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NUMERICAL INVESTIGATIONS OF LOW-REYNOLDS BIO AERODYNAMICS INSPIRED AIRFOILS

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ABSTRACT

The observation of the natural flight behavior provides inspiration for Unmanned Aerial Vehicles (UAVs). A comparison of a man-made-bird-like AS6095 airfoil against the owl airfoil operating at a range of low Reynolds (Re) number is performed. For the capability of the prediction of the aerodynamic characteristics of these low Re airfoils, Spalart- Allmaras (SA), SST-enhanced K-Omega and transition Shear Stress Transport (SST) turbulence models are applied. The flow behavior is simulated around AS6095 airfoil at Re number of 100,000 and Owl-like airfoil in two different Re number conditions of 100,000 and 23,000. The numerical results were compared to the published data. The failure of the turbulence models in capturing accurately the non-linearity of the lift coefficient was observed.

INTRODUCTION

Many bird species fly at the flight conditions of low Re number where UAV operate. Therefore, the improvement of the MAV aerodynamic efficiency requires studies on the natural flyers wing. The biomimetics and bio-inspiration studies of moderate Reynolds number airfoils and aircraft has been gaining attention in order to provide insight into the new possible design in the field of UAVs (Hanna, 2020).

Low Reynolds Number Re

The observation of the natural flight behavior provides inspiration for Unmanned Aerial Vehicles (UAVs). The integration of biological theory of natural flight and aerodynamic approaches to address the MAVs based on the bird's endurance is among the aspects of the investigations on the aerodynamic performance and flight properties of birds in steady non-flapping flight (Aldheeb *et al*., 2016).

Therefore, natural flyers are occupying researchers to understand the adaptation of swifts such as eagles, storks, owls and albatross in their gliding modes of flight (Omar *et al*., 2020). Some birds exhibit inspiring aerodynamic characteristics such as owls that are known for their silent flight (Jaworski & Peake, 2020). (Liu *et al*., 2006) extracted a bionic airfoil from the cross-section at the 40% owl wing (Figure 1.c). The aerodynamics of barn-owl was investigated

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experimentally by Anyoji *et al*. (2018) and numerically by Kondo *et al*. (2014). Ananda & Selig (2018) Inspired by birds and designed a feather-like airfoil profile section AS6095 (Figure 1.b) to operate at the MAV Reynolds number regime of Re =10^5.

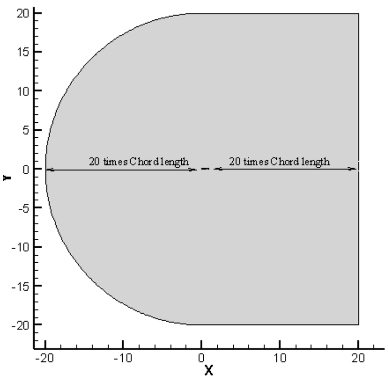
Although many numerical studies have been made to investigate the aerodynamic performance and flow characteristics of bionic airfoils, rare studies have been focused on the simulation of turbulent flow around the thin airfoils especially the biologically inspired airfoils especially considering at low Reynolds number. In this work, the flow past a Man-made-bird-like airfoil AS6095 will be captured numerically using RANS solver with various turbulence models at Re number of 10^5. The CFD results will be validated against the published data and Xfoil code results. Later, the study of the aerodynamic features of owl wings that promote silent flight is investigated at both Re number of 100,000 and 23,000 and the capability of CFD turbulence modelling is examined.

METHOD

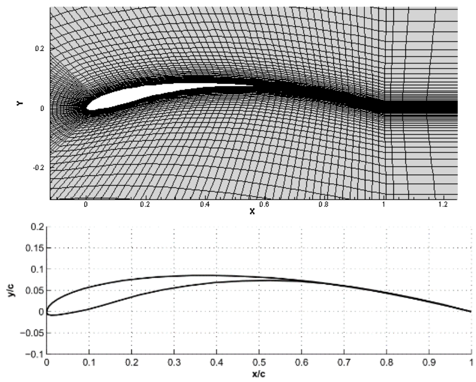
The prediction of the flow past the AS6095 airfoil is conducted using different numerical methods. Mainly, the one-equation Spalart -Almaras (S-A) turbulence model (SPALART & ALLMARAS, 1992), the two-equation SST-enhanced K-Omega (Menter, 1994) and the Four-equation transitions Shear Stress Transport (SST) (Menter et al., 2006) turbulence models in addition to XFoil panel method (Drela, 1989).

