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Aerodynamics Investigation of Delta Wing at Low Reynold's Number

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ABSTRACT

A numerical simulation has been carried out to investigate the aerodynamics of an oscillating delta wing and to evaluate the flow structure over the leading edge at different low Reynolds numbers. The numerical results of coefficient of lift (CL) vs angle of attack is validated with the experimental results from the previous study. Effects of Reynolds number and angle of attack is investigated for the wing lift coefficient, and the aerodynamic efficiency. Pressure contour and turbulence kinetic energy are also observed for each case. Vortex formation from each case is noted from pressure contour and lift coefficient. The stall condition is also observed. Considering the three Reynolds number at max CL, which is at angle of attack of 40 degrees, the CL only increased by 0.01, which is not a very significant increase. But L/D ratio has in-creased significantly for Reynolds number in the range from 8x104 to 1.5x105 and from Re 1.5x105 to 2.68x105. Whereas for each Reynolds number, the lift coefficient CL seems to attain highest value of 0.4 at angle of incidence between 10 degrees and -10 degrees to -20 degrees.

Keywords:
Delta wing, angle of attack, MAV, oscillation, ANSYS fluent, SST *k-w*, coefficient of lift.

1. Introduction

Micro air vehicle (MAV), which defined by Korukonda *et al.*, [1] as a micro-size aircraft with dimension linearly not over 150 mm (six inches). The technology is developing extremely fast after the development of microprocessor and small batteries for small-scaled aircraft as it gives extreme advantages particularly in military application. here is also a lot of other equally relevant and extensive use of MAV: reconnaissance, map-ping, surveillance, scientific purpose, police and commercial applications by Kurtulus [2]. Through nature, researchers are inspired by how the small insects flying mechanism works and there is ongoing research on bio-mimicking the insect and bird flights: flapping wing, rotary wing, fixed wing, flexible wing and biplane wing Excell [3]. Delta wing is one form of a fixed wing. The reasons for using fixed wing are for its high efficiency and long flight time. Thus, it will be suitable for long endurance and high range mission where it needs loitering and

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observation, such as for reconnaissance and surveillance mission. It also can fly faster making it highly recommended for enemy chasing, etc.

To embody the delta wing into the MAV, it is important to know the aerodynamic characteristic of the delta wing at low Reynolds numbers, suitable for a low near to ground flight application and with the typical speed of a MAV. The operational Reynolds number range for MAV is extremely low opposed to commercial aircraft or even supersonic fighter aircraft, which operate at $Re > 10^6$. While MAV generally operates at $Re < 2x10^5$ Korukonda *et al*., [1]. While typical speed for MAV depends on the electronics being used, and usually the velocity is around 5-20 m/s [3]. According to Korukonda *et al*., [1], not a very significant amount of re-search is being done in the recent past for both numerical and experimental in the low Reynolds number regime. And whatever that has been done so far shows that aerodynamics efficiency suffers drastically due to flow separation resulting in the formation of separation bubbles.

The structure of the paper is organized as; In Literature Review, section 2.1, delta wing configuration is presented. In section 2.2 and 2.3, the aerodynamics of delta wing, and vortices over a delta wing are explained. Coming to Numerical Methodology section, in section 3.1, Geometrical Modelling is showed. In section 3.2, Finite Element Meshing, Boundary condition, and Turbulence model is elaborated. In section 4, the results and discussion are presented. Lastly in section 5, the conclusion is projected.

2. Literature Review

2.1 Delta Wing Configuration

Delta wing is a wing, shaped like an isosceles triangle when looked from the top view, or inspiringly from the Greek alphabet, delta (Δ). Often having a sharp rearward sweep angle typically at 60° or more. While the angle between the trailing edge of the wing and the fuselage is a right angle, 90° Korukonda *et al*., [1], Polhamus [4]. It is accustomed to having thin aero-foil and a sharp leading edge. Figure 1 below shows few of delta wing types.

