Aerodynamics Performance of Barn Swallow Bird at Top Speed: A Simulation Study

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ABSTRACT

This paper presents a simulation study of aerodynamics performance of Barn Swallow bird (Hirundo Rustica) during gliding at top speed. Barn Swallow is generally known as a bird in which can make abrupt changes of direction during flying even at top speed. This is because it has long narrow wings and a forked tail. It could inspire engineers and scientists for the development of small flying machine such as micro-air-vehicle (MAV). Therefore, investigations on its aerodynamics is worthwhile to be carried out. The simulation work has been performed using a commercial computational fluid dynamics (CFD) software, i.e. Ansys Fluent version 15.0 and CATIA as the modelling software. According to previous studies, the fastest that the Barn Swallow can fly is about 13 m/s which is equivalent to Re=48000, thus becomes the constant speed during the simulation. From the simulation, the results of lift and drag coefficients were compared with the experimental data from past study. It is found that the simulation results are in fairly good agreement with the experimental data by showing the same trends and profiles. The significant differences between simulation and experiment is believed mainly due to the effects of feathers attached to the bird's body and wings which could reduce the skin friction significantly. The significant findings of CFD work, which are the illustrations of the pressure contour and velocity vector around the bird's body and wings. The contours could provide the approximate values of pressure and velocities around the bird's body and wings and it is found obeys the Bernoulli's principle.

Keywords: *Barn Swallow; Bird Flight; Lift Coefficient; Drag Coefficient; Computational Fluid Dynamics*

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Nomenclature

C_w	Maximum wing chord
L_a	Length of the alula
L_b	Bird span
L_t	Length of thorax
L_w	Length of the extended wing
M	Mass of the bird
S_b	Total lifting surface
S_w	Wing area
α	Angle of attack
C_L	Lift coefficient
C_D	Drag coefficient

Introduction

Without a doubt, bird's flight has contributed a lot in inspiring engineers and scientist during the development of flying machine. In fact, the word "aviation" comes from the Latin "avis" meaning "bird". In the past, great efforts have been devoted to analyze the flight of bird. In 1970, Lissaman and Shollenberger [1] in their studies have found that the birds gain some aerodynamic advantage when in a linear formations such as 'V', 'J' or echelon. This statement was agreed by Seiler et al. [2], especially for the 'V' formation of flying.

Several studies on the effects of bird's anotomy to their flying characteristics have been conducted. Tricker and Tricker [3] have found that the bird's wing is similar to the human arm in many aspects. Both comprise shoulder, elbow and wrist joints followed by metacarpals (fingers). The portion of the wing between the shoulder joint and the elbow joint is not aerodynamically significant for most birds and can be neglected in calculations. Houghton and Carruthers [4] have observed that the cross-section of a bird's wing is almost similar to the airfoil section of an aircraft. Meseguer et al. [5] have studied the alula effects for high lift device. The influence of the alula in the wing aerodynamics is similar to that of leading edge slats in aircraft wing, which are only operating during take-off and landing operations.

Barn Swallow bird or scientifically named *Hirundo Rustica* is a small bird found almost in every continent in the world. They can be classified as a small type bird with long narrow wings, forked tail and weak feet. With these characteristics, they can make abrupt changes of direction during flying even at top speed. In the past, most of the works on aerodynamics studies, researchers have used the wind tunnel test when conducting the experiments. Those experiments were not cheap and time consume. With the advancement of nowadays computer technology and performance, two-dimensional and three-dimensional flow structures prediction around a body can be performed cheaply and consume less time. Present work uses Ansys Fluent version 15 as a CFD tool to perform a simulation study on the aerodynamics performance of Barn Swallow bird at top speed. The simulation results will be compared with the experimental work done by Yusoff et al. [6].