The preparation of the geometry and the multizone structured grid is built using ICEM tool of ANSYS. In the current investigations, the mesh generation considers the first layer height that is normal to the airfoil surface by setting the y^+ value below 1. The C-H type grid domain (Figure 1.a) is constructed using the ICEM ANSYS meshing tools to split blocks around the airfoil surface.

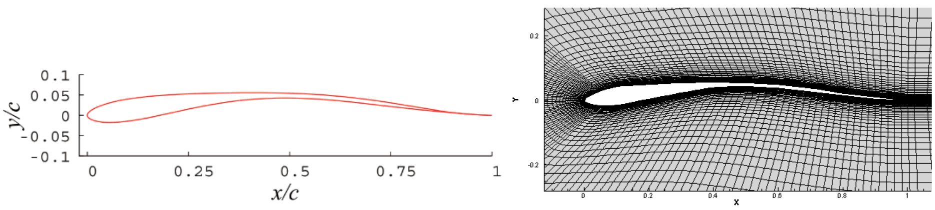
The current CFD results are to be validated with PROFOIL code results from Ananda & Selig, (2018). Later, a similar mesh is constructed around the owl-wing section (Figure **1**. c). The flow around the owl-like airfoil was investigated numerically using SST-enhanced K-Omega and the four-equation transitions SST turbulence models at Re number of and 23,000 and 100,000. The numerical results were compared to published experimental and numerical results.



(a) Computational domain



(b) AS6095 bird like airfoil and mesh distribution



(c) Owl-like airfoil with mesh

Figure 1 Airfoil geometries and computational domain

RESULTS AND DISCUSSION

Flow around Bird-like AS6095 airfoil:

The turbulence models results are validated by comparison with the results from Ananda & Selig (2018).The transition SST and SST-K-Omega turbulence models are in a good agreement with little differences after the stall angle. Poor agreement was observed for the Spalart Allmaras (SA) turbulence model at an angle of attack higher than 12˚. Figure 2 shows that CFD and XFoil have a good agreement with the PROFOIL published data by Ananda & Selig (2018) up to the maximum lift coefficient is reached at the stall angle around α= 12˚. The transition SST models predict the flow transitions from laminar to turbulent better than SST K-ω due to the unsteadiness of the separated flow. Figure 3 shows the turbulence model prediction of the separation bubble on the upper surface of the airfoil AS6095 at Re=100,000.at the angle of attack α= 12˚ as expected to occur near stall conditions.

