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Research paper

Effect of Outward and Inward Dimple Located on Different Positions of Aerofoil Section at a Typical Low Reynolds Number

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Abstract

The main objective of this paper is to investigate the enhancement of the aerodynamic characteristics of NACA 4415 aerofoil section. This enhancement includes introduction of dimple on the aerofoil section which creates vortices and delays the flow separation. The work describes the computational analysis of dimple at different positions for different aspect ratios. This study has been carried out on an aerofoil section for a typical low Reynolds number of 47,000 using CFD tool ANSYS FLUENT.

Keywords: *Inward dimple; Laminar separation bubble; Lift coefficient; Ratio of lift to drag coefficient ; Outward dimple; Vortex generators*

1. Introduction

Birds and insects have always fascinated towards aerospace field and motivated to strive hard. Aircrafts are vehicles which are capable to fly by being supported by air or atmosphere. MAV (Micro Aerial Vehicle) and UAV (Unmanned Aerial Vehicle) and are part of them. The forces acting on aircraft are lift, drag, thrust and weight besides moments. All these forces take a prominent place for an aircraft during flight while wings are the surfaces that produce lift on an aircraft. Airfoils are streamlined bodies which provide lift with minimum drag**.** Airplane wings produce lift by creating pressure difference between top and bottom surfaces. Lifting surfaces (airfoil section and wing plan form) for any aircraft design plays a major role. Thus it is essential to achieve maximum aerodynamic efficiency at its operational Reynolds numbers. An aerofoil design directs the overall performance and aerodynamic efficiency of an aircraft. Aerodynamic efficiency is defined in terms of the ratio of the net lift force generated to the drag force. Hence performance of an aircraft can be evaluated.

An MAV/UAV (Micro/Unmanned Aerial Vehicle) is defined as micro sized aircraft with size restriction and is autonomous which are mostly used for civilian and military applications. The operational range of Reynolds number of these MAV/UAV is extremely low with respect to the commercial aircrafts which operate at Reynolds numbers $>10^6$. UAV and MAV fly at low Reynolds number and low maintenance cost unlike aircraft. In this low Reynolds number range at lower angles of attack, the flow over upper surface of the airfoil is laminar boundary layer and is liable to separate. When this laminar boundary layer separation occurs, the progression of separated shear layer has a very strong impact on the entire flow field. Generally for this Reynolds number, the flow does not reattach whereas it leaves a wide wake behind the aerofoil. While at higher Reynolds number, the separated shear layer undergoes laminar to turbulent transition over the aerofoil surface. This might eventually lead to reattachment of the separated flow, closing the re-circulating flow into a separation bubble as shown in figure 1.

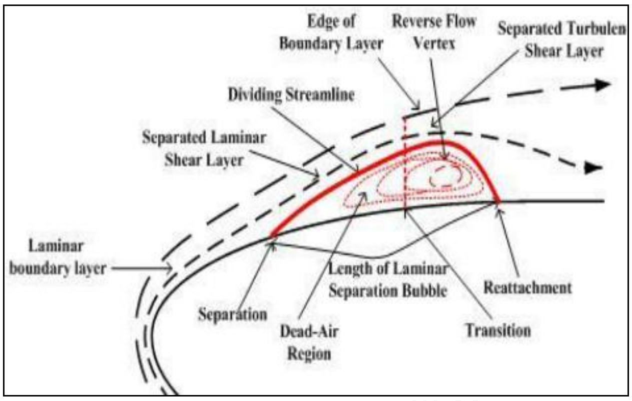

Fig. 1: Laminar Separation Bubble [1]

The pressure distribution on the section changes due to the occurrence of laminar separation bubble on the aerofoil surface. The pressure distribution is almost same till the point where the flow transition occurs from laminar to turbulent. The flow reattaches to the surface as it is active and energetic and the pressure gains to recover to its original as it occurs in inviscid flow. Short bubble and long bubbles are two types of laminar separation bubble. The classification of the laminar separation bubble is very essential as it affects the aerofoil performance and plays a crucial part in attaining lift and reduction of drag when it comes to the design of the aerofoil. As Reynolds number increases, the laminar separation bubble size is reduced. Hence it is very important to identify the type of laminar separation bubble that is forming and also to understand the evolution of shear layers. [8]

Laminar separation bubble (LSB) influences aerofoil performance with attaining lift and drag reduction as shown in figure 2. If the ability to predict the formation of the laminar separation bubble is done, then elimination of the laminar separation bubble can be done using vortex generators.

