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***Research paper***

# Performance of a Monarch Butterfly for Various Flapping Angle

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**Abstract**

The butterfly is an insect highly evolved to perform various flight regimes. From gliding flight to manoeuvers involving spontaneous changes in direction, the butterfly is considered a marvel of aerodynamic evolution. Recent demand in the development of micro-aerial vehicles (MAVs) has led scientists to study these creatures in greater depth to get a better understanding of the lift generating mechanisms adopted by them. This study focuses on the evaluation of gliding performance of the Monarch butterfly. A CAD model of a Monarch butterfly wing is modelled using CATIA, taking into account only a single wing of wingspan 53.381 mm which is used to simulate the gliding motion of the butterfly. The gliding performance analysis suggests that a maximum aerodynamic coefficient of 3.597 is achieved for the current wing orientation at 8° AoA.

***Keywords***: *Monarch Butterfly; Gliding; MAV; CFD.*

## 1. Introduction

The need for UAVs (Un-manned Aerial Vehicles) has increased in the last two to three decades. Micro-Aerial Vehicles or MAVs are a class of UAVs characterised by their small size. On understanding what is required from MAVs scientists have focused their attention on smaller creatures for inspiration rather than larger ones to adapt their flight mechanisms. Butterflies in particular serve as suitable subjects to study for designing MAVs due to their dynamic flight regime. There is limited research in the field of MAVs and especially in areas pertaining to biomimicry of butterflies. Butterflies make use of subtle mechanisms like wake capturing, active and inactive upstrokes, clap-and-fling mechanism and leading edge vortex generation to sustain flight [1]. Monarch butterflies are known to travel long distances during their migratory period and serve as suitable subjects to study for designing ornithopter like MAVs. The flight behavior of Monarch butterfly (Danaus plexippus) is characterized by a high flight velocity (Steppan, 2000) [2] and each wingbeat covers a relatively long distance (Sterry & Mackafy, 2004) [3]. Consequently, its aerodynamic investigation would serve as the standard for development of MAV which desire similar performance at low Reynolds number effects.

Butterflies have a flight regime which is a combination of both flapping and gliding. To optimise the aerodynamic efficiency during gliding they orient their forewings and hindwings which helps them glide more efficiently (Sterry & Mackay, 2004) [3]. A study on the aerodynamic evaluation on the wing shape and wing orientation in four butterfly species [4] explains the importance of the orientation of the forewing relative to the hindwing on the gliding performance of the butterfly. To do so, four butterfly species were considered; Monarch, Glasswing, Four-Barred Swordtail and Orange Plane. By modelling different shapes of the wings, ranging from those that maximise span to those that spread the forewings forward, and testing them in a low-speed wind tunnel for different angles of attack, the lift coefficient was calculated. On plotting the values of the lift coefficient for each wing and its different orientations against the varied angles of attack it was concluded that the wing configurations that maximised span had the maximum aerodynamic efficiency (lift-to-drag ratio) implying that the gliding performance was best for such configurations. Also, configurations in which the forewings are oriented towards the front result in an increase in effective chord of the wing, generating more lift. CFD simulations were carried out with the same conditions and similar results as the experiments were obtained.

In yet another study on the importance of body rotation during the flight of a butterfly [1], the formation of the vortices in the wake region was observed and the force generation associated with them was explained. The body of the butterfly is observed to oscillate periodically while it is in flight. The results of the above study also revealed that the initial body angle and the amplitude of the body rotation play an important role for the flight modes of the butterfly. Along with the wings flapping about the longitudinal axis of the body the stroke plane also rotates.

The study conducted by Phan HV et al. [5] explains the significance on the clap-and-fling mechanism adopted by winged insects to overcome the increased drag experienced while flapping their wings. A proper understanding of the flapping mechanism with the different stages in a flapping cycle is provided in AK Brodsky's study on vortex formation in the tethered flight of the Peacock butterfly [6]. R.B. Srygley et al. [7] carried out wind tunnel experiments to provide experimental visual proof of the vortex formation and few other salient mechanisms.