Barn Swallow wing characteristics

In years 1997 and 1998, several parameters of the wing geometry of almost four hundred and fifty birds, belonging to forty different species living in Spain, have been measured. The following parameters are used to obtain the characteristic of bird's wing as shown in Figure 1 as suggested by Alvarez et al. [7]. In Figure 1, the wing area S_w and the total lifting surface of each bird S_b have been obtained. The S_b has been defined by Pennycuick [8] as $S_b = 2S_w + L_tC_w$ where the L_t is the width of the thorax, $L_t = L_b - 2L_w$. The measurement of the Barn Swallow wing has been conducted by Yusoff et al. [6] and is shown in Table 1.

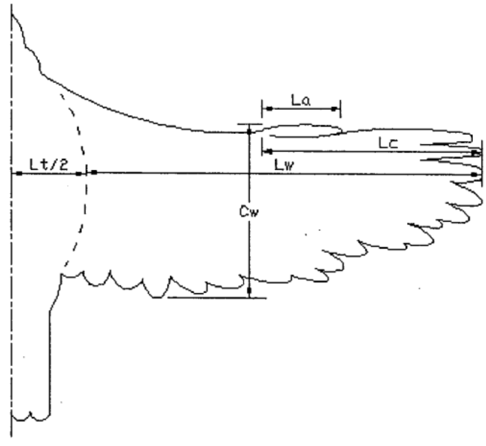

Figure 1: Bird’s wing parameters [7]

Table 1: Measurement of Barn Swallow wing [6]

Number of samples	Wing Load $W_l = Mg/S_b$ (mN/cm^2)	Wing Area, S_w (cm^2)	Aspect Ratio $AR = L_b^2/S_b$
1	0.140	66.5	9.778
2	0.146	70	9.657
3	0.186	69	9.647
Average	0.157	68.5	9.694

Methodology

Geometry model and mesh generation

A three-dimensional of Barn Swallow has been modelled at full scale based on the measurement data in Table 1 above, by using a commercial aided design software i.e. CATIA. The Barn Swallow model has been located in a box which has a similar size of wind tunnel test section in the experiment by Yusoff et al. [6]. The bird's body and wings are considered solid surface without any feather attached on it, to avoid complexity in the modelling. The Barn Swallow model is depicted in Figure 2. For the mesh generation, a default meshing process has been generated to the model; however, a relatively small mesh has been applied close to the Barn Swallow model surface. The meshed model is shown in Figure 3.

