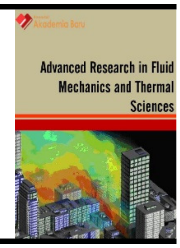
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 51, Issue 1 (2018) 31-41

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html

ISSN: 2289-7879



Aerodynamic Analysis of a Dragonfly

Open Access

Shiva Prasad Uppu[1,*], Dindigala Manisha[1], Gudey Dharani Devi[1], Pranav Chengalwa[1], Boppana Vaishnavi Devi[1]

[1] Department of Aeronautical Engineering, Institute of Aeronautical Engineering, JNT University Hyderabad, 500043, India

ARTICLE INFO

Article history:
Received 21 June 2018
Received in revised form 20 October 2018
Accepted 28 October 2018
Available online 6 November 2018

Keywords:
Bio-inspired airfoil, Corrugated cross-section, Dragonfly airfoil, Low Reynolds number

ABSTRACT

The aim of this work is to determine the Aerodynamic properties of the corrugated dragonfly airfoil in comparison to the traditional smooth NACA 2.5411 airfoil. A simplified dragonfly airfoil is analysed in the current work, at low speeds. A 3D printed model is tested using Six Component strain gauge and the results are compared with NACA 25411 airfoil. Aerodynamic performance is evaluated at low Reynolds number to associate the results with the regular section. In order to streamline the results both experimental and numerical work is carried over the model at different wind speeds and wind angles. Data obtained provides a valuable insight to the physics of the model which showed a completely nonlinear behaviour resulting in positive aerodynamic forces.

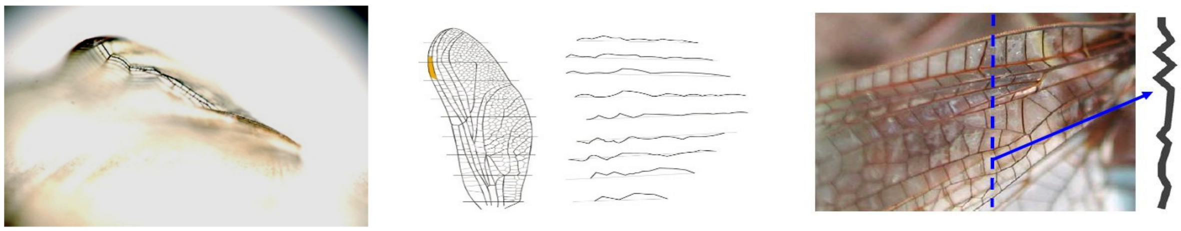
1. Introduction

The basic idea of flying and its evolution is an inspiration from the natural fliers i.e. birds and insects. After decades of studies and advancements in technology, we have successfully developed the aircraft and other aerial vehicles for various civil purposes like transportation, communication and military purposes like surveillance, targeting, bio-sensing etc. [5,14]. Yet today, it is still not possible for the technology to exactly imitate the flying techniques of birds and insects which mostly fly in low Reynolds number regimes [2,23]. This area of aeronautics, which is focused on bio-inspired models, is still in its infancy.

Of all the natural fliers, dragonfly stands out for its peculiarity in wing structure and flying [24]. While most of the birds and insects have only a pair of wings, the dragonfly has two sets of wings i.e. forewings and hind wings. These powerful and agile fliers flap their forewings 180º out of phase with their hind wings. Dragonflies can act in different ways during their flight, mostly it would be classical type, supercritical lift, and high angle lift vortex lift [4]. The cross section of its wing is unusual and it is expected to be the reason behind the peculiarity in dragonfly's flight. Unlike other bio-inspired

[*] *Corresponding author.*
E-mail address: shivaprasad047@gmail.com (Shiva Prasad Uppu)

wing cross-sections which are simple and smooth cambered surfaces, dragonfly wing's cross-section is found to be a corrugated surface. Many studies are being conducted to learn the advantages; the corrugated cross-section has to offer. Dragon fly could delay the stall and large flow separations at higher angle of attack up to 12.5 deg when compared with regular GA-1(W) airfoil and with flat plate as measured with PIV [7,3]. A study conducted on spanwise cross-sections at different locations of a dragonfly wing, where the geometry of cross-sections varies for each location [7].



(a) (b) (c)

Fig. 1. (a) Corrugated Dragonfly Airfoil [19,20] and its (b) structure at various spanwise locations [19,20] (c) Cross-section at the mid-section of the fore wing [17]

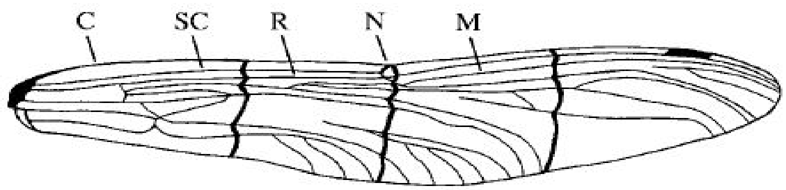


Fig. 2. Cross-sections of Dragonfly Airfoil [3]

The dragonfly cross section produced high lift at low Re flight regime during gliding [8]. This was found to be due to an increase in negative lift on the upper surface of the wing because of the corrugated cross-section. This shows that geometrical location of valleys, the bends as shown in Figure 2 and the asymmetric nature of the airfoil along the chord length also plays an important role for negative lift generation [14,16]. This work is focused on the experimental analysis of dragonfly airfoil cross-section forewing of a dragonfly at the mid chord at section N as narrated in Figure 2 at low Reynolds number is tested. The bio-inspired airfoil can be incorporated in Micro Air Vehicles which usually fly in the same Re as that of a dragonfly.