The current study involves evaluating the gliding performance, i.e., calculating the aerodynamic efficiency at different angles of attack and determining the AoA best suited for gliding for the monarch butterfly wing orientation.

## 2. Methodology

### 2.1. Modelling the Wing

A detailed study on the flow regime around a dragonfly wing [8] was carried out in which it was found that the main body of the dragonfly has negligible effect on the flow pattern over the wing. The body rotation of a butterfly does play an important role in its flight but for simple gliding and single DOF flapping the findings from the dragonfly wing analysis can be applied to this case. A research carried out by Martin Thompson on the evolution and functioning of a wing-pattern mimicry supergene in the African butterfly Papilio Dardanus reveals that butterflies are genetically hard-wired to have symmetric wings, barring a few exceptions [16]. Hence taking into account the above two findings it was decided to model only one wing instead of both and that too without the central body. First a top view image of the Monarch butterfly was imported into Sketch Tracer which is shown in Fig. 1. Only one half of the wing was developed in this work due to its symmetry by following the external contour of their respective models (Sterry & Mackay, 2004) [3] as shown in Fig 2. The wingspan of a single wing measured 53.349 mm and the root chord length was 15.779 mm. The thickness of the wing was assumed to be 0.15 mm which was similar to the work of Ortega-Ancel et al [4]. Projecting this scaled down image onto two planes that were symmetrically offset on either side of the original plane and using volume multi-section gave a solid wing of constant thickness 0.15 mm. Total surface area of the wing was 4036 $mm^2$. The dimensions of the model are provided in Table 1.

**Fig. 1:** Top view image used for tracing the wing

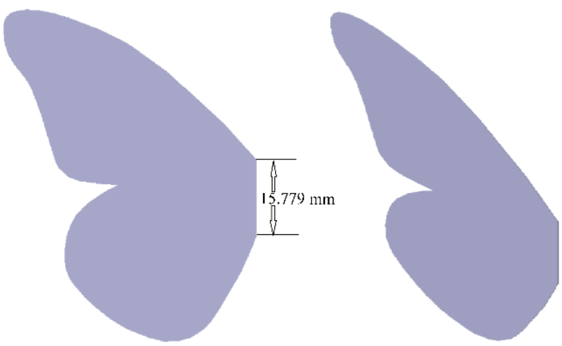



**Fig2:** Symmetric half of the wing model; measurements in 'mm'

**Table 1:** Dimensions of the modelled wing

| Parameter | Value |
|---|---|
| Wingspan (mm) | 53.381 |
| Root chord (mm) | 15.779 |
| Total wing length (mm) | 68.87 |
| Wing thickness (mm) | 0.15 |
| Surface area ($mm^2$) | 4036 |

### 2.2. Meshing

A cuboidal domain was chosen with dimensions 1700 x 1200 x 800 mm and the wing was placed inside it as shown in Fig 3. ANSYS Meshing was used to mesh the domain. In order to keep the number of elements as low as possible without compromising the accuracy of the result a second domain was created enclosing the wing with a smaller element size criteria. Furthermore face sizing was given to all the faces of the wing to enable the flow and flow parameters around the wing to be well defined and calculated. The overall fluid domain was meshed using tetrahedral elements to give a total of 2 million volume cells for the course mesh case. This was subsequently increased with a growth rate of 1.5, so that the grid points were clustered around the wing, and gradually increased in size towards the far-field to obtain the optimal case of 5.8 million elements using the grid dependency study. The near-field fluid domain was 4 chord lengths away from the wing root, and meshed such that the grid was denser near the tips and edges of the wing, and coarser towards the far-field.

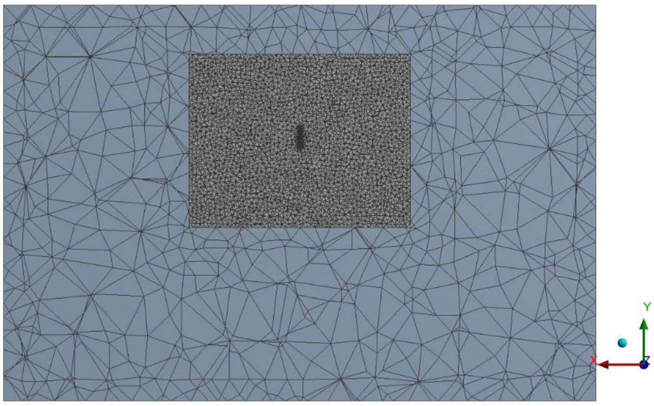



**Fig. 3:** Meshing of the cuboidal domains; the inner domain has finer meshing than the outer one. Close to the wing the mesh is highly detailed.