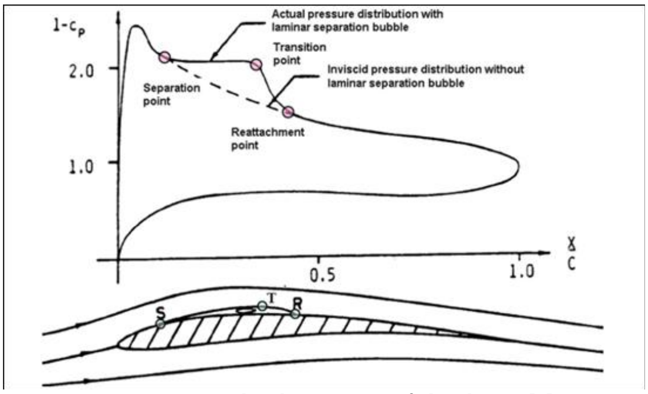

Fig. 2: Pressure distribution over airfoil with LSB [2]

Vortex generators are the most frequently used modifications to an aircraft surface for enhancement of lift which can create turbulence by creating vortices which delays the boundary layer separation resulting in decrease of pressure drag and also increase in the angle of stall as shown in figure 3. It helps to reduce the pressure drag at high angles of attack and also increases the overall lift of the aircraft. In this paper, the effect of dimple as a conventional vortex generator is studied computationally on NACA 4415 airfoil. Dimples are quite effective at different angles of attack and also can change angle of stall to a greater extent.

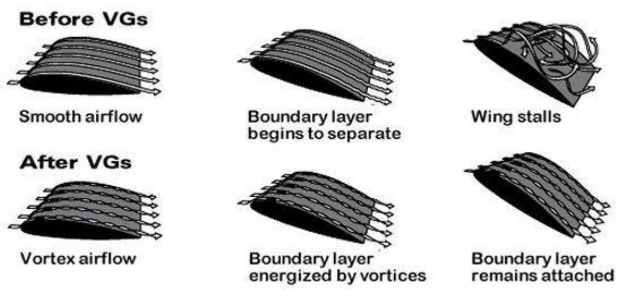

Fig. 3: Effect of vortex generators [3]

A slight natural indentation on the surface is called dimple. They behave as protrusions on the surface of the wing. These dimples induce turbulence at lower Reynolds number, providing extra energy or momentum to the boundary layer and delaying the flow separation. This leads to smaller wake or swirl regions around the body thus reducing the total drag and hence improving the aerodynamic lift by changing the stall angle as shown in figure 4 [7 and 12] . A stall is a condition in which as angle of attack increases beyond a certain point, lift begins to decrease. The angle at which this occurs is called critical angle of attack.

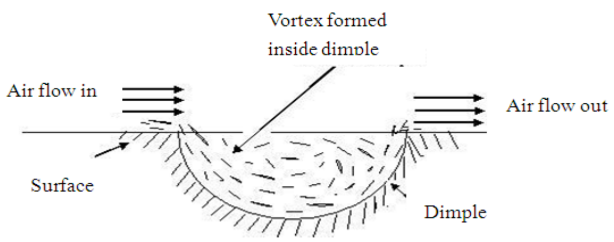

Fig. 4: Vortex formation inside dimple. [4]

The air flow is accelerated over the surface of the aerofoil with dimple and hence the boundary layer changes from laminar to turbulent. When dimples are incorporated over the airfoil section it makes an aircraft more maneuverable and increases the aircraft's fuel economy. Flow separation over the airfoil begins to occur at small angles of attack while attached flow is still dominant. As angle of attack increases, the separated regions on the top of the wing increase in size and delay the wing's ability to create lift [11]. At the critical angle of attack, separated flow is so dominant that further increase in angle of attack produce less lift and more drag.