2. Methodology

2.1 Numerical Analysis

2.1.1 Introduction

Numerical analysis is a technique that uses mathematical formulations to determine and analyze the solutions of various fluid flow problems[26]. Though it has the advantages like no requirement for a physical setup, there are also limitations like understanding, mathematical modeling and availability of computational power. Also, the results obtained by using this technique may not be exact, but approximate solutions.

Computational Fluid Dynamics is one of the applications of the numerical techniques where the flow conditions are simulated and analyzed using supercomputers, which are advanced than manual operations, accurate and fast[25][26]. The Navier-Stokes equations are the basis of CFD problems, from which various other equations like Euler equations, full potential equations and linearized potential equations are derived according to the flow model defined in the problem [10,18]. These CFD results can be validated either by a Wind-Tunnel Test or a full-scale flight test.

In this work a numerical tool is used, to perform a 2-D numerical analysis over NACA 2.5411 airfoil and Dragonfly airfoil at different angle of attacks for a range of velocities. The numerical analysis procedure consists of following steps.

2.1.2 Geometry

The 2-D geometries for NACA 2.5411 airfoil and Dragonfly airfoil are created using the Design Modeler and Space-claim design modules respectively. For the NACA 2.5411 airfoil, the coordinates are directly imported to Design Modeler, which are obtained from mathematical formulations using MATLAB. The Dragonfly airfoil geometry is taken from [23]. A comparatively large rectangular boundary is drawn in Figure 3 and 4 around the airfoils to imitate the wind-tunnel test section conditions, so as to compare them.

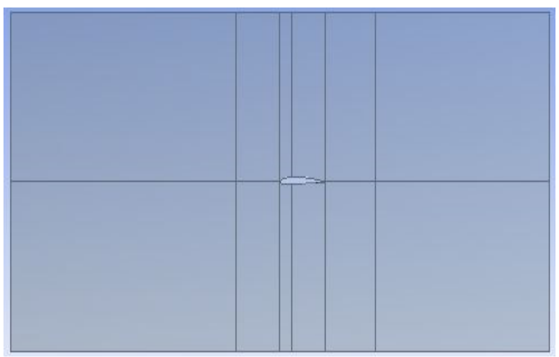


Fig. 3. Geometry of NACA 2.5411 Airfoil

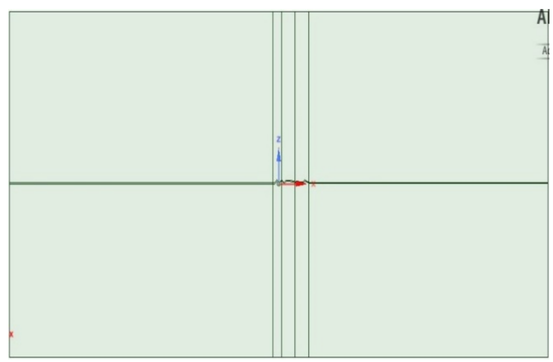


Fig. 4. Geometry of Dragonfly Airfoil

2.1.3 Mesh

An intelligent mesh tool is utilized in current study, which generates the best possible accurate and efficient mesh for the given geometry in a single click. It provides full control over the mesh, for experienced users to further fine-tune it with fine mesh is shown in Figure 5 leading edge and Figure 6 trailing edge. The geometry of NACA 2.5411 and Dragonfly airfoil that are created earlier are directly used, for the mesh process. Figure 7 and 8 presents the clear details of the mesh boundary which are utilized in capturing the physics effectively.

2.1.4 Solver

The Solver tool uses Finite Volume Method for calculations, where the domain is divided into discrete finite number of control volumes. Post-Processing is performed by a tool CFD-Post. It gives the user an insight of the simulation results. The results like plots, animations and high quality images of flow phenomena can be visualized and understood easily. There are a wide range of options for the user can choose from, depending on the requirement and understanding. Verification and validation of obtained results can also be done. In this work, post-processing involves contour images of dynamic pressure and velocity, and important end data like values of C_l and C_d.

2.1.5 Results

This is the last step in the numerical analysis process. It simply displays the end results of the flow simulation in tool format. Which need to be converted or reproduced as per the requirement of the research analysis.