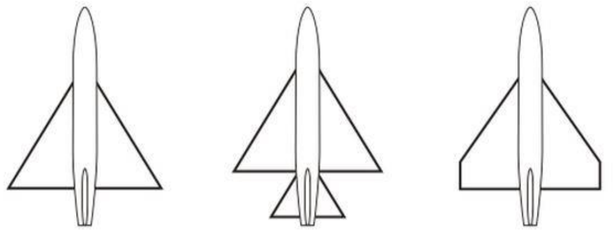


Fig. 1. Some of delta wing types [7]

Each low, moderate, or high sweep angle have significant effects on the flow structure over the delta wing. Moderate sweep wing (non-slender wing) has a sweep angle range between 30^o-50^o which is not optimum for supersonic flight but well-suited for high lift and long-range mission as in case of unmanned aerial vehicle (UAV). Very few study has been conducted on this moderate sweep wing with respect to high sweep wing (slender wing) which has a sweep angle range of $\Lambda \geq 65^o$, where the flow is stable and most-suited for the supersonic flow associated with the delta wing Brett and Ooi [5].

2.2 Aerodynamics of Delta

For aerodynamics characteristic of a wing, the effect of the wing having a leading-edge sweep creates the vortex lift which can cause flow separation that gives more lift to the wing. While having low relative wing thickness can reduce the wave drag if it has enough sweep angle so that the wing leading edge does not touch the shock wave formed at the nose of the fuselage. Paired with the rearward location of the trailing edge of delta wing which will produce high pitching moment. The large surface area of the wing can reduce the minimum speed of the aircraft, which makes the delta wing stable in pitch as it can have a higher stall angle of attack. But due to this large surface area of the wing, it will have more viscous drag for the same amount of lift as it has low L/D ratio Nd [6]. To compensate for the poor low-speed delta-winged aircraft, the angle of attack must be increased during the low-speed regime to gain lift. Due to the high sweep-angle of the delta wing, during high angle of attack, leading edge vortex system will be formed around the delta wing. To realize the fundamental study aerodynamic features and their influence on box wing aerodynamics, CFD analysis was carried out based on various design parameters using ANSYS code Sahana and Aabid [7]. Aabid et al., used CFD simulation to analyze flow variable from inlet to the outlet through supersonic nozzle [8,9]. CFD simulation of wedge for different half-wedge angle and Mach number studied performed using finite element method [10].

2.3 Vortices over a Delta Wing

LEV is originally coming from the lower surface of the wing. There are two dividing streamlines below consist of flow inboard and flow outboard. The flow inboard will travel downstream following the stream-wise velocity component. While the flow out-board is the one who will travel out and try to curl around the leading edge to get to the upper surface Gortz [6]. Provided with a sharp leading edge, the flow gets separated along the leading edge forming a strong shear layer that spiral up resulting in a large bound vortex to form the LEV as shown in Figure 2 and 3.

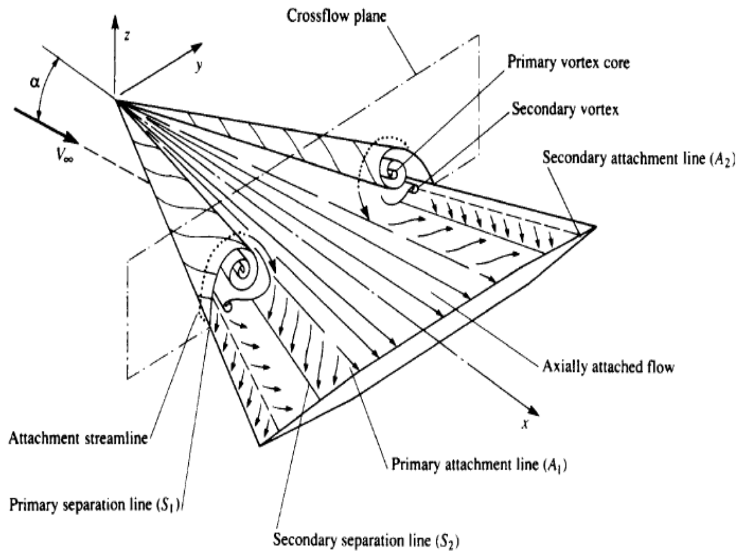


Fig. 2. Schematic of the subsonic flow field over the top of delta wing at an angle of attack [3]