There are mainly two types of dimples based on shape namely inward dimple and outward dimple [10]. Considering the chosen speed of the aerofoil and the circumstances at which it flies, the model chosen for this investigation was viscous-laminar model also at the speed at which an MAV flies generally encounters a laminar flow over the aerofoil [9].

2. Literature Survey

Importance of vortex generators has been investigated in recent times as they tend to reduce the drag and increase the lift in a particular range of angle of attack. The studies on dimple have been of extreme benefit for making an aircraft more maneuverable by changing the flow characteristics. The literature survey has been made on change in flow characteristics as mentioned below:

- According to the paper "**Effect of dimple at low Reynolds number flow over NACA 4415 aerofoil**" by **Aswatha Narayana et.al** best results were found for the dimple position at 90% of the chord from the leading edge and with aspect ratio of 0.4, i.e. (2/5) mm. At other positions of the dimple, the lift and drag values were not sufficient enough or to meet the standards of a UAV wing design. Hence the following dimple position was considered [6].
- According to the paper "**Computational analysis of cavity effect over aircraft wing**" by **Booma Devi and Dilip A. Shah.** The results show that lift is increased for the cavity placed on wing than that of plain base model. Introduction of dimple is an effective controlling method to increase in stall angle and lift coefficient. The results showed inward placed cavities are showing superior control over the stall phenomena [13].
- Paper entitled "**Aerodynamic analysis of dimple effect on aircraft wing**" by **Livya et.al** shows both computational and experimental analysis of dimple effect on aircraft wing, using NACA 0018 airfoil. Dimple shapes of semi-sphere, hexagon, cylinder and square were selected for the analysis. This analysis favors the dimple effect by increasing L/D ratio and providing the maximum aerodynamic efficiency. The results showed that semi-sphere shows 20% lower value of lift coefficient. Square as well as compound configurations behave in a similar manner. Square dimple shows effective increase in coefficient of lift [9].
- "**Effect of performance of an MAV/UAV with a dimpled wing surface**" by **Shravan Korukonda and Swaroop Nagnoori** analysed the 3D- CFD simulations at Re 140,000 on an E212 wing by considering a segment with only one dimple on it, to evaluate its aerodynamic efficiency both in the presence and absence of dimple on the upper surface. It was noticed the presence of dimple did not alter the pressure drag owing to its aerodynamic shape. But it did improve the overall aerodynamic efficiency [11].
- "**A review on study of aerodynamic characteristics of dimple effect on wing**" by **Saarang S. Mahamuni** briefly explains the overall review over the change in aerodynamic characteristics of an airfoil by applying certain surface modifications in the form of dimples [12].
- "**Conceptual study of airfoil performance enhancements using CFD**" by **Armin Ghoddoussi [2011],** Master of Science thesis, Wichita state university, worked on inward dimples located after and before the maximum thickness to preserve laminar flow closer to leading edge. The study indicates

as the dimple move towards leading edge, maximum lift decreases and drag increases [14].

- "**Flow control over airfoils using different shape dimples**" **IPCSIT vol. 33 [2012] IACSIT press, Singapore** by **Deepansu Srivastav[2012]** presented work on inward and outward dimples on NACA 0018. It is shown that outward dimple has noticeable decrement in drag coefficient [15].
- "**Experimental study- flow characteristics of dimpled wing**" **International journal of engineering research and technology vol.3 [2013]** by **K. Manoj Kumar, P. Manivannan, E. T. Chullai** experiments were done in a water flow channel in low speed wind tunnel, over awing section of NACA 2412. Addition of hemi-spherical dimple at 20% of chord has altered the flow characteristics over a surface of an airfoil. It has been shown that addition of dimples has proven to be effective in altering various aspects of the flow structure [16].

3. Methodology

For the current study NACA 4415 airfoil section is considered which can be used for MAV/UAV applications. Details of the airfoil sections and the schematic are shown in figure 5.