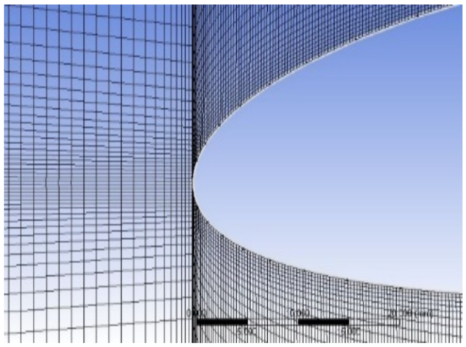


Fig. 5. Mesh at the leading edge of NACA 2.5411

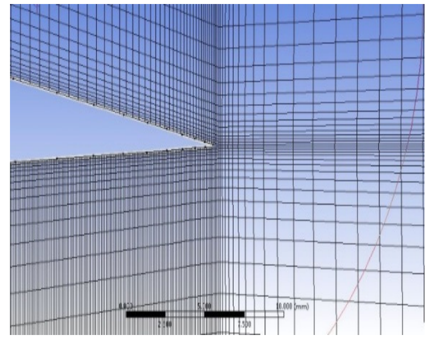


Fig. 6. Mesh at the trailing edge of NACA 2.5411 Airfoil

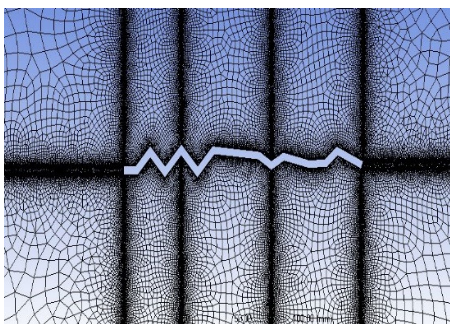


Fig. 7. Expanded view of the Dragonfly Airfoil's mesh

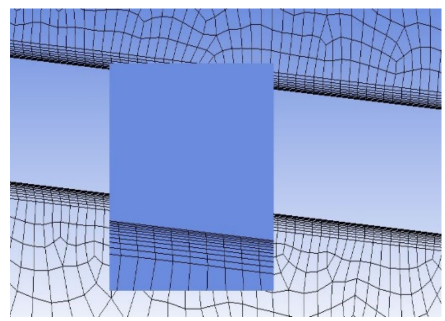


Fig. 8. Inflation layers over the surface of Dragonfly Airfoil

2.2 Experimental Analysis
2.2.1 Introduction

Experimental analysis is different from numerical analysis in many ways. Numerical analysis is done using a computer, whereas experimental analysis is performed using a physical setup of special equipment like a wind tunnel. The results obtained from experimental analysis are more exact and reliable than those obtained from numerical analysis [11,12]. This is because the experimental setup depicts the real-life scenarios. It is also easy to understand. But, the setup being costly, confined to a place and requiring additional gauges and sensors for measurements are the major disadvantages [2].

A wind tunnel is a physical experimental setup used to determine the flow effects over different bodies [1]. The main concept of it is, air flow is allowed to move past the test body to determine data such as aerodynamic forces, moments, pressure distribution etc. A typical wind tunnel parts consist of fan, inlet, settling chamber, test section and diffuser. The fan rotates when power is supplied and sucks in the air. The air that has been sucked in through the inlet is turbulent and is made to pass through a series of flow straighteners in the settling chamber to obtain laminar flow [10]. In the test section, a scaled or real-size model is placed depending on the test section dimensions and testing is done. Then the flow is expanded and slowed down in the diffuser part and exited [2,22].

Aerodynamic forces and moments can be calculated by pressure calculations, where static pressure and local pressures at particular positions on the body are noted, from which lift and drag are obtained. Experimental investigation is carried at IARE low speed tunnel facility in Figure 9 to measure aerodynamic forces and moments over the model. The most basic type of instrument in Figure 10 used in this type of testing is the force balance, where three forces (lift, drag, and side force) and three moments (pitch, roll, and yaw) can be determined. In this work, the wind tunnel used is a low-speed wind tunnel with a maximum speed of 50m/s and test section dimensions 600mm x 600 mm x 2000mm, in which the fabricated models of NACA 2.5411 airfoil and Dragonfly airfoil is tested.

2.2.3 Fabrication

Fabrication of NACA 2.5411 airfoil is made as per the details given in table 1, the geometry created in the Airfoil tools, using which ribs are cut out of foam board and wood. The ribs are joined using spars, one at the quarter-chord point and one at the rear end. The ribs are then covered with architecture sheet, which acts as skin for the model. An L-clamp is affixed on the lower surface of the model to enable it to be fixed to a 6-component balance for testing in Figure 13. For Dragonfly airfoil, the ribs are printed in a 3-D printer. The ribs are joined using heavy bond. An L-clamp is affixed on the mount of the setup lower surface of the model.

Fig. 9. Low-speed Wind Tunnel

Fig. 10. Six Component Balance

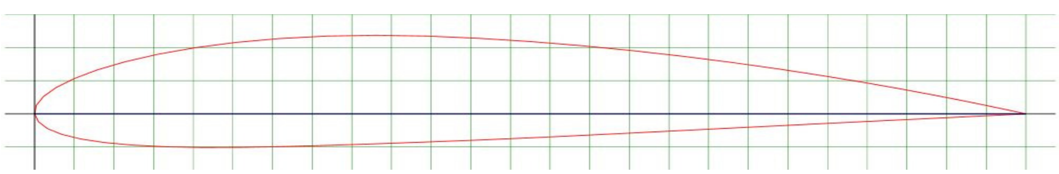


Fig. 11. Geometry of NACA 2.5411 Airfoil generated in Airfoil tools

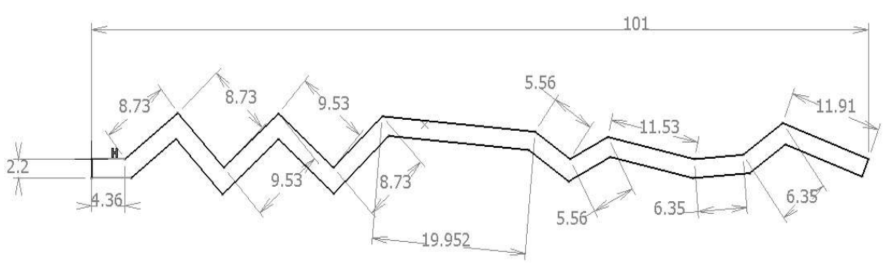


Fig. 12. Geometry of Dragonfly Airfoil [13]

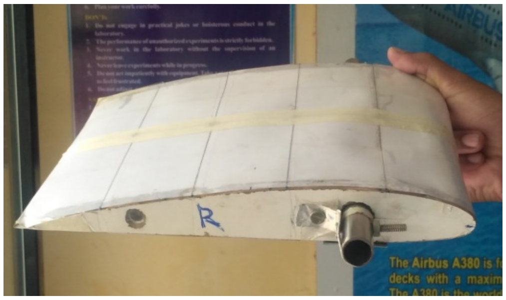


Fig. 13. NACA 2.5411 Airfoil Fabricated Model

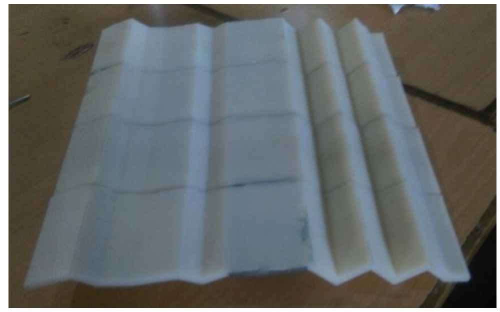


Fig. 14. Dragonfly Airfoil Fabricated Model

2.2.4 Testing

Both NACA 2.5411 airfoil and dragonfly airfoil are tested on a six component balance, at different angle of attacks over a range of velocity.