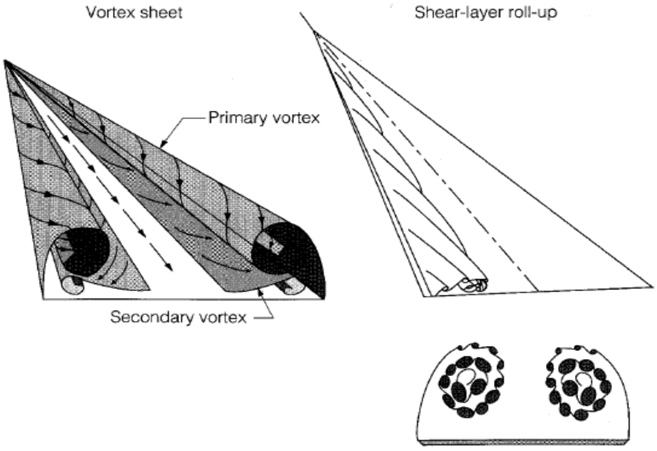


Fig. 3. Formation of Vortex sheet from shear layer spiraling [6]

As the flow passes around the primary vortex and flows back towards the leading edge, an adverse pressure gradient causes the reattached flow to separate forming a secondary counter-rotating vortex (it is also possible to have tertiary structures in the vortex). The formation of the secondary vortex (which is most evident at high incidence) moves the primary vortex core inwards and up-wards above the surface of the wing Allan [11].

This shift is greater if the boundary layer on the upper surface is laminar since flow separation is earlier and forms a larger secondary vortex. Reynolds number has little effect on the structure of the vortices on sharp leading edged delta wings. For the case of a sharp-edged delta wing at high incidence (with fully developed leading edge vortices) the flow pattern depends on Reynolds number Allan [8].

This LEV will induce the increment of velocity near the wall above the wing, where it consequently will produce high suction peaks as the velocity increases, the pressure will drop and sucks more of the air flow. While pressure at the surface below the wing will rise and cause an increment of lift Gortz [6], Buzica [12], and Allan [8] and stalling of the wing is also delayed. The location of the surface suction peaks indicates the location of the primary lead-ing-edge vortices. This results in an increase in the lift- usually referred to as non-linear or vortex lift Allan [8]. It varies approximately by the square of the angle of attack Raymer [13].

From the Figure 4 the response and state of the vortices at high angles of attack are important, as any variation in vortex lift will strongly influences the forces and the moments on the aircraft.

It has been observed by Allan [8] as the sweep angle is in-creased, the strength of the leading-edge vortices decreases (for a given angle of incidence). While the size of a vortex formed by roll up of a vortex sheet is independent of Reynolds number, although the radius of the viscous sub core decreases with increase of the Reynolds number.

When the flight enters stall regime which surpasses the stall angle of attack, the flow separating from the leading edge confronts a very steep adverse pressure gradient and consequently does not roll up into a vortex-like structure. Rather, encloses a massive dead-water region over the entire wing Buzica [9]. Figure 5 below clearly shows the stages of vortex formation and breakdown as a function of the angle of attack and sweep angle.

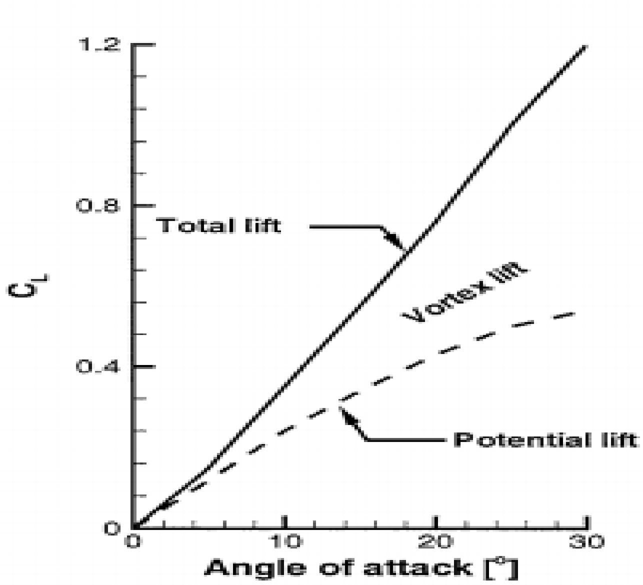


Fig. 4. Potential and vortex lift contribution for a 75° delta wing [8]