NACA 4415 airfoil	
Max thickness:	15% at 30.9% chord.
Max camber:	4% at 40.2% chord
Max camber position:	40%

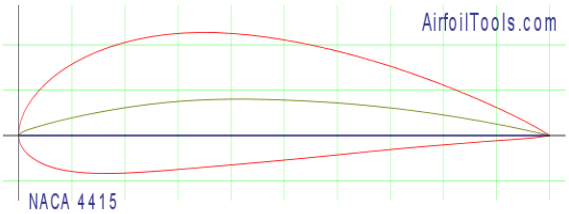

Fig. 5: NACA 4415 airfoil section [5]

3.1 Geometry

The geometrical design of NACA 4415 aerofoil design was carried out in ANSYS WORKBENCH as it is highly automated and its flexibility to customize according to the type of application. The geometry of the aerofoil was created as shown in figure 6.

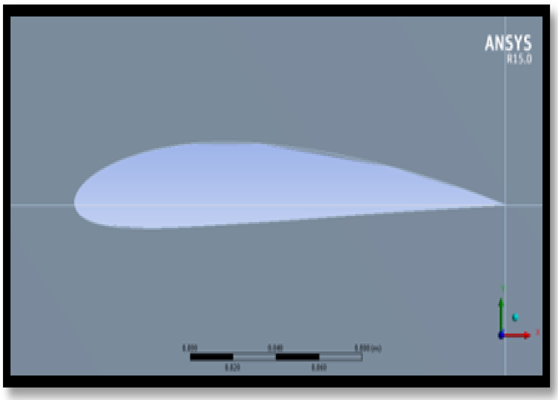

Fig. 6: Geometry of NACA 4415 aerofoil created in ANSYS

The geometries were created in ANSYS geometry modeling for inward dimple and outward dimple with different aspect ratios on different locations of chord length with dimple on the wing at 90% of chord length with 0.4 and 0.2 aspect ratio (AR) and also at 80% of chord length with 0.2 aspect ratio (AR) of dimple. One of the inward dimples is shown in Figure 7.

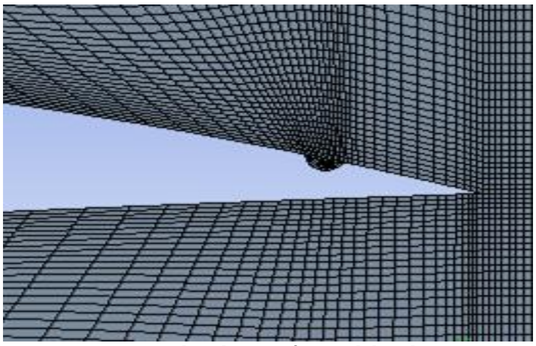

Fig. 7: closed view of inward dimple

The domain was created around the aerofoil which is five times the length on the chord to capture the flow around the aerofoil as shown in figure 8.

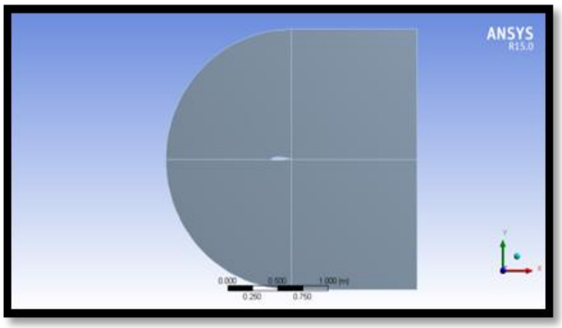

Fig. 8: Domain around the aerofoil for NACA 4415

3.2 Meshing

ANSYS meshing was used as it is produces most appropriate mesh. ANSYS meshing is automatically integrated with each solver within the ANSYS workbench. Many different mesh designs were carried out and results were tested. Grid independent studies were carried out for both structured and unstructured mesh and the better results were found in structured mesh as shown in figure 9.