### 2.3. Simulation Setup

ANSYS Fluent was used to carry out the simulation. The wing longitudinal axis is oriented along the z-axis with the leading edge in the positive z direction and the trailing edge in the negative z direction with respect to the origin. The aim of the steady analysis was to evaluate the gliding performance at different angles of attack. To change the angle of attack the wing was rotated about the y-axis. The Spallart-Almaras turbulent model was chosen for solving the simulation due to its simplicity. The S-A model has proved to be effective in studies involving airfoils [9-12]. It is a simple one equation model designed for applications involving wall-bounded flows. It also shows good results for boundary layers subjected to adverse pressure gradients. An inlet velocity of 2 m/s in the negative z direction was chosen to examine the flow regime around the wing at a slightly lower velocity than normal and outlet of the domain was maintained at atmospheric pressure. The assumption of taking the inlet velocity as 2 $m.s^{-1}$ is based on the study carried out by Ortega et al. [4] who also assumed the same condition. In general, the Monarch butterfly moves in the velocity range of 0.38 $m.s^{-1}$ to 2.36 $m.s^{-1}$ according to the study conducted by Davis AK et al. [13].J.M. Wakeling [14] has characterized the velocity for different insect species such as butterflies and dragon flies operating at velocities less than 2 m/s. The convergence criteria for the simulation was set to 0.0001 for all cases. The faces of the domain surrounding the wing and perpendicular to the x- and y-axis were defined as far field. The face perpendicular to z-axis and in the positive z direction was defined as inlet and the face opposite to it was the outlet. The wing was defined as a rigid wall and the simulation was carried out for different angles of attack of the wing. A no-slip wall conditions was

applied on the wing surface. For the solution method, the pressure-velocity coupling was accomplished via the SIMPLE algorithm with the second-order upwind spatial discretization.
The governing equations for CFD are the continuity equation and the Navier-Stokes equation. The flow is considered to be 3D, incompressible, and steady. In Equ. (1), U, ρ, P, and μ are the mean velocity vector of flow, density, pressure, and the coefficient of viscosity, respectively.

$$\begin{cases} \nabla . U = 0 \\ (\frac{\partial U}{\partial t}) + (U.\nabla)U = -\frac{1}{\rho}\nabla P + \frac{\mu}{\rho}\nabla^2 U \end{cases} \tag{1}$$

The angles of attack that the wing were simulated at were 0°, 4°, 6°, 8° and 10° as shown in Fig. 4. The wing was rotated about the z axis. The solid line represents the wing at 0° AoA and the dotted lines represent the wing rotated at 4°, 6°, 8° and 10° respectively with respect to the z axis.

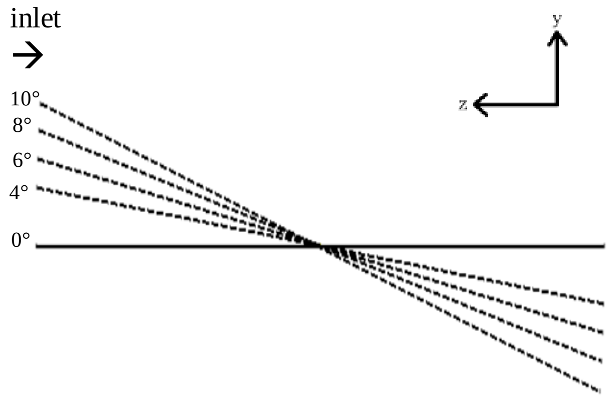



**Fig. 4:** Left side view of wing oriented at different AoA; solid line represents wing at 0°, dotted lines represent the wing at 4°, 6°, 8° & 10° respectively

