. As seen in the figure, at Re 1000 and at angle of attack 15^0, the largest gliding ratios are obtained. Figure 3b shows that invariably at all Reynolds number, minimum Drag coefficient is obtained at AOA 15^0. Further it was noted 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^o. But flow always remained steady at AOA 0^o and 5^o for all the Reynolds numbers. The basic step in understanding the aerodynamic performance at a chord Reynolds number of 100, 200, 500 and 1000 was to analyse the flow at zero angle of attack. The mean force coefficients are tabulated in table 1. At zero incidence, 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.

4. Conclusions

In this work, we investigated the aerodynamic characteristics and spatio-temporal dynamics of a cut section of Aeshna Cyanea's wing. Numerical simulations were performed at ultra low Reynolds numbers (100 to 1000) at different angle of attacks ranging from 0^o to 15^o. The results give a satisfactory measure of confidence in the fidelity of the simulation. The effect of the Reynolds number on the gliding ratio is that at Re 1000 and at angle of attack (here after, AOA) 15^o, the largest gliding ratios are obtained. Flow invariably for all Reynolds number, minimum Drag coefficient is obtained at AOA 15^o

Table 1: Aerodynamic performance parameters at different Reynolds number and AOA.

Re	AOA	CD	CL	Gliding Ratio (CL /CD)	Sinking Rate (CL3 /CD2)	Steady (S)/Unsteady (US)
	0	0.399	0.172	0.429	0.031	S
	5	0.3783	0.545	1.440	1.131	S
100	10	0.334	0.797	2.386	4.535	S
	12.5	0.317	0.894	2.820	7.110	S
	15	0.290	0.949	3.268	10.137	S
	0	0.272	0.186	0.684	0.087	S
	5	0.251	0.5	1.988	1.978	S
200	10	0.212	0.726	3.426	8.518	S
	12.5	0.196	0.783	3.996	12.504	S
	15	0.184	0.812	4.425	15.912	S
	0	0.168	0.204	1.217	0.309	S

	5	0.147	0.482	3.275	5.174	S
500	10	0.128	0.627	4.898	15.044	US
	12.5	0.126	0.754	5.957	26.744	US
	15	0.126	0.888	7.070	44.388	US
	0	0.119	0.216	1.814	0.710	S
	5	0.109	0.398	3.651	5.315	S
1000	10	0.107	0.611	5.720	19.988	US
	12.5	0.095	0.935	9.883	91.338	US
	15	0.087	1.048	12.00	151.027	US

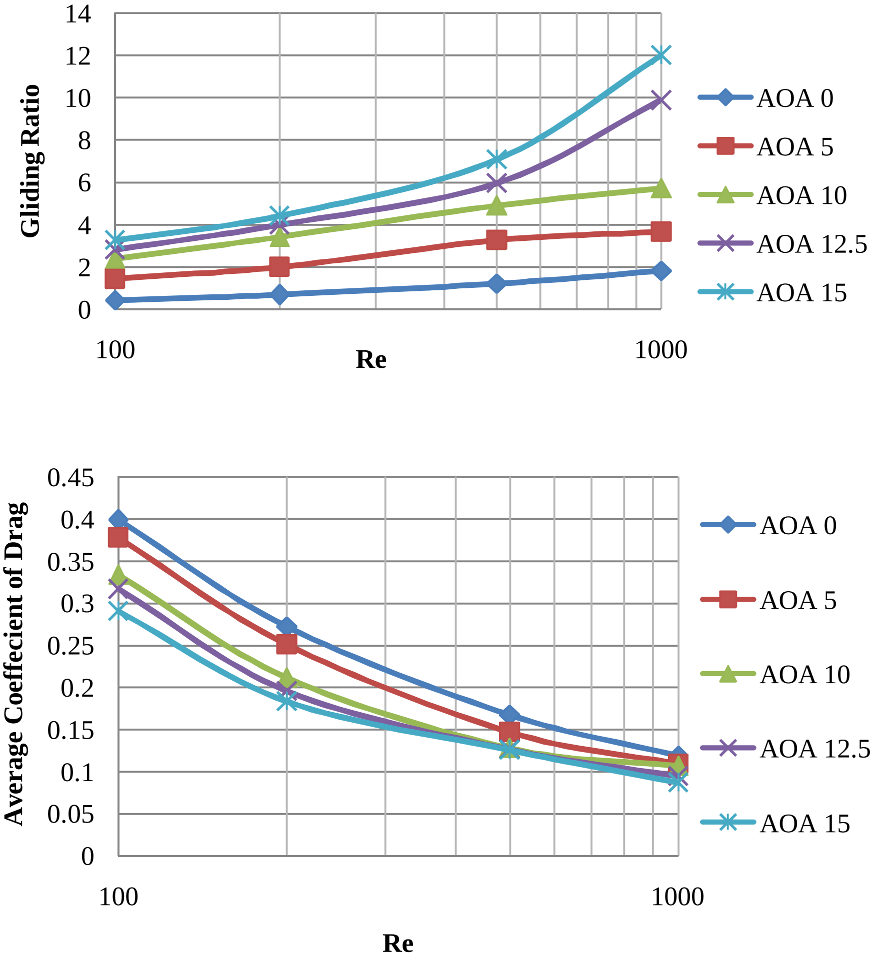

Figure 3: Comparison of (a) Gliding Ratios and (b) Average. Drag Coefficient for different Angle of Attacks (AOA)

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