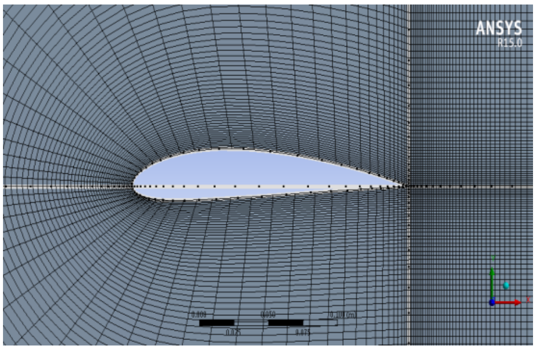

Fig. 9: Structured mesh for the entire domain

4. Analysis

Aerodynamic analysis was carried out using ANSYS FLUENT.15 which is one of the tools for the airfoils, wings and planes operating in low Reynolds number. The software contains broad physical modeling capabilities needed to model flow, turbulence and heat transfer. The analysis for the investigation was carried out using averaged Reynolds Navier-Stokes equations.
Figure 10 shows the reverse flow and the vortex created on the surface of the NACA 4415 aerofoil.

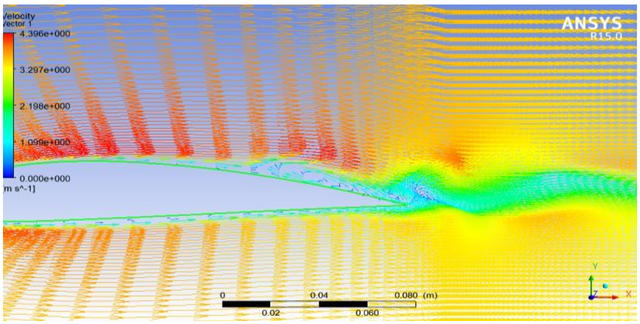

Fig. 10: Velocity vector for NACA 4415

After the analysis was done for the NACA 4415 airfoil, the laminar separation bubbles were spotted at different parts of the aerofoil and at different angles of attack. The drag and lift characteristics were obtained and pressure distribution was plotted in ANSYS workbench as shown in figure 11. After plotting the pressure distribution curve for various angles of attack, the point of drastic decrease in pressure was positioned and dimple was introduced. After setting the position of the dimple, the size of the dimple was experimented with two aspect ratios like 0.2 and 0.4. These aspect ratios were also experimented with various points on the wing at 90% of chord length and also 80% of chord length. The best results were found at 0.2 aspect ratio of dimple at 80 percent of the chord length. Hence with the same aspect ratio and position, the outward dimple was placed and research was carried out.

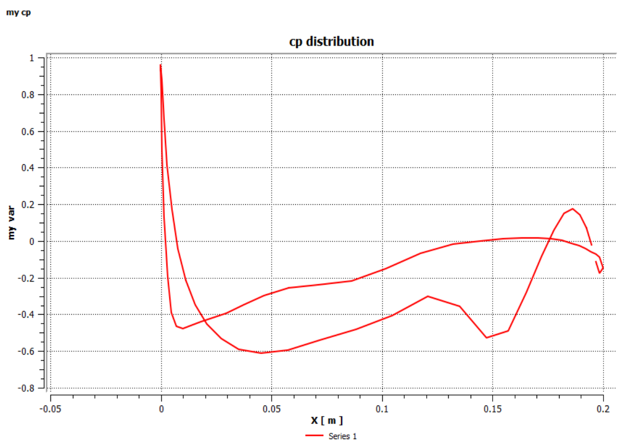

Fig. 11: Pressure distribution curve

The figures 12, 13 and 14 show different velocity contours at zero degree angle of attack with three different conditions - outward dimple, inward dimple and plain airfoil. It is observed that due to vortex generators, boundary layer separation is delayed resulting in decrease in the pressure drag and also increase in the stall angle.