Fig. 15. Models Mounted on a six component strain gauge balance strut

3. Results and Discussions
3.1. Results

Test data obtained from graphs of C_l and C_d at different angle of attacks over a range of velocity are drawn in Figure 16 and 17. From the numerical results of Figure 16 and 17, it can be seen that the values of C_l for the Dragonfly Airfoil are higher when compared to the NACA 2.5411 Airfoil. Although, the values of C_d for the Dragonfly Airfoil are more than that of NACA 2.5411, owing to the corrugated cross-section of Dragonfly Airfoil. But, the aerodynamic efficiency, which is determined by lift-to-drag ratio, is seen to be higher for Dragonfly Airfoil especially at higher angle of attacks [9,15]. The experimental results above, the similar trend can be observed at higher angle of attacks i.e. higher C_l and C_l/C_d values for the Dragonfly Airfoil than those of NACA 2.5411, despite having more Cd as shown in Figure 18 and 19.

Table 1
Geometric Specifications of Dragonfly Airfoil

Geometric Specifications of NACA 2.5411		Geometric Specifications of Dragonfly Airfoil	
C	25 cm	C	20 cm
m	0.025c		
p	0.4c	T	2 mm
t	0.11c		

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 51, Issue 1 (2018) 31-41

From both the dynamic pressure and velocity contours for NACA 2.5411 Airfoil, it can be deduced that the flow follows Kutta condition i.e. it leaves the trailing edge smoothly [10]. Also, according to traditional smooth airfoil theory NACA 2.5411 has lower pressure on upper surface and sufficient high pressure on the lower surface at AOA>5, so that lift is generated. This means the flow must have low velocity on the lower surface and higher velocity on the upper surface [6,13,21], which is also justified which is shown in Figure 20 to Figure 27.

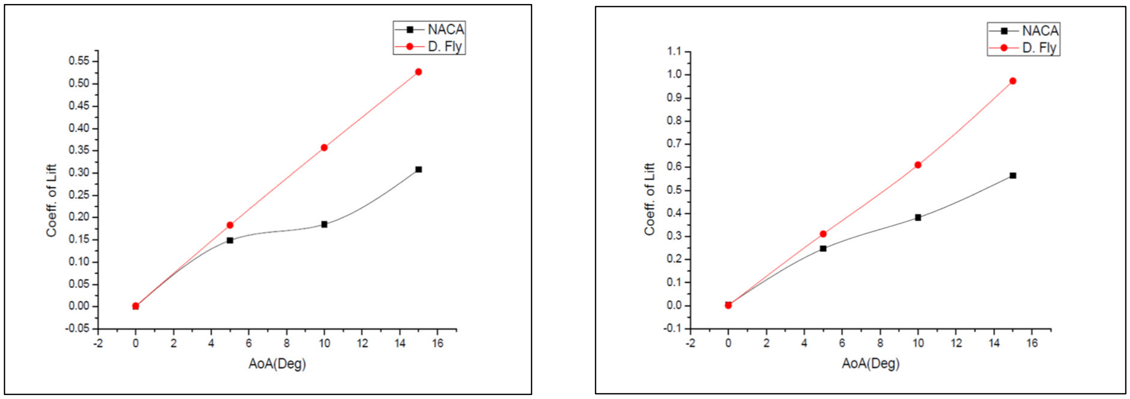


Fig. 16. C_l vs AoA plot for Numerical Results of airfoils at V= 11.8 m/s and V=15.4m/s

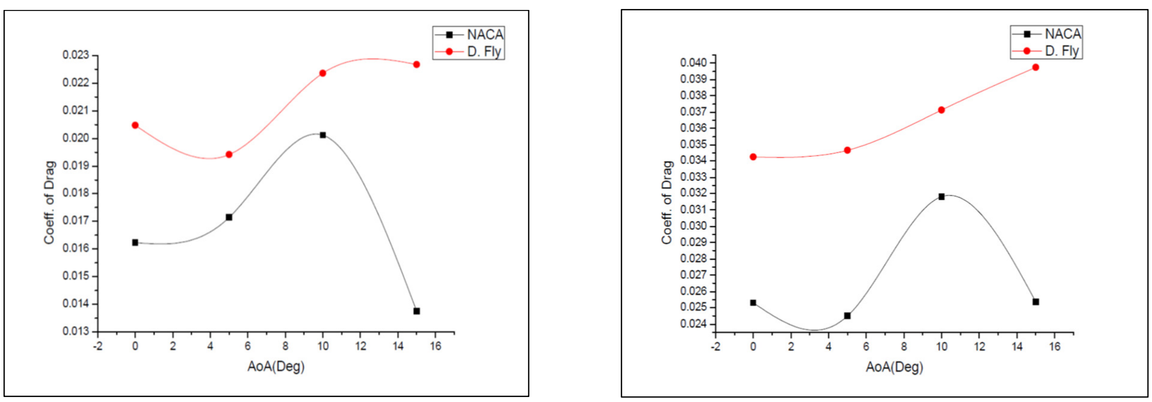


Fig. 17. C_d vs AoA plot for Numerical Results of airfoils at V= 11.8 m/s and V=15.4 m/s