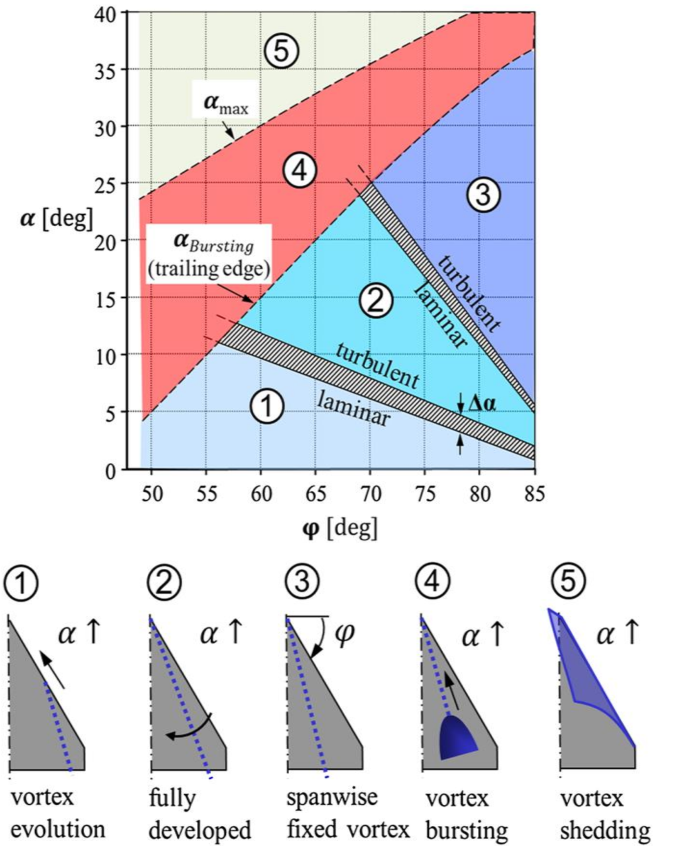
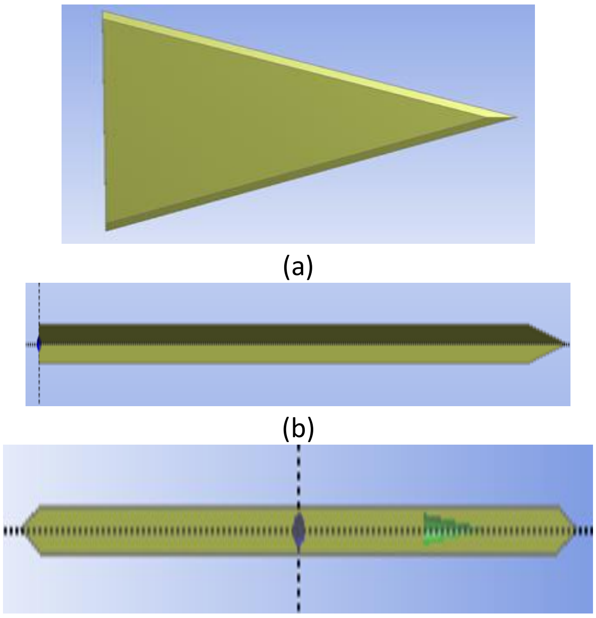


Fig. 5. Delta wing vortex flow stages as a function of angle of attack (α) and leading-edge sweep angle Λ for planar, sharp-edged delta wings [12]

3. Numerical Methodology

3.1 Geometry Modelling

The model is a simple slender flat plate delta wing of 70-degrees leading edge sweep, 0.523494 m (20.61-in) root chord and 0.381 m (15-in) span at the trailing edge. The wing has a sharp bevelled leading and trailing edges(Figure 6).



(a) (b) (c)

Fig. 6. The delta wing model, (a) Top View (b) Side View (c) Back View

An enclosure domain is created around the model. The domain is made a parabolic cone shape, so that the incoming flow can smooth-ly go inside and out without having much trouble with reverse flow. Then, it is made half symmetric around the wing symmetry. After that, 'slice material' option is used to make a multi-block H-H grid for a structural mesh later.