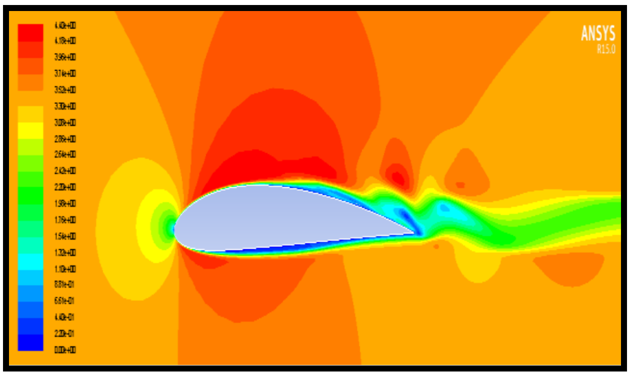

Fig. 12: velocity contour at 0 degree AOA without dimple

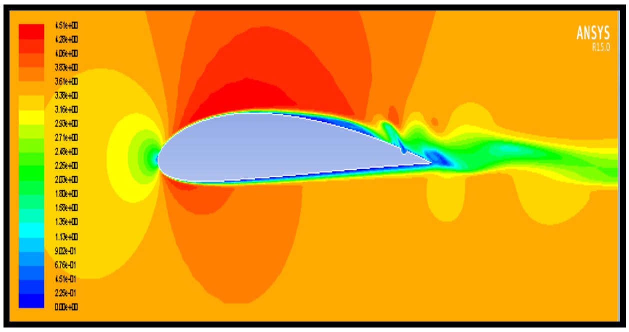

Fig. 13: velocity contour at 0 degree AOA with inward dimple

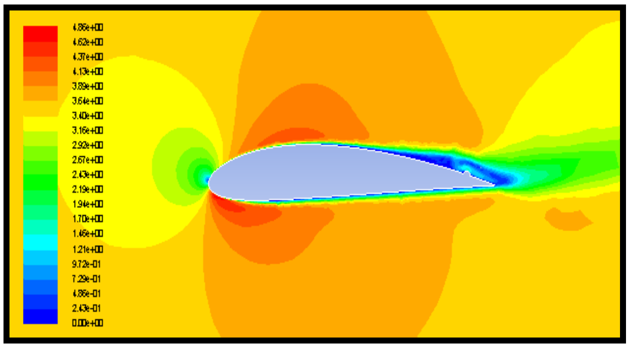

Fig. 14: velocity contour at 0 degree AOA with outward dimple

5. Results

5.1 Lift Coefficient

Figure 15 shows lift coefficient against angle of attack for different positions of dimple on the airfoil section. The cases considered are without dimple, outward dimple on 90% of chord length, and structured mesh dimple at 90% and 80% of chord length with 0.2 and 0.4 AR of dimple.

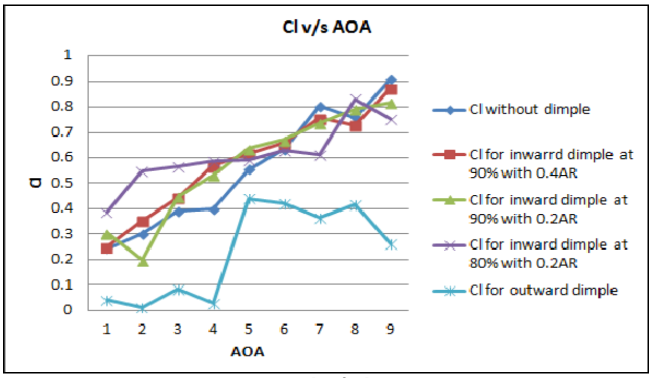

Fig. 15: Graph of Cl v/s AOA

It is observed that aerofoil without dimple shows small lift. When dimple is introduced, lift coefficient is gradually increased. In the present work, inward dimple is placed at different positions of the airfoil for different aspect ratios. Lift is high for inward dimple at 80% of chord length for 0.2AR compared to inward dimple at 90% of chord length for 0.2AR and 0.4AR at 0, 1, 2, & 3 degrees of angles of attack. As angles of attack increases, lift increases for both the positions.
The outward dimple has very high reduction of lift compared to the standard aerofoil. At 5 degrees of angle of attack, lift is high and then drops.

5.2 Drag Coefficient

It is seen in figure 16, with the introduction of inward dimple reduces the drag coefficient at low angles of attack till 8 degree. The drag coefficient is highest for the plain airfoil. But for dimpled airfoil at different positions, the drag coefficient is significantly more compared to the airfoil without dimple. In the case of outward dimple, the drag has significantly increased compared to the standard airfoil. There is a drop in the Cd curve at 8 degree angle of attack compared to the inward dimple and standard airfoil, but the curve increases as the angle of attack increases.