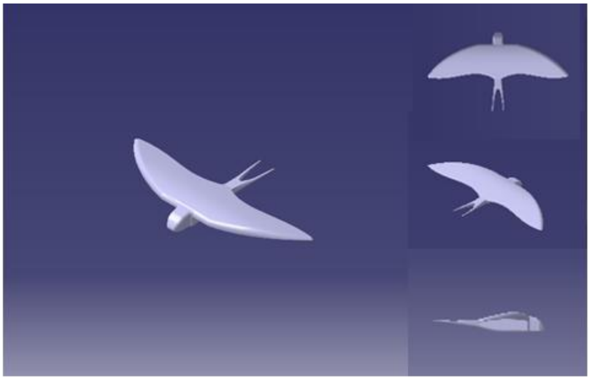

Figure 2: Three-dimensional model of Barn Swallow

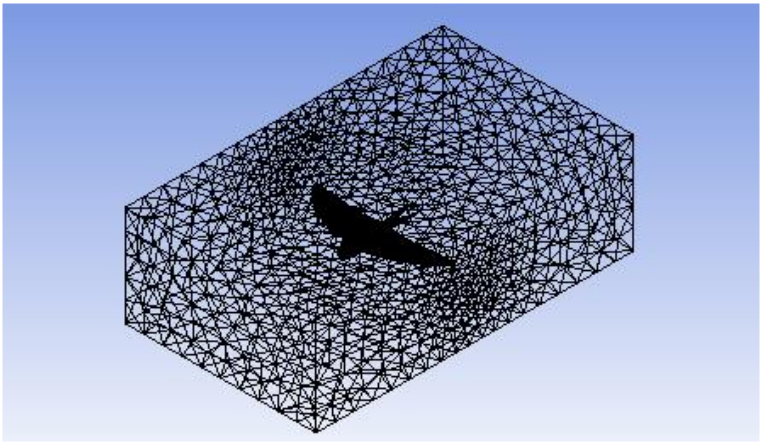

Figure 3: Meshed domain

CFD method and formulation

A commercial CFD code i.e. Ansys Fluent version 15 has been used to compute the air flow around the Barn Swallow model. The steady flow of a viscous incompressible fluid flow around the Barn Swallow is considered. The basic equations used in the simulation are the equations of continuity and the Navier-Stokes;

$$\vec{\nabla}.\vec{V} = 0 \tag{1}$$

$$\left(\vec{V}.\vec{\nabla}\right)\vec{V} = -\vec{\nabla}P + \rho\vec{g} + \vartheta\nabla^2\vec{V} \tag{2}$$

$$\text{where } \vec{\nabla} = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \tag{3}$$

where P is the static pressure and $\rho\vec{g}$ is the gravitational body force. Since the square size of wind tunnel is relatively small compared to the bird's size, therefore the air flow condition is very much influenced by the walls. Thus Reynolds number in internal duct flow case is used to determine the types of flow regime. With the top speed of Barn Swallow is about 13 m/s which is Re≈48000, the flow can be considered completely turbulent. With such flow regime, the standard k-ε turbulence model is used with a Standard Wall Functions for the Near-Wall Treatment. The equations describing the relationship between turbulent viscosity μ_t, turbulence intensity I, turbulence kinetic energy k, and turbulence dissipation rate ε are as follows;

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{4}$$

with

$$k = \frac{3}{2}(U \times I)^2 \tag{5}$$

$$\varepsilon = C_\mu^{\frac{3}{4}} \frac{k^{\frac{3}{2}}}{l} \tag{6}$$

where $C\mu$ — model constant ≈ 0.09
l — turbulence length scale ≈ $0.07C_w$
C_w — maximum wing chord
U — free stream velocity
I — turbulence intensity ≈ $0.16Re^{-\frac{1}{8}}$

The relationship between velocity and pressure corrections is calculated using a SIMPLE algorithm. The fluid flow around the Barn Swallow model is set as air with the inlet and outlet are shown in Figure 4. In simulation, the angles of attack of the Barn Swallow model are varies from α= -32° to α= 32º.