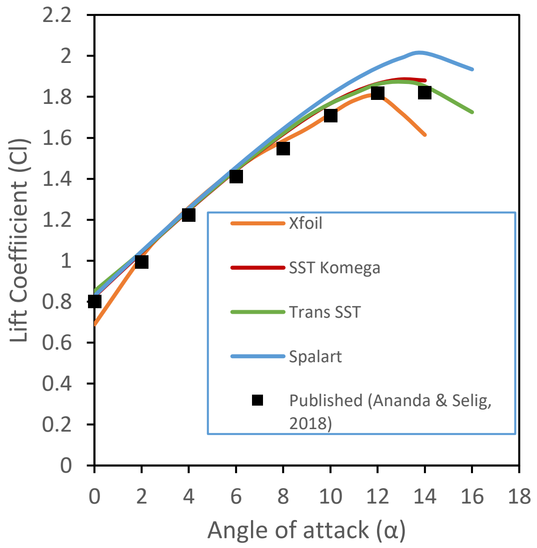


Figure 2 AS6095 Cl results from various numerical methods at Re= 100,000

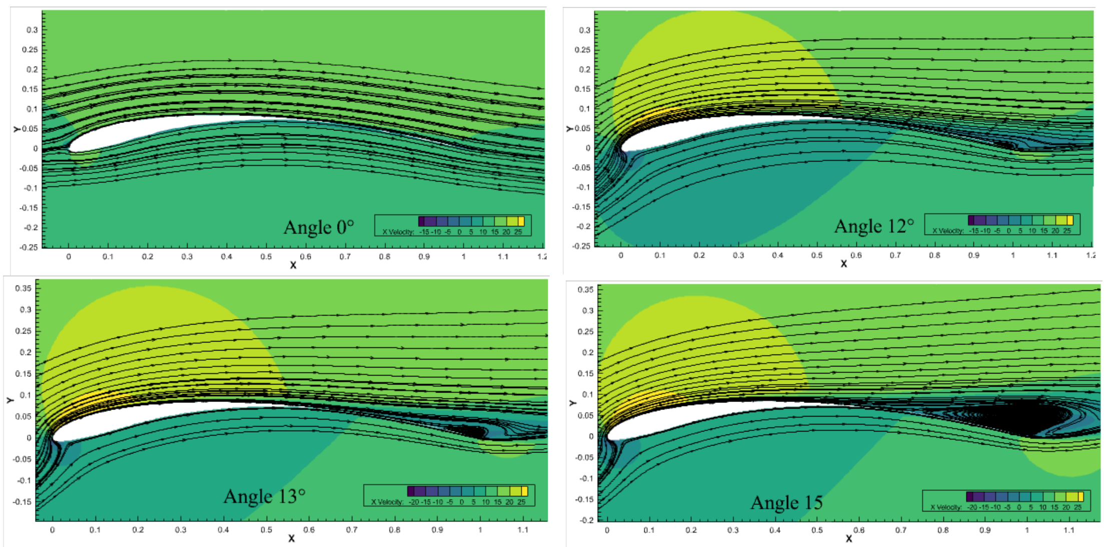


Figure 3 Streamlines with X-component velocity contour at angles 0°,12°,13° and 15° respectively

Owl-like airfoil at Re=100,000 RANS Turbulence modelling

The aerodynamic characteristics of the owl-like airfoil are investigated at a Re number of 100,000. The results in Figure 4 show that, for angles of attack less than 9°, the CFD SST- K-model appears to predict the lift coefficient in good agreement with the Xfoil code. The Xfoil data shows the stall occuring at 9°. At this angle and beyond, the CFD results are deviating from Xfoil ones. In other words, within the stall angle and beyond, the turbulence model fails to capture the flow. The turbulence model's ability to predict the aerodynamics features of the owl-like airfoil at this Re number of 100,000 and high angles of attack is influenced by the unsteadiness of the flow physics, as illustrated in Figure 5. Figure **5**(a,b) show the steady solution of the lift coefficient at angles 9° and 10°. The difficulty in averaging the aerodynamics characteristics require the use of the transient solution. Figure **5**(c,d) show the convergence time history of Cl.

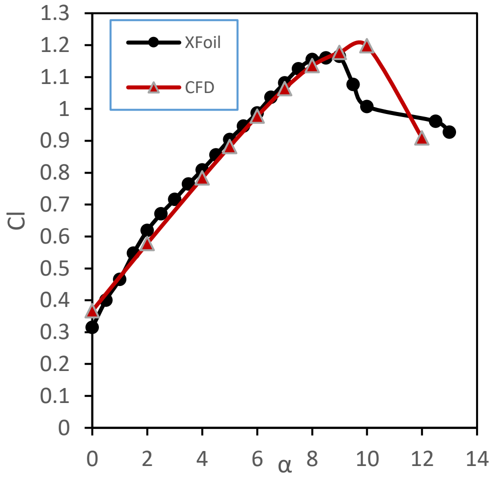
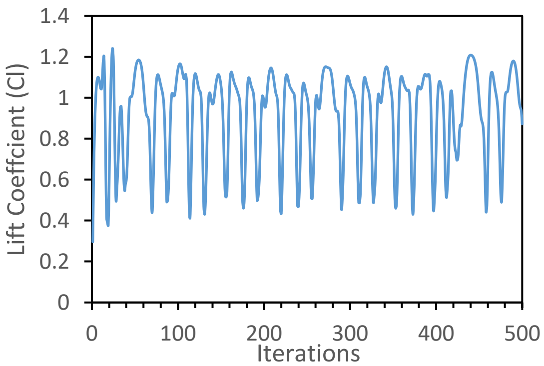
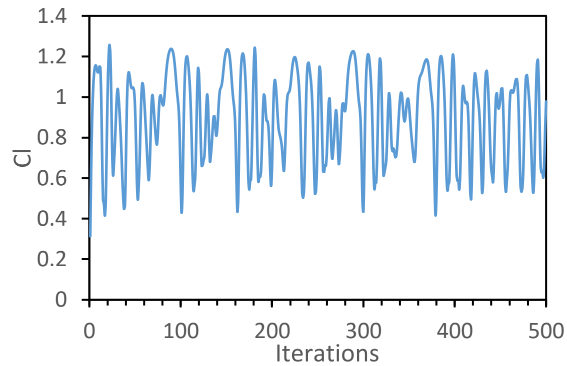