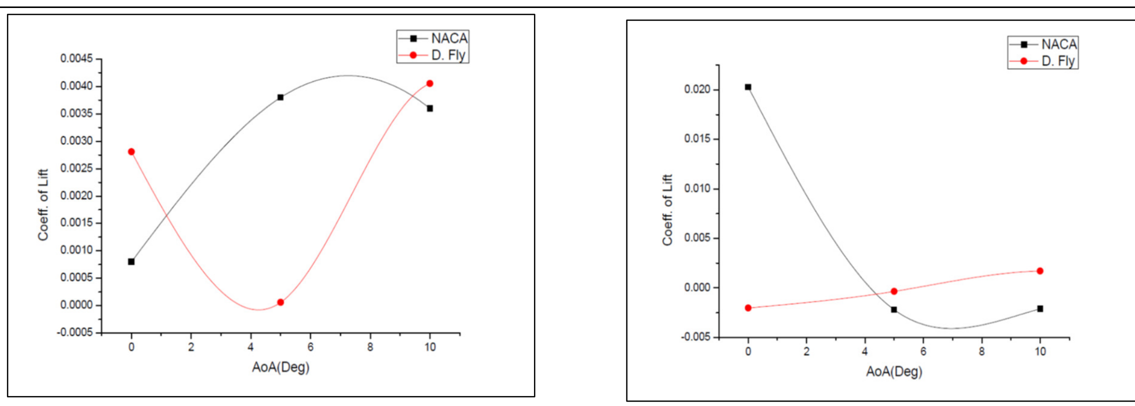


Fig. 18. C_l vs AoA plot for Experimental Results of airfoil at V= 11.8 m/s and V= 15.4 m/s

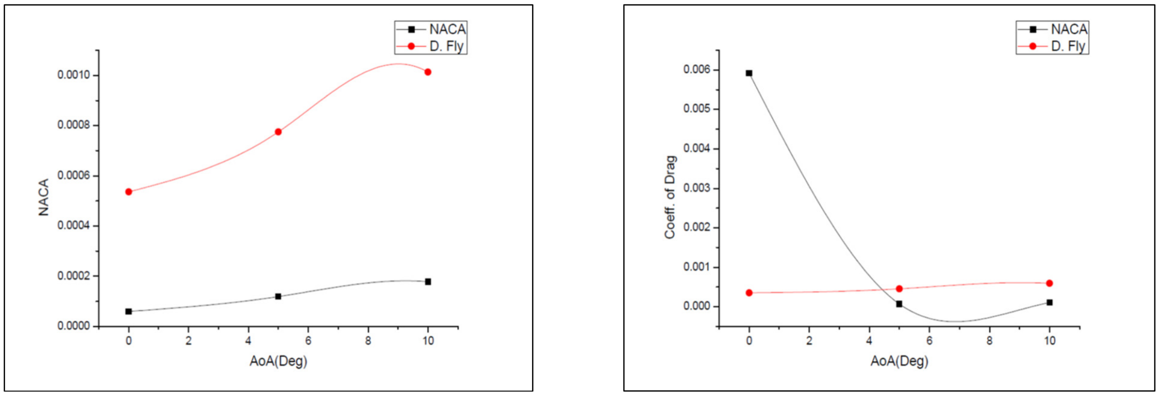


Fig. 19. C_d vs AoA plot for Experimental Results of airfoil at V= 11.8 m/s and V= 15.4 m/s

From the plots of numerical analysis, it can be inferred that the Dragonfly Airfoil has better aerodynamic performance for both the speeds than NACA 2.5411 Airfoil, especially at high angle of attack. From the graphs for experimental results, it can be inferred that the Dragonfly Airfoil has better aerodynamic characteristics over NACA 2.5411 Airfoil. *Dragonfly Airfoil:* It can be observed from the dynamic pressure contours, that a small vortex bubble has been formed at the first valley on the lower surface in Figure 20 to 27. This means the flow tends to rotate in the valleys due to vortex. Also, the high pressure on the upper surface of airfoil tends to decrease with increase in AOA from 0 deg to 15 deg.

3.2. Dynamic Pressure and Velocity Contours

The below results are shown for Reynolds number 180,545.

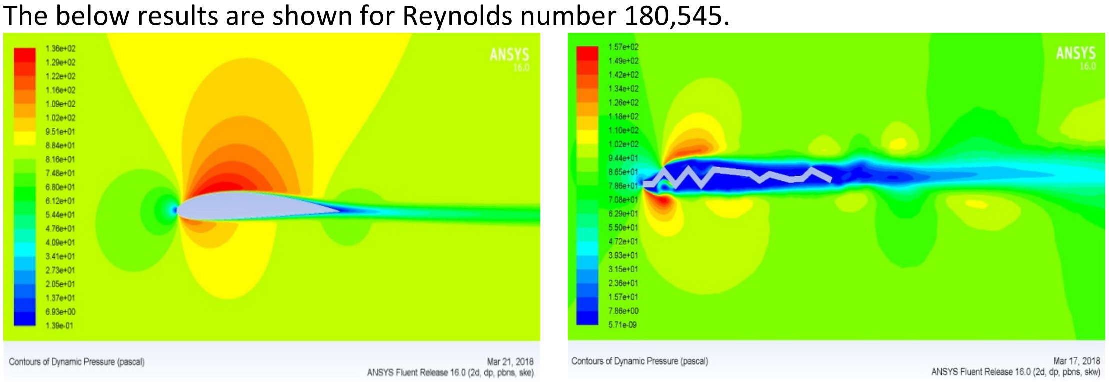


Fig. 20. Dynamic Pressure and Velocity Magnitude contours at AOA= 0 Deg, V= 11.8 m/s

