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Three-Dimensional Computational Fluid Flow Analysis of Bio-inspired Corrugated wing at Low Reynolds Number

Cover Page Footnote

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Three-Dimensional Computational Fluid Flow Analysis of Bio-inspired Corrugated wing at Low Reynolds Number

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Abstract—A computational study was performed to analyze the airflow over bio-inspired corrugated wings. The bio-inspired corrugated wing profiles were derived from the mid-span section of the forewing of *Aeshna Cyanea* dragonfly species. Additionally, a hybrid non-corrugated profile was also created possessing geometric similarities with the corrugated airfoils to compare and visualize the effects of corrugation on the fluid flow. The computational analysis was conducted for 4, 8-, and 12-degrees angles of attack. Streamlines obtained from the computational analysis results (carried out on ANSYS CFX) showed the formation of secondary flows or vortices that are trapped in the valleys of the corrugated wings which was not observed in the hybrid airfoil. This study also compares the effects of corrugation geometry on fluid flow behavior. It was also seen that the intensity and quantity of the secondary flows increased with the increase in the angle of attack.

Keywords—*Bio-inspired; Aeshna Cyanea; Dragonfly wing; corrugated; non-corrugated; streamlines; secondary flows; vortices*

1 INTRODUCTION

Nature has been an excellent source of inspiration for human beings to develop new kinds of technology. This is because various living species in nature have evolved for

millions of years to adapt to the living conditions and exist in the most efficient manner possible. Nature has been especially influential when it comes to flight as birds and various other insects have developed a distinct set of wings and have become agile fliers by developing many biomechanical processes that enable efficient flight. Due to these factors, researchers are trying to study and understand the physics behind the flight of birds and insects, which mainly involve a flapping process to produce lift and thrust, so that they can derive means to improve current technology and make aircraft more efficient at various speeds while also exploring and understanding flapping wing aerodynamics in a better manner. This field of research can prepare us for better and more efficient design for low-speed applications and future applications in micro aerial vehicles (MAVs) (Murphy & Hu, 2010; Tsuzuki N, 2005).

The fact that dragonflies are one of the most efficient and agile flying insects at low Reynolds number flying conditions was discovered and understood during the 1970s and 1990s. Since then, a lot of research has been conducted which shows that dragonflies have superior maneuverability. They also possess a very effective hovering capability that is facilitated because of their unique wing structure and flapping mechanism. Their unique flapping mechanism also provides great bending resistance to the wing while flapping. Subsequent studies revealed

that dragonfly wings consist of corrugations or peak-valley patterns which resulted in better aerodynamic efficiency (L/D ratio) and also was nearly insensitive to Reynolds number variation. Further research showed that corrugated wings are superior compared to existing conventional airfoils at a low Reynolds number flow regime. These characteristics of the dragonflies and their wings gathered the attention of researchers to study the reasons and possibly implement some of these concepts in man-made aircraft to make them more aerodynamically efficient at low-speed flight.

Later, numerical and computational studies suggested that secondary flows or vortices are formed in the valleys of the corrugation. (Obata & Sinohara, 2009) These vortices which are unsteady further reduce the pressure on the upper surface of the wing thereby producing more lift and also facilitating the transition of the laminar boundary layer to the turbulent boundary layer. This causes the flow to reattach to the upper surface delaying the boundary layer separation thereby delaying the stall of the wing (Dwivedi & Sudhir Sastry, 2019).

A vast majority of the existing studies compare the result between the bio-inspired corrugated wings and flat plates or symmetrical airfoils (Tamai et al., 2007). However, a flat plate does not provide much insight into understanding the true difference that corrugations cause on an airfoil, as the flat plate has less thickness and no camber. In this study, we have considered two corrugated airfoil geometries from the mid-span section of the forewing of *Aeshna Cyanea* dragonfly obtained through the works of (Kesel, 2000) and (Vargas et al., 2008) with slight modifications made to achieve the same maximum thickness for the airfoils. Additionally, a hybrid non-corrugated airfoil was then generated by filling the corrugations and closing the peaks

of the airfoil obtained from the works of (Vargas et al., 2008), and this airfoil was then compared with the two corrugated airfoils. The main objective of this study is to analyze and understand the effects of corrugation on the fluid flow at a low Reynolds number region using computational fluid dynamics. The computational work was carried out using ANSYS CFX software at 4, 8-, and 12-degree angles of attack. A 15m/s inlet velocity was given which results in a Reynolds number of 80,000 which falls in the low-Re flow regime. The flow over the different wings was obtained through the computational analysis results using the CFD Post tool.