3.2 Finite Element Meshing, Boundary Condition, and Turbulence Model

The simulation was performed on a structured grid with triangular prism around the boundary layer of the wing, and tetrahedral else-where. The main domain has 285686 nodes and 679112 elements. The mesh was refined within the grid near the delta wing for better capturing of the vortices around it. The final mesh was obtained after excessive simulation for mesh independence. The inflation layer has a first wall spacing of y+=1, which is appropriate for the turbulence model used, SST k- ω [6]. The inflation layer also is made to have 12 layers with a thickness according to the Reynolds number of the flow using the formula

$$\delta = \frac{0.37x}{Re^{\frac{1}{5}}} \tag{1}$$

Under the mesh detail (Figure 7) , the sizing of the mesh is set to have an advanced size function of curvature. The relevance center must be fine, smoothing is made high, and have a slow transition.

The resultant average element quality is 0.6172, while it is better to have it less than 1.00, and best is if it is near 1.00. The resultant average aspect ratio is 3.64.

For the boundary condition, the curvy enclosure is set to be an inlet, the flat back of it is set as an outlet, while the symmetric half plane is set as symmetry. The boundary of the delta wing body inside is set as a wall. The flow field is assumed to be fully turbulent, so the two equation SST k- ω is applied, which according to Hadidoolabi [14] and several other researchers, very well capture the vortex can flow over a delta wing. Density is set to be ideal gas and viscosity by Sutherland's law. Static simulation for the oscillation of the delta wing for the angle of attack -40^o to +40^o was studied.

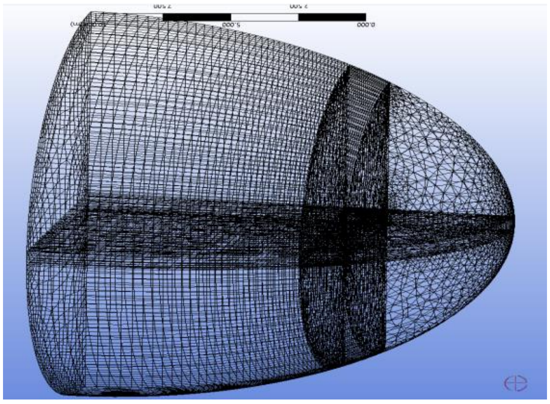


Fig. 7. Finite Element Mesh around the delta wing

4. Results and Discussion

The experimental results shown by Soltani *et al*., [15] in their study of "Measurements on an Oscillating 70^o Delta Wing in Sub-sonic Flow" is as Figure 8 followed by Figure 9 which is the comparison done between experimental and a numerical method. It agrees well when compared with the experimental result done by Soltani *et al*., [12], for the same geometry of 70^o swept delta wing with the same dimension.

As for this study, a set of multiple low Reynolds numbers were tested. For all the three low Reynolds number tested, Re = 80 000 (V_∞ = 4.46 m/s), Re = 150 000 (V_∞ = 8.371 m/s), Re = 268 783 (V_∞ = 15 m/s), C_{Lmax} increases from 1.16, 1.17, 1.18 respectively as the Reynolds number increases. Aerodynamic efficiency also indicates that it assumes higher values as the Reynolds number increases. Turbulent kinetic energy also shows significant increment in its value as the Reynolds number increases, which indicates that the leading-edge vortex (LEV) strength is getting stronger as Reynolds number is increases.

Considering the three Reynolds number at max C_L, which is at the angle of attack 40 degrees, the C_L is only increased by 0.01, which is not exactly a very significant increase (Figure 10). This conforms well what Polhamus [16] has stated that Reynolds number does not have a significant effect on delta wing lift. Soltani *et al*., [12] also said that Reynolds number does not influence much for the sharper wing. But L/D efficiency has significant increase of 0.09 and 0.1 respectively for Reynolds number in the range from Re 8x10^4 to 1.5x10^5 and from Re 1.5x10^5 to 2.68x10^5.

While for the each Reynolds numbers, C_L seems to attain highest value of 0.4 at an angle of attack in the range from 10º to 20º and -10º to -20º (Figure 11). This result indicates that LEV starts to form at this point where the lift from leading edge vortex has surpassed the potential lift. (Figure 12 and 13). At a higher angle of attack of 30º to 35º (pitch up) and -30 degrees to -40 degrees (pitch down), C_L is increasing but this increase is marginal of 0.07 for pitch up, and 0.03 for a pitch down.