## 3. Results and Discussion

The wing configurations corresponding to different angles of attack were simulated at a speed of 2 $m.s^{-1}$. The angles of attack that the wing were simulated at were 0°, 4°, 6°, 8° and 10°. Gliding performance or aerodynamic efficiency of the wing is defined as the lift to drag ratio. The aerodynamic efficiency was estimated according to the relationship below

$$aerodynamic\ efficiency = \left(\frac{L}{D}\right) = \left(\frac{C_L}{C_D}\right) \tag{2}$$

In equation (1), $C_L$ is the lift coefficient and $C_D$ is the drag coefficient. Higher the value of the ratio given in equation (1) better is the gliding performance. A comparison of this ratio for different angles of attack is carried out. Fig. 5 shows that the trend for L/D ratio from the present work closely matches with the literature [4]. The maximum performance is obtained at 8° AoA and the value of the aerodynamic coefficient measured was 3.597. Beyond 8° the butterfly wing shows decreasing performance indicating stall which was similar to the findings in the literature. It can be inferred from this study that, the monarch butterfly has the best performance at 8° AoA and hence it submits to this AoA during gliding.
The comparison of AoA between the present study and study by Ortega-Ancel et al is presented in Table 2. The minor difference in the results from the previous study can be attributed to changes in the geometry obtained owing to different butterflies considered. Consequently, the L/D ratio also would be marginally different. However, both the analysis follow the similar trend and the maximum possible L/D ratio for the monarch butterfly is obtained at 8° AoA.

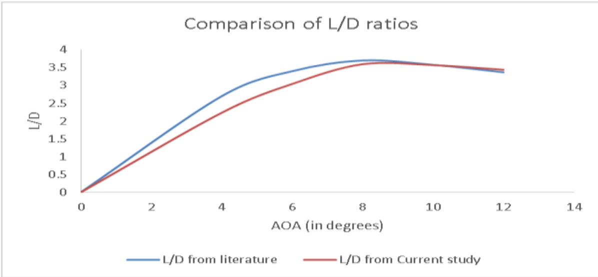
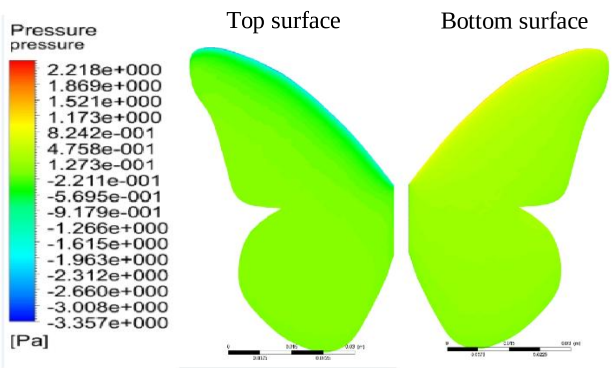



**Fig. 5:** Comparison of L/D ratio with literature [4]

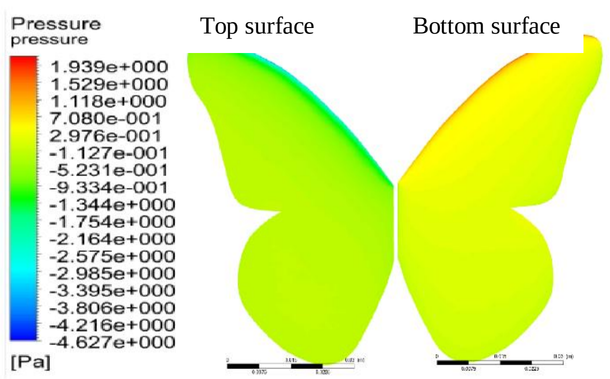
**Table 2:** L/D ratio at different AoA

| AoA | L/D from literature | L/D from Current study | % difference |
|---|---|---|---|
| 0 | 0.0045 | 0.0035 | 28.0 |
| 4 | 2.70 | 2.234 | 17.25 |
| 6 | 3.40 | 3.042 | 10.52 |
| 8 | 3.70 | 3.597 | 2.72 |
| 10 | 3.58 | 3.571 | 0.25 |
| 12 | 3.37 | 3.441 | 1.86 |