2 MATERIALS AND METHODS

2.1 Geometry:

The work done by (Kesel, 2000) on determining the geometry of corrugated airfoils by studying the forewing of *Aeshna Cyanea* species of dragonfly served as the inspiration for this study. The first corrugated profile of this study was thus derived from the mid-span section of the forewing of the said dragonfly species and was subsequently named as triangular peak corrugated airfoil. Another version of the corrugated airfoil based on the same forewing of the dragonfly was obtained by (Vargas et al., 2008) which was also considered in this study as the second corrugated. However, the airfoil was altered to match the maximum thickness of the triangular peak airfoil, and the highest peak was shifted to 39.08% of chord length and was hence named as modified simple corrugated airfoil for this study. A third, non – corrugated airfoil was then generated by joining the peaks of the modified simple corrugated airfoil, thereby making it a hybrid airfoil which was named hybrid airfoil. All the airfoils possess similar geometric characteristics like having the same maximum thickness (10.52 millimeters), and same chord length (80 millimeters). 3D wing

CAD models were then generated for the three airfoils taken into consideration using CATIA V5 software. The wings have a span of 400 millimeters resulting in an aspect ratio of 5 (Fig.1).

Fig. 1: 3D CAD models of (a) Triangular peak corrugated airfoil, (b) Modified simple corrugated airfoil, and (c) Hybrid airfoil.

2.2 Numerical Settings

2.2.1 Computational domain

To perform computational analysis, a cuboidal domain was constructed around the wings. It was constructed such that the domain walls were one chord length distance (80mm) apart from the leading edge, six times chord length distance (480mm) behind the trailing edge, and one chord length (80mm) distance above and below the wing.

2.2.2 Mesh generation

The meshing or discretization of the 3D domain for this study was accomplished by using the ICEM CFD software. The required mesh size around the wing to capture boundary layer effects and increase the accuracy of the calculation, wall spacing (Equation 1) was computed by using the wall y^+ function with desired y^+ value of 11 as the flow is low-Re. The density of air was assumed to be 1.225 kg/cm^3 , and the coefficient of viscosity of air was assumed to be $1.7894 \times 10^{-5} \text{ kg/m s}$ in the calculation of the wall spacing.

$$\Delta s = \frac{y^+ \mu}{U_{fric} \rho} \quad (1)$$

Fig. 2: Mesh

Block mesh was introduced for achieving more accurate mesh. The wall spacing was calculated to be 0.5 mm, so a fine mesh of 0.5mm element size was employed near the wing and some extent from the trailing edge for capturing the turbulence as well the boundary layer separation. The mesh thus generated (Fig.2) was a high-quality mesh which is evident by the parameters of quality (like skewness and orthogonality) which is ranging from 0.623 to 1, and an Aspect ratio of 51.8 with a minimum angle of 38.6 (Fig.3).

Fig. 3: Mesh Quality

2.2.3 Solver settings

ANSYS CFX solver was used to conduct the CFD simulation and analysis for the wing. This CFX solver is based on the finite volume method. The Reynolds number for this study is approximately 80,000, which is in the laminar region and hence the flow was

considered to be laminar. As, we are interested in the pressure distribution and velocity profile, so the energy equation is constant for this model of simulation. Since the flow is incompressible, the reference pressure is terminated to zero and the material is air at room temperature. The Viscous model which is worn by K-epsilon (2-equations) with standard K-epsilon and standard wall function is been used. Boundary conditions were symmetry to the wing and walls for the domain except (inlet as well outlet).

3 RESULTS AND DISCUSSIONS

The streamlines were obtained for the two corrugated wings and the hybrid non-corrugated wing in both front view (facing leading edge) and back view (facing the trailing edge) at 4-, 8-, and 12-degree angles of attack.