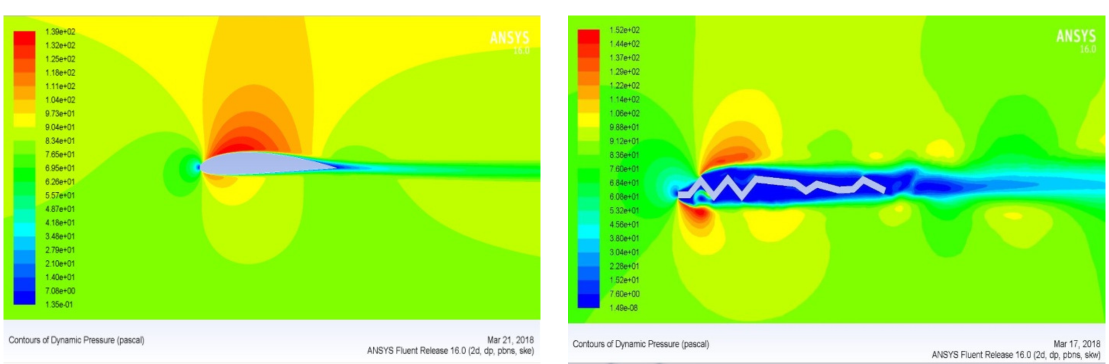


Fig. 21. Dynamic Pressure and Velocity Magnitude contours at AOA= 5 Deg, V= 11.8 m/s

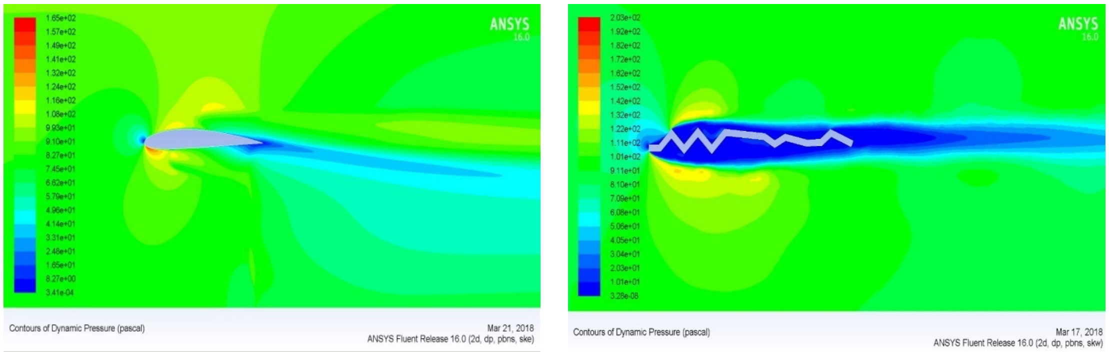


Fig. 22. Dynamic Pressure and Velocity Magnitude contours at AOA= 10 Deg, V= 11.8 m/s

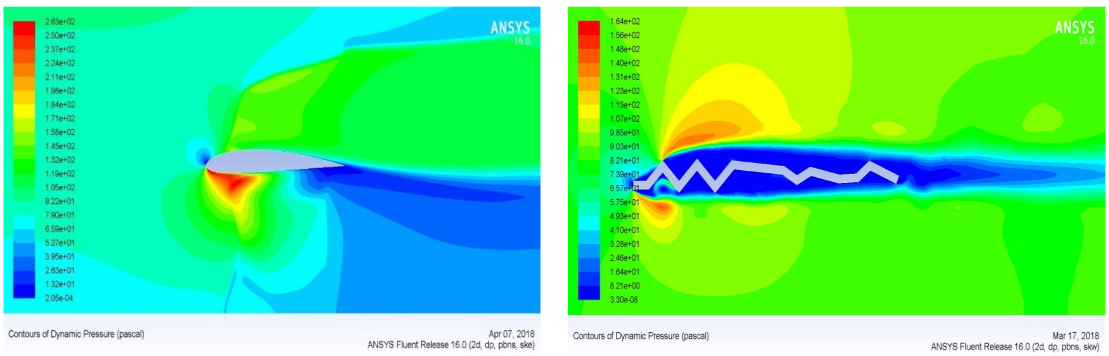


Fig. 23. Dynamic Pressure and Velocity Magnitude contours at AOA= 15 Deg, V= 11.8 m/s

The below results are shown for Reynolds number 243,894.

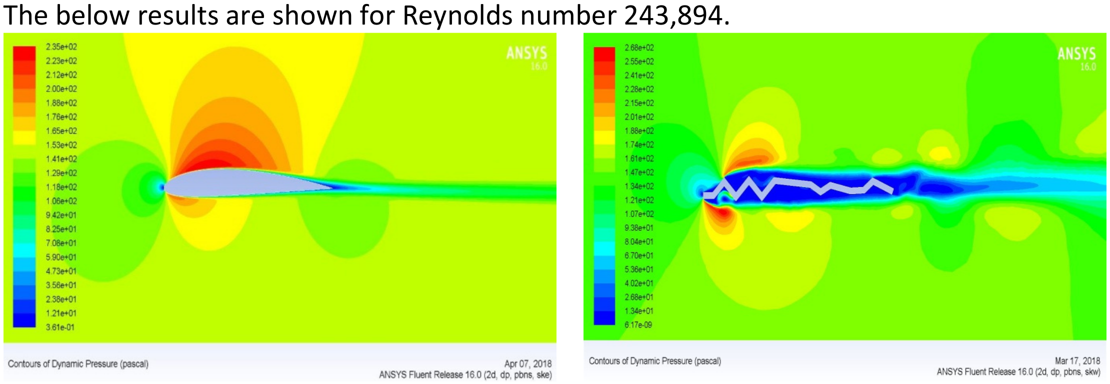


Fig. 24. Dynamic Pressure and Velocity Magnitude contours at AOA= 0 Deg, V= 15.4 m/s