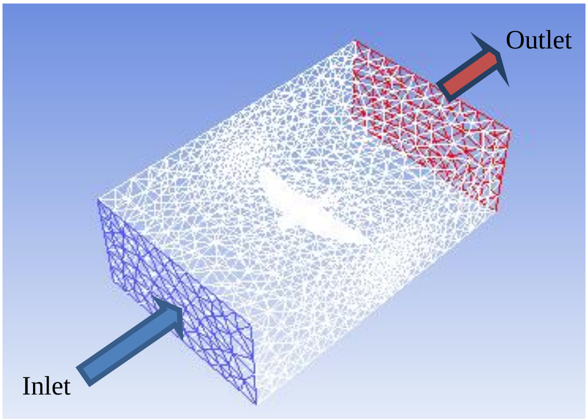

Figure 4: Boundary condition

Results and Discussion

Drag and lift coefficients

Three-dimensional steady-state analysis of the Barn Swallow bird has been performed in Ansys Fluent version 15 at the Reynolds number, Re = 48000 which is equivalent to 13 m/s as the approximate top speed of Barn Swallow. The angle of attack α of the model is varies from -32° to 32°. The simulation results have been plotted and being compared with the experimental data by Yusoff et al. [6]. Figure 5 shows the lift coefficient curves of present work and the experimental work [6]. In general, both curves show a quite similar profile with the higher values are observed for the simulation results. Such high differences could be explained as follows: the Barn Swallow model in CFD is a solid surface model but the real one in experiment has feathers, thus the CFD model is somewhat too ideal. This consideration has been taken is to avoid high complexity of CFD. With such comparison, the real Barn Swallow in experiment case which has feathers at body, it could possibly reduce the pressure and skin drags significantly. The simulation curve shows early stalled angle i.e. $C_L \approx 3$ which occurs at 10° whereas up to α=32°, there is no obvious stalled point for the experimental case. It is believed that the feather has played a significant role to delay the stalled angle. The feather has prevented the separation flow to occur at the upper side of the wing even at relatively large angle of attack i.e. α=32°. At α=0º, the value of C_L is 2.36 while at α=32°, lift coefficient is approximately 1.74.

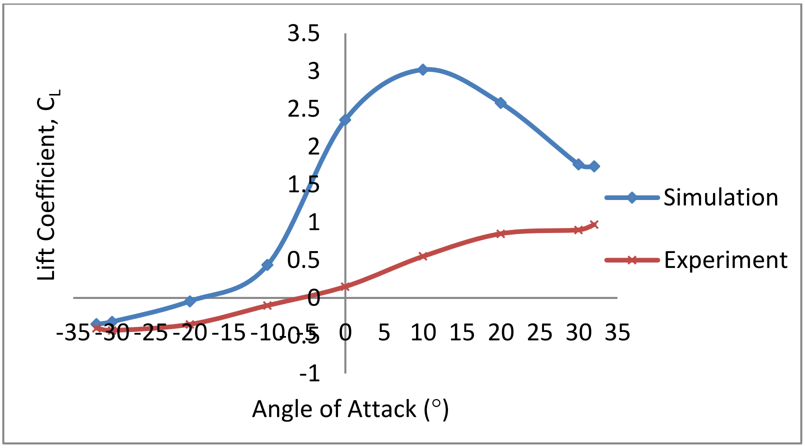

Figure 5: Lift coefficient curves

Drag coefficient curves against angle of attack are shown in Figure 6. The profile of the both drag curves have the 'V' shape. Similar to the lift curve, the simulation values show higher compared to the experimental data by Yusoff et al. [6] due to the feather effects as explained in Figure 5 above. The C_D is increased with the increasing of angle of attack α, in both positive and negative directions. In simulation result, the highest value of C_D=0.75 is occurred at α= 32°.

Lift to drag (L/D) ratio is an important parameter to determine the aerodynamics efficiency of a moving object. It could be explained that for an aircraft, the level of thrust required is depending on data of L/D ratio against angle of attack. The L/D ratio curves of Barn Swallow are shown in Figure 7. From the figure, the maximum L/D ratio for the simulation results is 7.4 at α=10° whereas the maximum L/D ratio of experiment [6] is 3.05 at α=10°. The differences of maximum L/D ratio between simulation and experiment is about 50%. The simulation drag polar curve of Barn Swallow is shown in Figure 8. The drag polar is a comparison of drag and lift with the angles of attack values are not really relevant. In the Figure 8, the highest value of C_L is 3.02 which at C_D=0.42.