The pressure contour plots from Fig. 6 show the pressure gradients that develop on the top (left) and bottom (right) surfaces of the wing. In all cases a higher pressure is created at the bottom surface of the wing as compared to the top surface which results in an upward force being generated. This helps in producing the lift required to glide. It also can be observed that, as the AoA increases the pressure at the leading edge of the bottom surface of the wing also increases. This drastic increase in pressure gradient at the leading edge helps the butterfly produce necessary thrust for gliding. Takahashi et al. measured the pressure using a micro strain sensor using microelectronic mechanical systems (MEMS) and showed the differential pressure on the fore wings was dominant over the pressure on the hind wings [15].




(a)

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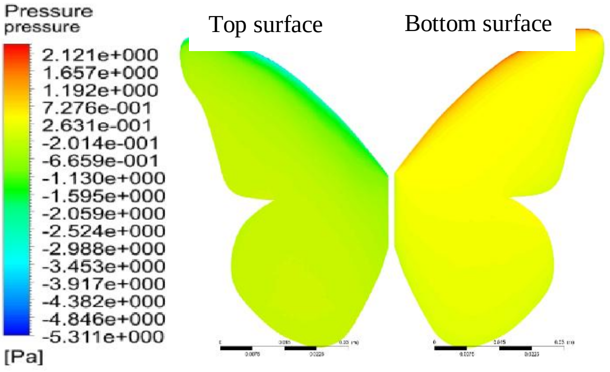
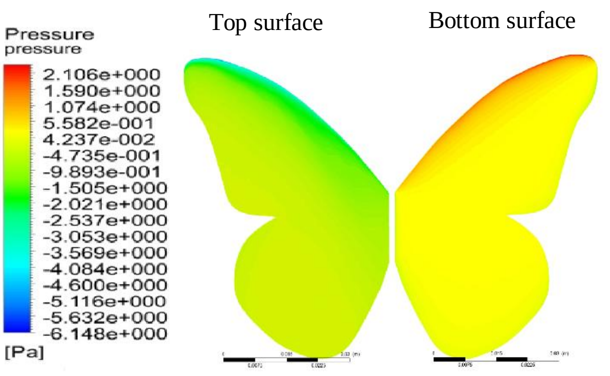


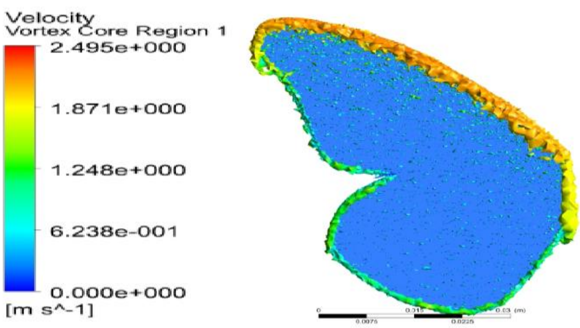

(c)



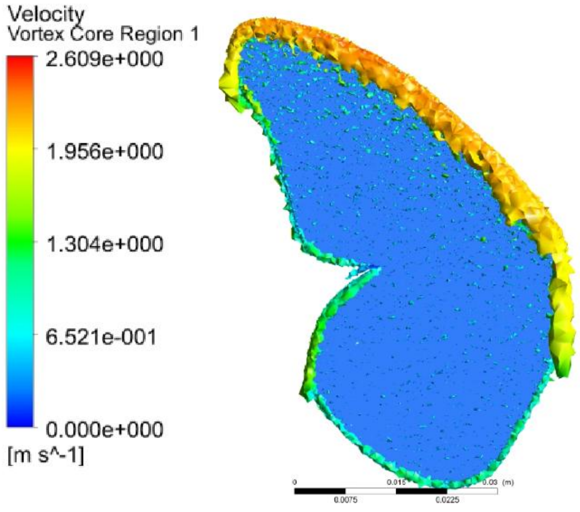

(d)