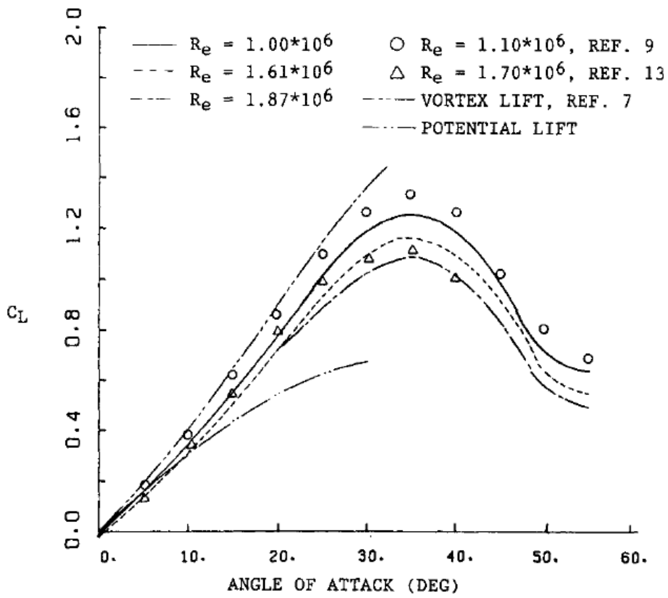


Fig. 8. Experimental results from Literature

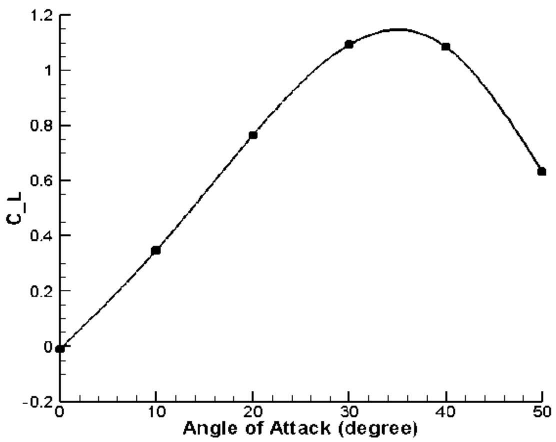


Fig. 9. Numerical Results for Comparison

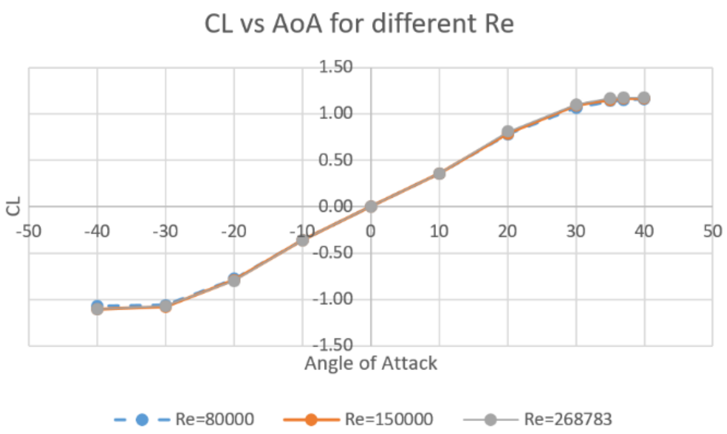


Fig. 10. C_L vs. AoA at different Re

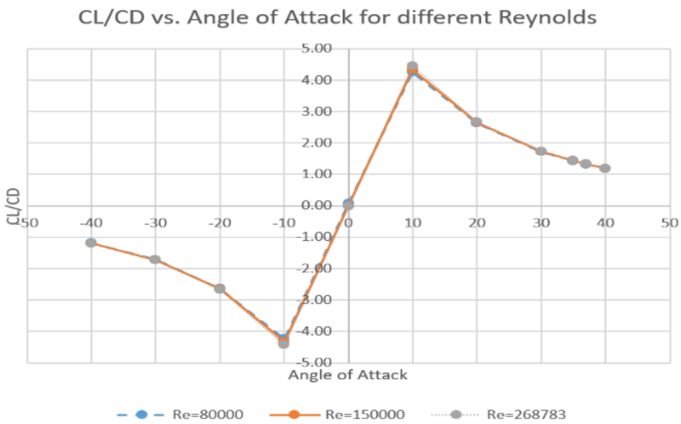
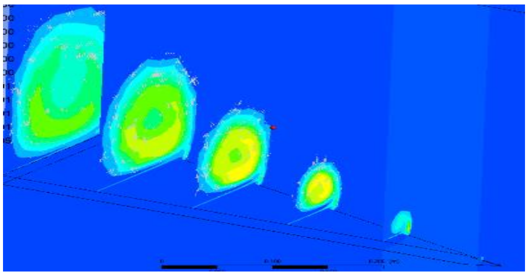
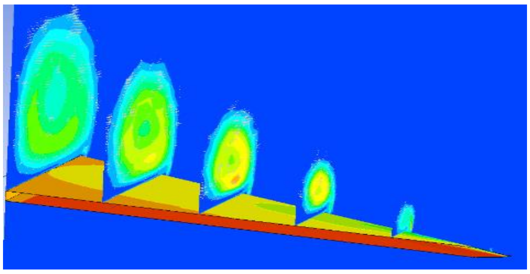


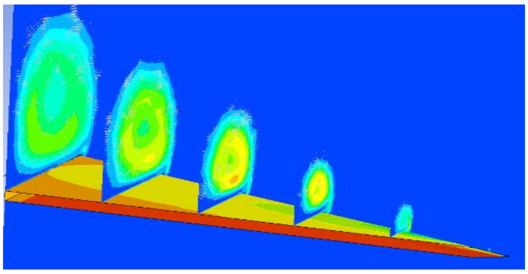
Fig.11. C_L / C_D vs AoA at different Re



(a)

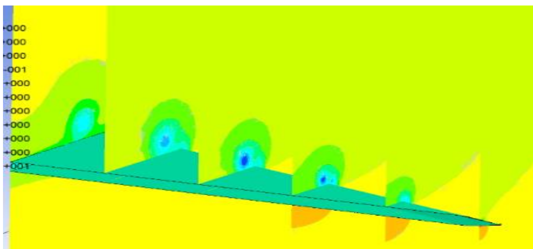


(b)

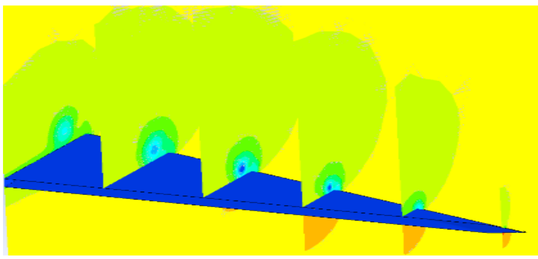


(c)

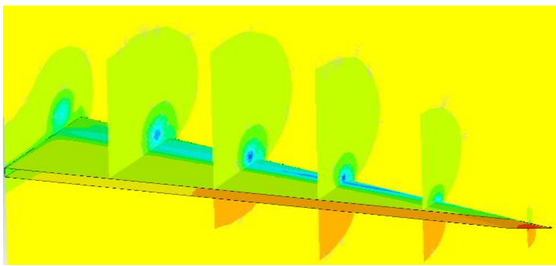
Fig. 12. Turbulence Kinetic Energy contour at AoA = 40deg for (a) Re = 80000 (b) Re = 150000 (c) Re = 268 783



(a)



(b)



(c)

Fig. 13. Pressure contour at AoA = 40deg for (a) Re = 80000 (b) Re = 150000 (c) Re = 268 783

5. Conclusions

The lift on sharp leading-edged delta wing is insensitive for the low Reynolds numbers from the range of 80, 000 and 200, 000 for static condition, so it is easier to predict the flow characteristics of a Micro Air Vehicle (MAV) that is not always using the same power source which affects the MAV velocity. But the C_{Lmax} for each case of Reynolds number showed some increment. The aerodynamic efficiency also increases marginally. The higher turbulent kinetic energy for each Reynolds number increment shows that the vortex energy is stronger as Reynolds number increases.

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