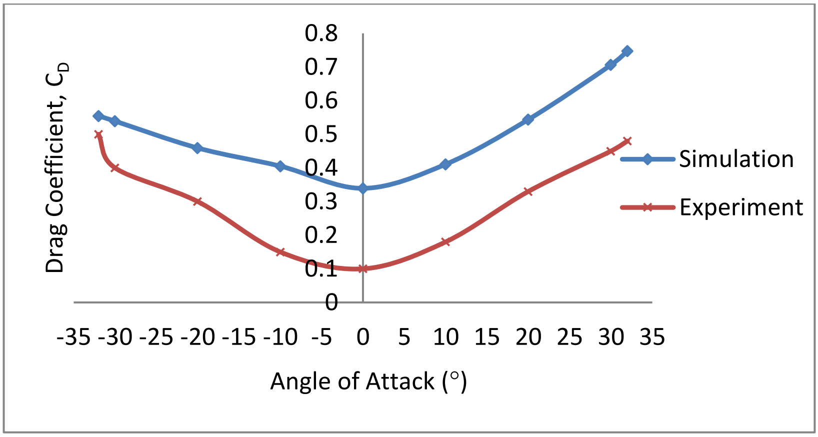

Figure 6: Drag coefficient curves

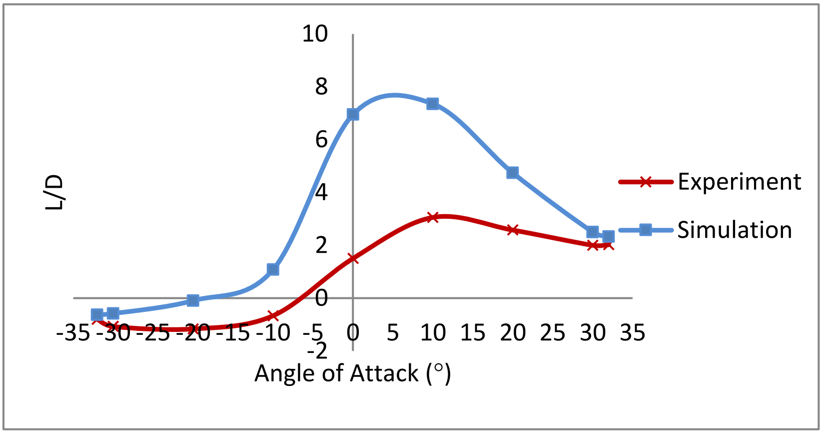

Figure 7: The lift to drag (L/D) ratio curves

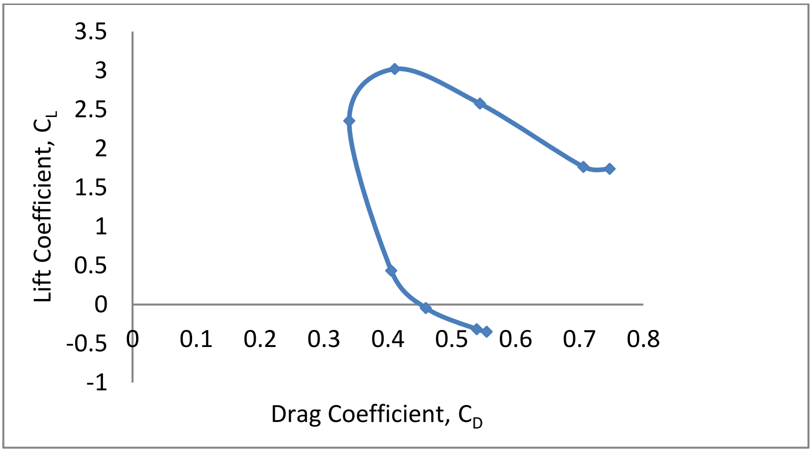

Figure 8: Simulation drag polar curve

Pressure contour around Barn Swallow

The pressure contours around the Barn Swallow for the angles of attack, α of -10° (declination), 0° (horizontal) and 10° (inclination) are shown in the Figures 9, 10 and 11 respectively. In the contours, the showing values are the values of increase or decrease from the ambient pressure. For all angles of attack, the highest pressure occurs at the beak and the wing leading edge. The upper side of the wing experiences lower pressure compared to the down side of the wing.

Figure 9 depicts the pressure contour when the angle of attack is -10°. In the figure, the highest pressure increases is about 126 Pa from the ambient pressure and is occured at the beak and the upper side of leading edge whereas the highest pressure decreases is at lower surface of the wing which is about -43.6 Pa from the ambient pressure. Therefore, the pressure diffence between the upper and the lower of the wing for the case of α= -10°, is about 169.6 Pa. For the case of α= 0° (Figure 10) in which the air flow is in parallel with the bird, the beak and the frontal leading edge of the wing experience the highest pressure increases (about 130 Pa from the ambient pressure). Towards the wingtip, the pressure is the lowest which is about -220 Pa from the ambient pressure. Thus, the pressure difference between the upper and lower wings for the case of α= 0°, is about 350 Pa.