**Fig. 6:** Pressure contour for different AoA (a) 4°**,** (b) 6°, (c) 8°, (d) 10°

Fig. 7 provides vortex tube formation along the leading edge of the butterfly wing. These vortex core region plots are represented with velocity magnitude for 4°, 6°, 8° and 10° AoA. It is observed that as the AoA increases from 4° to 10° the intensity of vortex tube at the leading edge increases. A large number of small vortices are formed at the leading edge in all four cases. However, the 10° AoA has a bigger blanket of vortices covering a larger area in the wing top surface. It can also be seen that close to the root of the wing the flow is less turbulent compared to ¾ span from root. The region between ¼ and ¾ wingspan experiences the maximum turbulent flow. The vortices detach from the wing tip of the leading edge in case of flapping. It is these vortices that augment lift generation. This is evident from the study carried out by Ortega et al. [4]. It can be seen in the results obtained in their work that at the optimum gliding wing orientation, much larger vortices are formed both in size and in magnitude. At the junction of the forewing and hindwing a very low intensity turbulent flow was present. In the current study, the 10° AoA showcased the formation of smaller vortex patches predominantly on all the edges of the wings. This was not the case for other angle of attacks. This may explain flow separation and deterioration of performance due to the countering of lift generating vortex formed at leading edge at 10° AoA.




(a)

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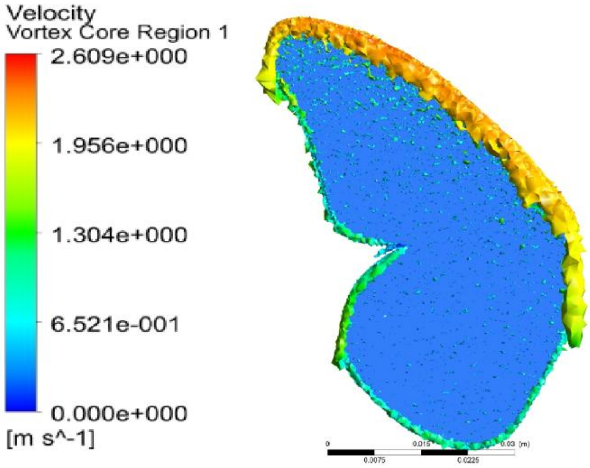
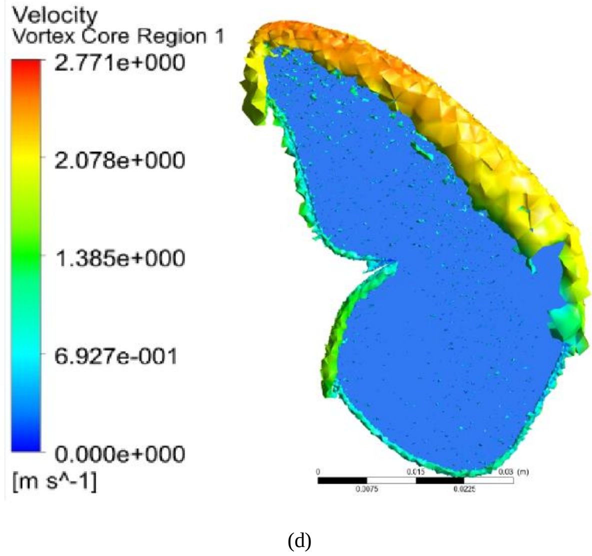



(c)




(d)

**Fig. 7:** Vortex tube formation on the leading edges: (a) 4°, (b) 6°, (c) 8°, (d) 10°

## 3. Conclusion

The butterfly makes use of different wing orientations in accordance with the flight regime it is following. For the given wing orientation which is mainly used for flapping flight, the gliding efficiency is calculated at angles of attack of 0°, 4°, 6°, 10° and 12°. It can be inferred from this study that the maximum (L/D) ratio or gliding performance is obtained for an AoA of 8°. Further increase in AoA leads to stall condition and a decrease in L/D ratio value. The increase in pressure gradient at the leading edge helps the butterfly produces necessary thrust for gliding.

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