Fig. 4: Flow over Triangular Peak Corrugated wing

The streamlines of flow over triangular peak corrugated wing (Fig.4) show the formation of vortices in a spanwise direction. It is also observed that the intensity of the vortices increases as the angle of attack increases. At 4 degrees AOA the vortices were mainly observed to be trapped inside the valleys of corrugation, but at 8 AOA degrees the vortices escape the valleys and get intense, and at 12 degrees the vortices are too strong to stay contained in the valleys of corrugation and engulf the entire wing section aft of the second peak showing that there is an onset of flow separation at 12 degrees angle of attack

and the wing is nearing its stall angle. From the back view, the wingtip vortices are observed to form which is a rotation of flow as the flows from the upper surface and lower surface mix. The wingtip vortices also increase in intensity as the angle of attack increases.

Fig. 5: Flow over Modified Simple Corrugated wing

The streamlines of flow over Modified simple corrugated wing (Fig.5) also show the formation of vortices in the spanwise direction which is a similar behavior shown by the triangular peak corrugated wing. It is also observed that the intensity of the trapped vortices increases as the angle of attack increases. Formation of wingtip vortices is also observed in the wing as the air from the lower surface, having high pressure tries to mix with air from the upper surface having low pressure. However, it is clear from the streamlines that the size and intensity of the wingtip vortices increase with an increased angle of attack. Another thing to note here is that at 4- and 8-degree angles of attack the spanwise vortices due to corrugations are majorly trapped in the valley sections of the wing, but at 12 degrees angle of attack, the vortices escape from the valleys and envelop

the entire wing section aft of the second peak.

Fig. 6: Flow over Hybrid wing

The hybrid wing streamlines (Fig.6) do not show any spanwise vortex formation which was observed in both the corrugated wings. At 4 degrees AOA, the flow is attached to the wing and there are no signs of flow separation or turbulent flow. The same case is observed at 8 degrees AOA, however, there is a small low-velocity region near the trailing edge section which indicates the onset of flow separation. At 12 degrees AOA, it is evident that flow separation has occurred and a turbulent flow is observed. This turbulence also extends in the span-wise direction which is visible in Fig 6 in both front view and back view. It is also observed that the variation of the angle of attack had an insignificant effect on the intensity of the wingtip vortices formed.

Fig. 7: Comparison between the three wings at 8 degrees AOA

Comparing the three chosen wings, we could notice a distinct difference in the flow at 8 degrees angle of attack. The flow was compared at three different locations from

mid-span at 10%, 60% and, 90% of semi-span from the root of the wing. It can be seen that the corrugated wings showed trapped vortices in the valleys which is absent in non-corrugated wings. Among the two corrugated wings, the modified simple corrugated wing showed a delayed onset of a stall than the triangular peak corrugated wing, because the vortices trapped in the valleys of the triangular peak wing escapes at a lower angle of attack than the modified simple corrugated wing. Also, the wingtip vortices were sensitive to the angle of attack in the case of corrugated wings whereas the hybrid non-corrugated wing showed insignificant change with change in angle of attack.

4 CONCLUSION

In this study, two corrugated wing profiles inspired from the forewing, mid-span section of *Aeshna Cyanea* dragonfly were modeled and simulated at Reynolds number 80000. The bio-inspired corrugated wings were compared with the non-corrugated hybrid wing profile generated by joining the peaks of one of the two corrugated profiles, in which chord, maximum thickness is the same to study the effects of the corrugation upon the fluid flow behavior. A modification was done to one corrugated airfoil where its highest peak was shifted to 39.08% of the chord aft of the leading edge. In this, the forward flight is considered at three different angles of attack that include 4-, 8-, and 12-degree angles of attack. The results gave rise to the following major conclusions:

- The corrugated wings produced span-wise vortices that are trapped in the valleys of the corrugation. This kind of flow behavior is not observed in the hybrid non-corrugated wing.
- The corrugated wings produced wingtip vortices which increase in size and intensity with the increase in the angle of attack. However, the wingtip vortices produced by the

hybrid non-corrugated wing showed negligible variation in size and intensity with a change in angle of attack.

- Out of the two considered corrugated wing geometries, the modified simple corrugated wing showed a later onset of the stall and flow separation compared to the triangular peak corrugated wing. However, the non-corrugated wing showed an early flow separation compared to both the corrugated wings.

Therefore, the computational analysis of airflow over two corrugated wings was conducted, and based on the results it can be said that the modified simple corrugated wing showed a better flow characteristic among the three wing geometries that were considered.

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