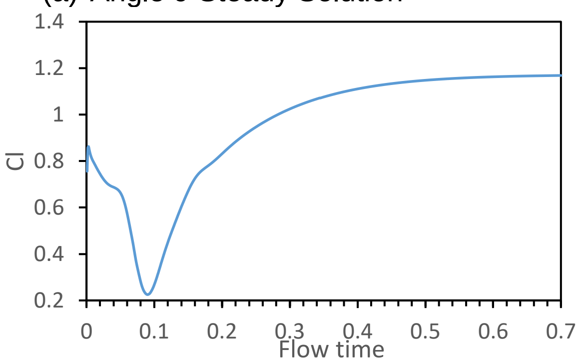
Figure 4 Lift coefficent of Owl airfoil at Re 100,000 compared to the Xfoil results



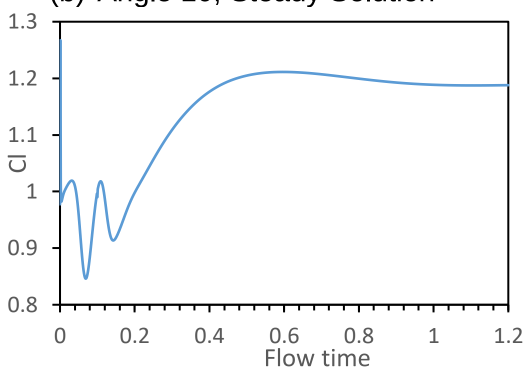
(a) Angle 9 Steady Solution



(b) Angle 10; Steady Solution



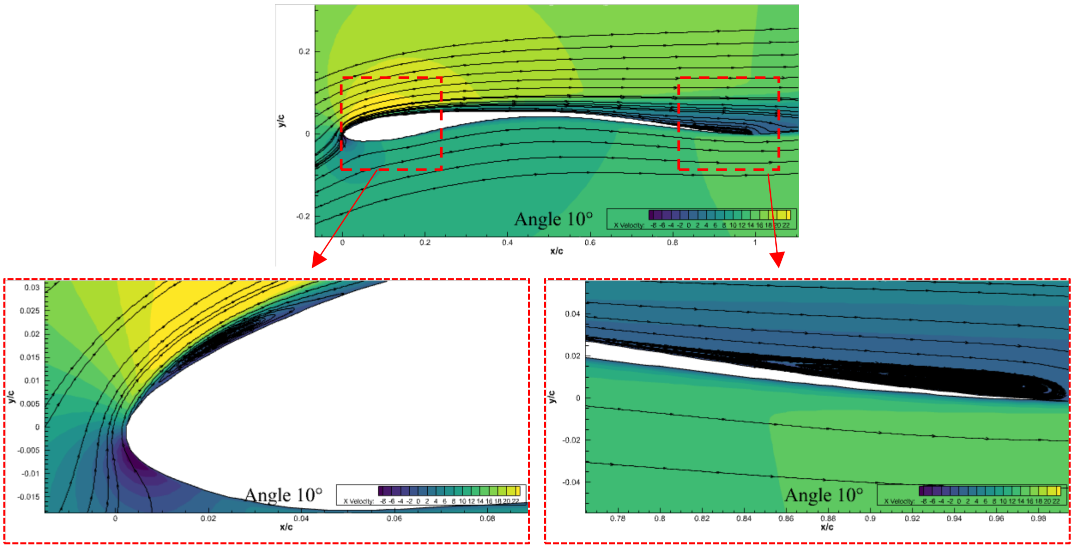
(c) History of transient Cl solution of the K-ϖ SST model at angle 9



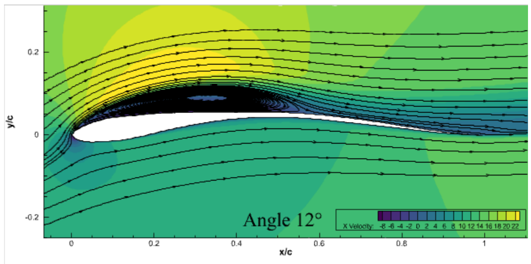
(d) History of transient Cl solution of the K-ϖ SST model at angle 10

Figure 5 Lifting behavior of the Owl-like airfoil at Re= 100,000 using SST-K-ϖ model.

To investigate the near stall flow behavior, Figure 6 shows the streamlines with X-component velocity contour at angles of attack of 10° (a) and 12° (b). A small laminar separation bubble (LSB) is clearly seen at the leading edge (Figure **6**a) along with a bubble at the trailing edge. The LSB is growing in diameter and moving towards the trailing edge (Figure **6**b). The length of the LSB in the chord-wise direction increased as the angle of attack increases.