In Figure 11 in which the case of α=10°, the upper wing experiences -134 Pa from the ambient pressure while at the lower wing, the pressure is about 251 Pa. Thus, the pressure difference between the upper and lower wings is about 385 Pa at which it could possibly the stalled point of Barn Swallow (Figure 5). From the Figures 9, 10 and 11, the pressure difference between the upper and lower wings is as predicted based on the theory of flight, where α increases, the pressure difference also increases. This CFD work is not just to confirm the theory of flight on the Barn Swallow, in addition it reveals the significant values of pressure difference between the upper and lower wings for different angles of attack.

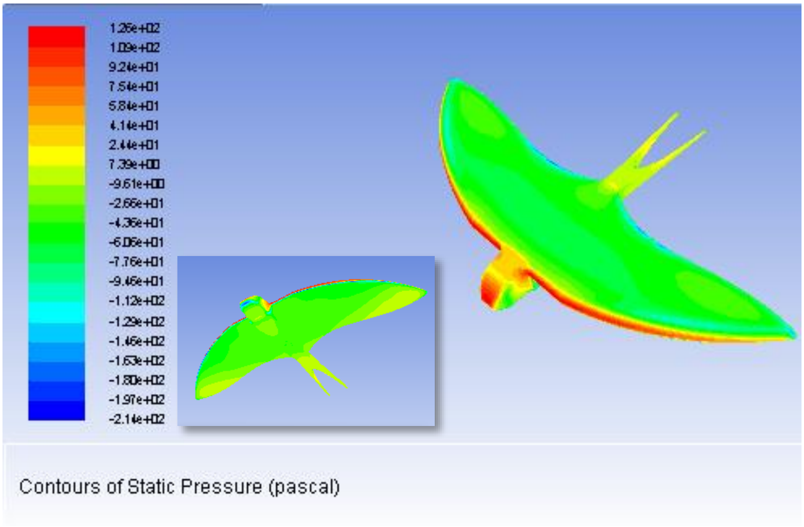

Figure 9: Pressure contour at α= -10°

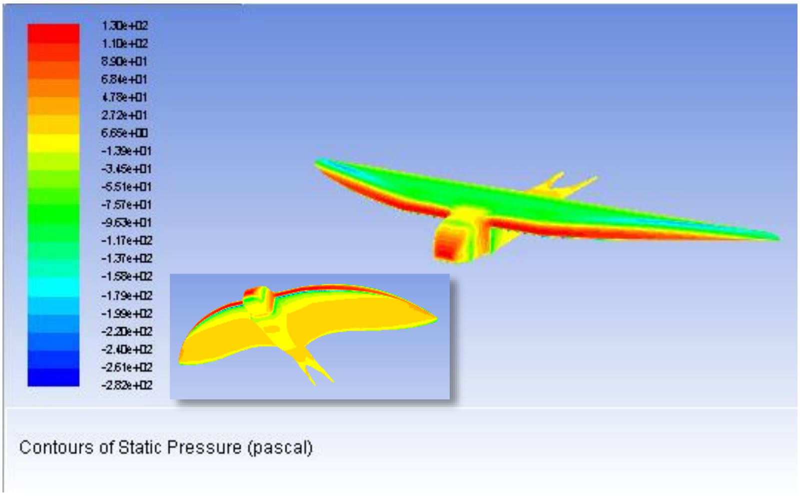

Figure 10: Pressure contour at α= 0°

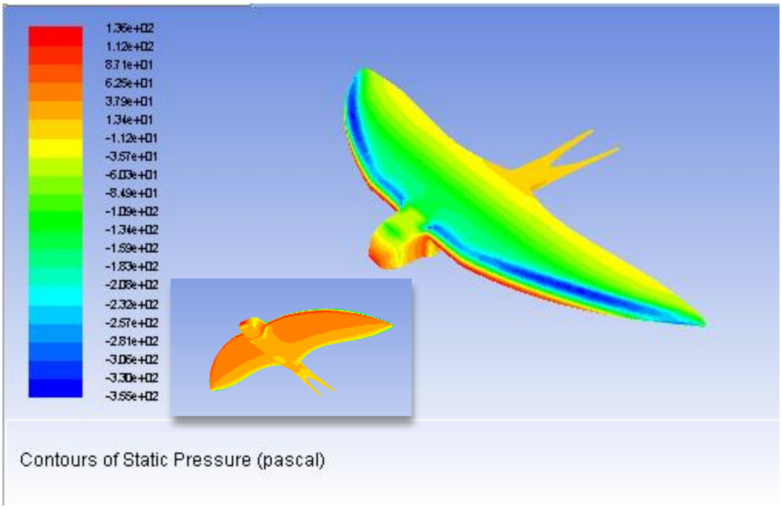

Figure 11: Pressure contour at α= 10°

Velocity vector around Barn Swallow

Figures 12, 13 and 14 depict the velocity vector around Barn Swallow at angles of attack -10º (declination), 0º (horizontal) and 10º (inclination) respectively. For the case of α= -10° as indicated in Figure 12, the velocity at the upper wing is about 14.5 m/s whereas at the lower wing, the velocity is about 17.8 m/s. At the beak and leading edge of the wing i.e. the highest pressure region, the velocity is at lowest which is about 1.11 m/s. When compared to the free stream velocity, the highest velocity shows an increment of about 37%. For the case of α= 0° (Figure 13), the highest velocity occurrs at the mid upper surface of the wing, which is about 21 m/s. At the lower wing surface, the velocity of air is about 13 m/s. At the beak and wing leading edge, the velocity is at lowest which is about 1 m/s. When compared to the free stream velocity, the highest velocity shows an increment of about 61.5%.

The velocity vector for the angle of attack, α= 10º is shown in the Figure 14. The highest velocity occurs on the upper wing which of about 25 m/s whereas the lowest velocity is about 0.02 m/s i.e. almost stagnant air at the small spot at the beak and wing leading edge. At the lower surface of the wing, the velocity is predicted 8 m/s. When compared to the free stream velocity, the highest velocity shows an increment of about 92%.