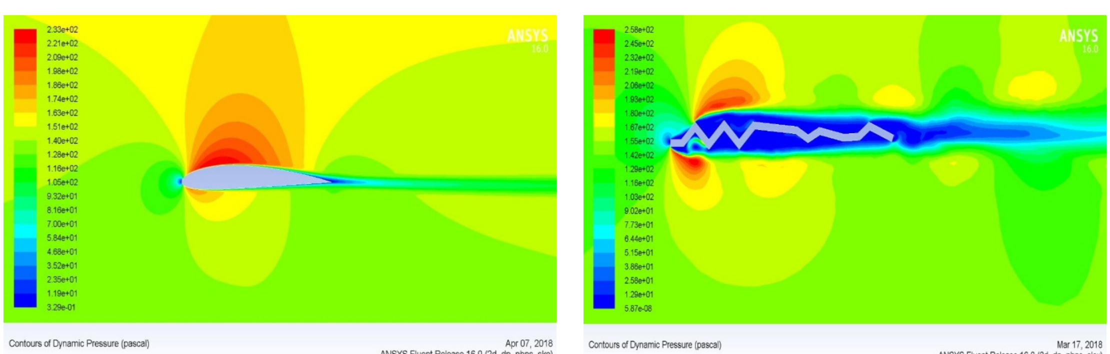


Fig. 25. Dynamic Pressure and Velocity Magnitude contours at AoA= 5 Deg, V= 15.4 m/s

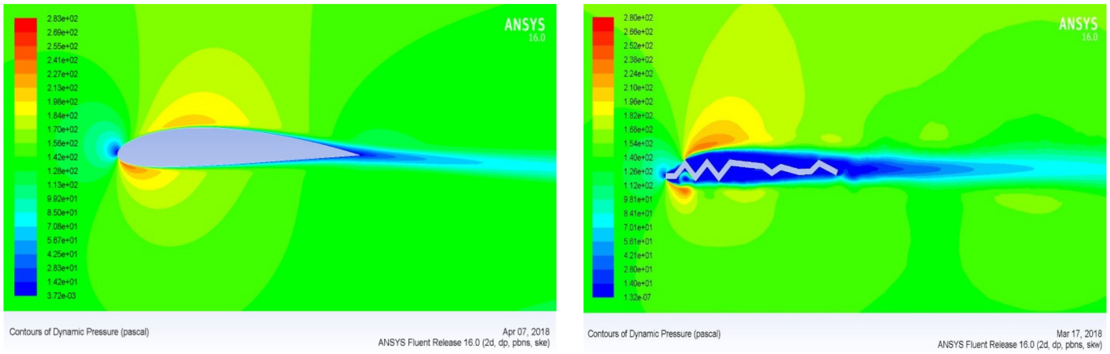


Fig. 26. Dynamic Pressure and Velocity Magnitude contours at AoA= 10 Deg, V= 15.4 m/s

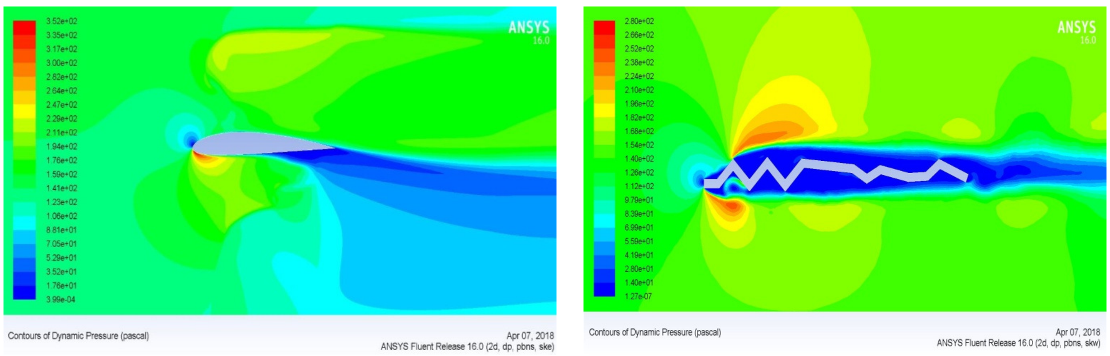


Fig. 27. Dynamic Pressure and Velocity Magnitude contours at AoA= 15 Deg, V= 15.4 m/s

4. Conclusions

From both the numerical and experimental analyses results obtained, it is concluded that the Dragonfly Airfoil has better aerodynamic characteristics like high C_l and C_l/C_d. It is obvious that the Dragonfly Airfoil has more C_d when compared to NACA 2.5411 Airfoil, due to its corrugated cross-section. But, the advantages it offers in producing lift are more, which can be clearly established from the high lift-to-drag ratio. The high lift of Dragonfly Airfoil is expected to be due to the vortices generated at the valleys in the cross-section. Negative pressure is developed due to the vortices, and a net negative pressure on the upper surface can be obtained for AOA greater than 0. Therefore, more lift is generated by the Dragonfly Airfoil when operated at an AOA. The data provides an insight to further research work to investigate from this baseline data to analyse on complete fly wing by integrating the current data with the full sections.