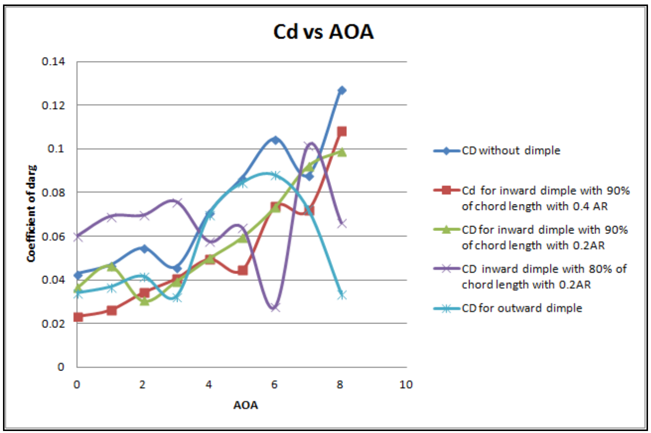

Fig. 16: Graph of Cd v/s AOA

5.3 Lift to Drag Ratio Analysis

The introduction of inward dimple increases the Cl/Cd compared to the standard aerofoil and outward dimple as shown in figure 17. At 0, 1, 2 and 3 angles of attack, Cl/Cd is comparatively small for dimple at 80% of chord length with 0.2AR, and is seen maximum at 7 degrees of angles of attack. The lift to drag ratio also helps us to indicate the efficiency of the aerofoil. When compared to the overall efficiency, the inward dimple has the edge over the other two aerofoil profiles at low angles of attack which are good enough for an MAV to maneuver.

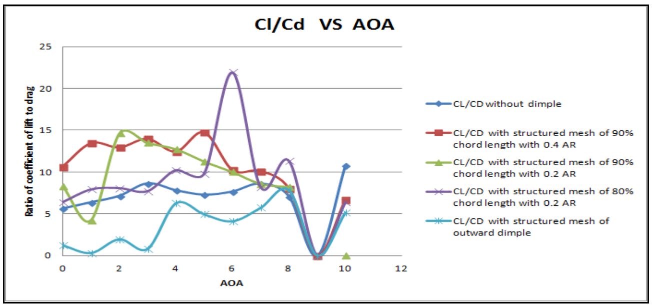

Fig. 17: Graph of Cl/Cd v/s AOA

As in figure 18 ,taken from the paper [6], it is seen that the airfoil with the dimple placed at 90% with 0.4 AR has the highest Cl/Cd ratio compared to dimple placed at 90% of chord length with 0.2 AR and without dimpled airfoil.

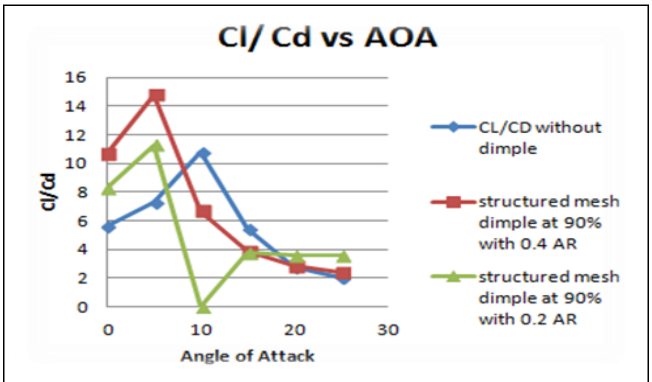

Fig. 18: Cl/Cd vs AOA [6]

In the present work as shown in figure 17, maximum Cl/Cd occurs for the structured mesh at 80% of chord length with 0.2AR compared to the structured mesh at 90% with 0.4AR in figure 18 [6]. The results are in line with analysis carried out with addition of inward dimple.

6. Conclusion

The position and dimensions of the dimple affect the drag and lift characteristics. Aerodynamic efficiency increases due to the reduced drag. Investigation with inward and outward dimple on NACA 4415 airfoil has been carried out for two different positions of dimple on the airfoil section of different aspect ratios. It was seen that lift to drag ratio is maximum for inward dimple placed at 80% of chord length with 0.2 aspect ratio of the dimple.

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