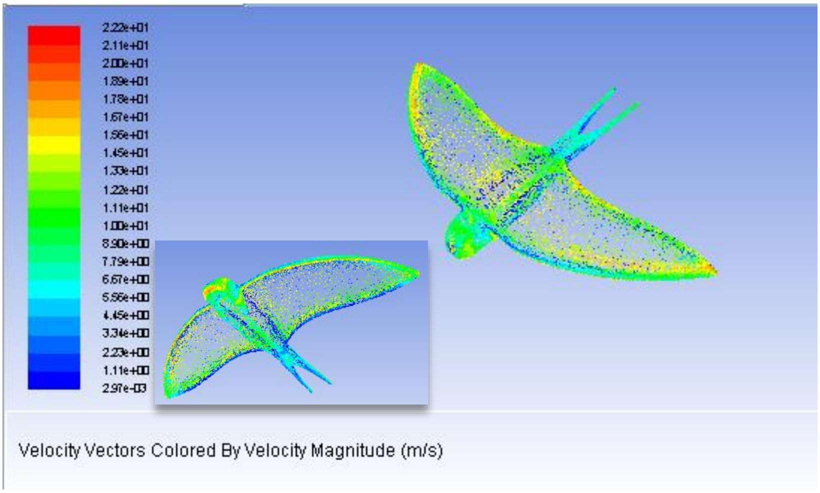

Figure 12: Velocity vector at α= -10°

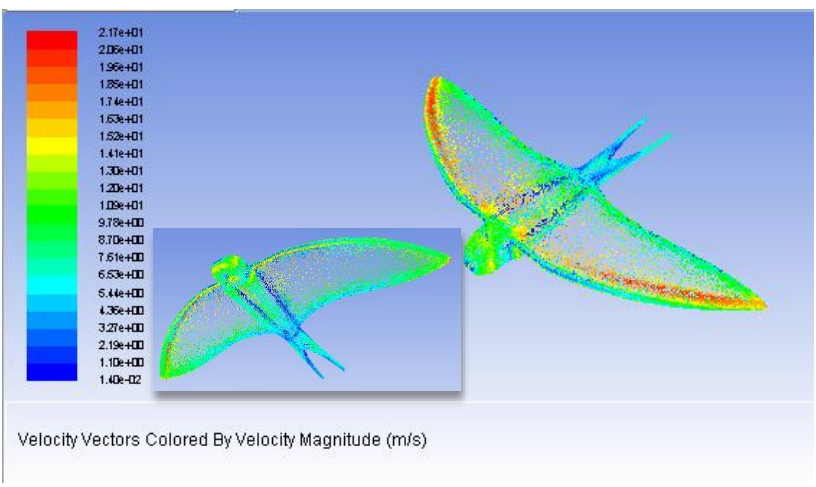

Figure 13: Velocity vector at α= 0°

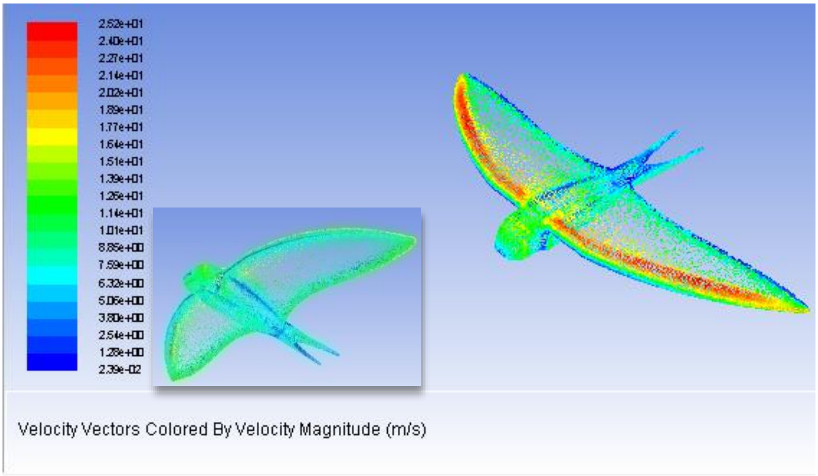

Figure 14: Velocity vector at α=10°

Conclusion

Simulation study of aerodynamics performance of Barn Swallow bird during gliding at its top speed (13 m/s) using a CFD code i.e. Ansys Fluent version 15 is successfully carried out. The simulation results have been compared with the experimental data by Yusoff et al. [6]. From the result of lift coefficient, it shows that the stalled angle occurs at the α=10°, relatively small angle of attacks compared to the experimental data [6]. These significant discrepancies of lift and drag between simulation and experimental works are believed due to the simplification of bird model in CFD. The Barn Swallow is modelled without feather attached on the wing and body, thus can be said that the feather has delayed the separation point and reduces the friction drag. Overall contours illustrate that high velocity and low pressure occurred at the upper wing and wingtip meanwhile the parts like beak, trailing edge, lower wing and also the tails have low velocity with a high pressure in nature which obeyed the Bernoulli's principle.

Analysis of pressure around the Barn Swallow shows that the pressure difference between the upper and lower wings is found increases when the angle of attacks increased with the pressure difference 169.6 Pa, 350 Pa and 385 Pa for the respective α= -10º, 0º and 10º. Meanwhile in velocity analysis, it is found that the maximum velocities with respect to free stream velocity is increased with the α increases. From the result, the increment is about 37%, 61.5% and 92% for the respective α= -10º, 0º and 10º.

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