References

[1] Anderson, J. M., K. Streitlien, D. S. Barrett, and M. S. Triantafyllou. "Oscillating foils of high propulsive efficiency." *Journal of Fluid Mechanics* 360 (1998): 41-72.

[2] Ansari, Salman A., Nathan Phillips, Graham Stabler, Peter C. Wilkins, Rafał Żbikowski, and Kevin Knowles. "Experimental investigation of some aspects of insect-like flapping flight aerodynamics for application to micro air vehicles." In *Animal Locomotion*, pp. 215-236. Springer, Berlin, Heidelberg, 2010.

[3] Kesel, Antonia B. "Aerodynamic characteristics of dragonfly wing sections compared with technical aerofoils." *Journal of experimental biology* 203, no. 20 (2000): 3125-3135.

[4] Kesel, Antonia B., Ute Philippi, and Werner Nachtigall. "Biomechanical aspects of the insect wing: an analysis using the finite element method." *Computers in biology and medicine* 28, no. 4 (1998): 423-437.

[5] Dudley, Robert. *The biomechanics of insect flight: form, function, evolution*. Princeton University Press, 2002.

[6] Levy, David-Elie, and Avraham Seifert. "Simplified dragonfly airfoil aerodynamics at Reynolds numbers below 8000." *Physics of Fluids* 21, no. 7 (2009): 071901.

[7] Newman, B. G. "Model test on a wing section of a dragonfly." *Scale effects in animal locomotion* (1977): 445-477.

[8] Gao, Haiyang, Hui Hu, and Z. J. Wang. "Computational study of unsteady flows around dragonfly and smooth airfoils at low Reynolds numbers." In *46th AIAA aerospace sciences meeting and exhibit*, p. 385. 2008.
[9] Wooton, R. J., K. E. Evans, R. Herbert, and W. Smith. "Morphology and operation of the locust hind wing." *J. Exp. Biol* 203 (2000): 2921.
[10] John D. Anderson, Jr., "Fundamental of Aerodynamics", 3rd edition, McGraw Hill series, 2009.
[11] K Vamshi, Shiva Prasad U, Vihar R. S, Babitha, Govardhan D. "Feasibility study of power generation using a turbine mounted in aircraft wing", International Journal of Engineering & Technology no. 7, (2018): 433-436.
[12] Kesel, Antonia B., Ute Philippi, and Werner Nachtigall. "Biomechanical aspects of the insect wing: an analysis using the finite element method." *Computers in biology and medicine* 28, no. 4 (1998): 423-437.
[13] Mueller, Thomas J., ed. *Fixed and flapping wing aerodynamics for micro air vehicle applications*. American Institute of Aeronautics and Astronautics, 2001.
[14]. Wakeling, J. M., and C. P. Ellington. "Dragonfly flight. II. Velocities, accelerations and kinematics of flapping flight." *Journal of experimental biology* 200, no. 3 (1997): 557-582.
[15] Milano, Michele, and Morteza Gharib. "Uncovering the physics of flapping flat plates with artificial evolution." *Journal of Fluid Mechanics* 534 (2005): 403-409.
[16] Newman, B. G., S. G. Savage, and D. Schouella. "Model Tests on a Wing Section of an Aeschna Dragonfly. Scale Effects in Animal Locomotion (1977) edited by Pedley, TJ."
[17] Okamoto, Masato, Kunio Yasuda, and Akira Azuma. "Aerodynamic characteristics of the wings and body of a dragonfly." *Journal of experimental biology* 199, no. 2 (1996): 281-294.
[18] Prasad, U. S., V. S. Ajay, R. H. Rajat, and S. Samanyu. "Aerodynamic Analysis Over Double Wedge Airfoil." In *IOP Conference Series: Materials Science and Engineering*, vol. 197, no. 1, p. 012076. IOP Publishing, 2017.
[19] Rees, Christopher JC. "Form and function in corrugated insect wings." *Nature* 256, no. 5514 (1975): 200.
[20] Rees, Christopher JC. "Aerodynamic properties of an insect wing section and a smooth aerofoil compared." *Nature* 258, no. 5531 (1975): 141-142.
[21] Sunada, Shigeru, Akitoshi Sakaguchi, and Keiji Kawachi. "Airfoil section characteristics at a low Reynolds number." *Journal of fluids engineering* 119, no. 1 (1997): 129-135.
[22] Sunada, S., T. Yasuda, K. Yasuda, and K. Kawachi. "Comparison of wing characteristics at an ultralow Reynolds number." *Journal of aircraft* 39, no. 2 (2002): 331-338.
[23] Thomas, J. Mueller. "Fixed and flapping wing aerodynamics for Micro Air Vehicle applications." *a) 30deg (Down Stroke)*(2001): 232-237.
[24] Wakeling, J. M., and C. Pt Ellington. "Dragonfly flight. I. Gliding flight and steady-state aerodynamic forces." *Journal of Experimental Biology* 200, no. 3 (1997): 543-556.
[25] Hashim, Ghasaq Adheed, and NA Che Sidik. "Numerical study of harvesting solar energy from small-scale asphalt solar collector." *J. Adv. Res. Des.* 2 (2014): 10-19.
[26] Jehad, D. G., G. A. Hashim, A. K. Zarzoor, and CS Nor Azwadi. "Numerical Study of Turbulent Flow over Backward-Facing Step with Different Turbulence Models." *Journal of Advanced Research Design| Vol* 4, no. 1 (2015): 20-27..
[27] Razali, A. A., and A. Sadikin. "CFD simulation study on pressure drop and velocity across single flow microchannel heat sink." *J. Adv. Res. Des.* 8 (2015): 12-21.