(a) The separations at the angle 10°; LSB (left) and bubble at trailing edge (right)



(b) The laminar separation bubble increase in diameter (angle 12°)

Figure 6 Streamlines with X-component velocity contour at angles 10° and12°, highlighting the Separation bubbles and LSB.

Owl-like airfoil at Re=2.3E4 RANS Turbulence model

The computational study of the owl-like airfoil is performed by keeping the previous independent grid study of the AS6095 with a change of the first element corresponding wall spacing. It aimed to compare the turbulence model SST K-Omega with available experimental data (Anyoji et al., 2018) and CFD works (Kondo et al., 2014). Figure 7 shows the owl airfoil lift coefficient Cl compared to the K-omega SST with Xfoil, other CFD results by (Kondo et al., 2014) and published experimental data by (Anyoji et al., 2018). It has been found that the XFoil could only predict correctly the non-linearity of the Cl curve. The turbulence models prediction of flow field behavior in terms of separations is shown in Figure 8. A jump in the separation prediction is suddenly appearing with the increase of the angle of attack from 10˚ to 12°.

Whereas the previous 2D Laminar work of (Kondo *et al*., 2014) and the experimental data of (Anyoji et al., 2018) and the XFoil method show a nonlinearity of the lift curve. The non-linearity of the lift coefficient curve is been a common phenomenon as reported by (Lee et al., 2015). While experimental data shows the stalling is occuring around the angle of attack α=9˚. The tested turbulence models fail to capture the separations on the surface of the owl-like airfoil at this angle of attack and appear to be inappropriate for the Re number of 23,000 simulations.

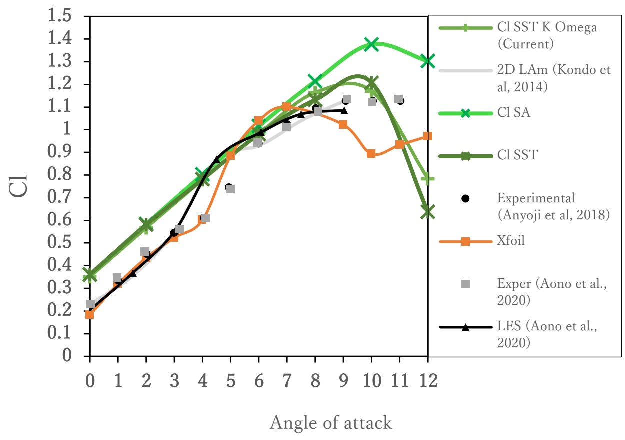


Figure 7 The RANS models comparison to the literature (Anyoji et al., 2018; Aono et al., 2020)

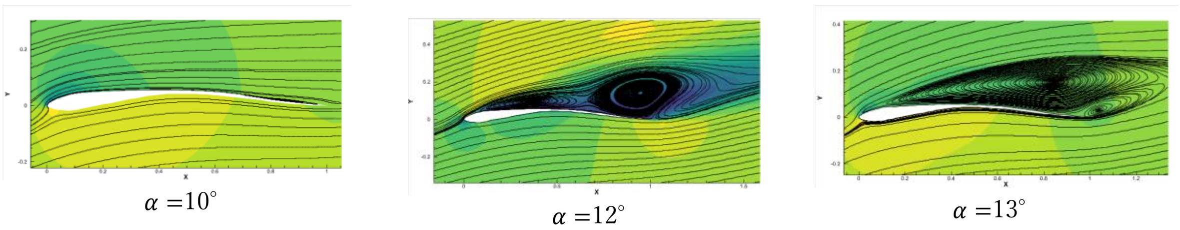


Figure 8 RANS SST-K-Omega flow capturing pressure contour with the streamline strace.

CONCLUSION

The aerodynamic characteristics of both bird-like AS6095 and owl airfoils are investigated at Re numbers of 23,000 and 100,000, respectively. At Re=100,000, the turbulence models capture the flow field around the airfoil surfaces but fail to capture the non-linearity of the lift curve at Re number of 23,000. Whereas, at this Re number of 23,000, the known lifting-line theory before stall is not applicable, the nonlinearity of the lift curve is obvious. Therefore, implementing other numerical methods to evaluate the airfoil aerodynamic characteristics such as the 2D-Laminar and 3D-LES can be used as an appropriate numerical method, but the latter requires a more computational resource.

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