

Computational Analysis of Cavity Effect over Aircraft Wing

P. Booma Devi, Dilip A. Shah

Abstract—This paper seeks the potentials of studying aerodynamic characteristics of inward cavities called dimples, as an alternative to the classical vortex generators. Increasing stalling angle is a greater challenge in wing design. But our examination is primarily focused on increasing lift. In this paper, enhancement of lift is mainly done by introduction of dimple or cavity in a wing. In general, aircraft performance can be enhanced by increasing aerodynamic efficiency that is lift to drag ratio of an aircraft wing. Efficiency improvement can be achieved by improving the maximum lift co-efficient or by reducing the drag co-efficient. At the time of landing aircraft, high angle of attack may lead to stalling of aircraft. To avoid this kind of situation, increase in the stalling angle is warranted. Hence, improved stalling characteristic is the best way to ease landing complexity. Computational analysis is done for the wing segment made of NACA 0012. Simulation is carried out for 30 m/s free stream velocity over plain airfoil and different types of cavities. The wing is modeled in CATIA V5R20 and analyses are carried out using ANSYS CFX. Triangle and square shapes are used as cavities for analysis. Simulations revealed that cavity placed on wing segment shows an increase of maximum lift co-efficient when compared to normal wing configuration. Flow separation is delayed at downstream of the wing by the presence of cavities up to a particular angle of attack.

Keywords—Lift, square and rectangle dimples, enhancement of stall angle, cavity.

I. INTRODUCTION

AN aircraft is basically a machine which is able to fly by gaining support from the air. Aerodynamics is the study of generation of force components, mainly lift and drag when the machine interacts with air. Enhancing the aerodynamic efficiency (L/D) is one of the key parameter that determines the weight and cost of an aircraft [1]. In addition, aircraft range is directly proportional to its aerodynamic efficiency without any increase in fuel usage.

For commercial usage, increase in efficiency reduces the operating cost. When the airflow separates from the upper wing surface, stalling range is invoked. Since, lift co-efficient is proportional to the angle of attack, increasing the angle of attack is required. Stall may occur during landing. [2]

Application of dimples on aircraft wing model will create turbulence which delays boundary layer separation and reduces the wake thereby reducing the pressure drag. Dimples are quite effective at different angles of attack and also they increase the stalling angle. In order to verify the effect of dimples, different

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shapes of dimples are analysed by placing over NACA 0012 aerofoil at flow separation point. [3]

Effects of dimples on aircraft wing were studied. In that the flow is accelerated at dimple surface and because of that, flow transits from laminar to turbulent and this transition results in flow separation which reduces the drag. At the same time, presence of dimple helps to increase stalling angle. [4]

Adding of small dimples along the entire upper surface, stopping at 8% chord length, provided benefits in both types of tests, symmetric and cambered. The delay in separation reduces the pressure drag and gives the airfoil less drag and more lift. Such surface modifications applied over to the surface of wing in form of dimples proves to optimize the value of lift coefficient of the wing by delayed flow separation. [5]

A study was carried out to reduce the flow separation over the airfoil. Different techniques are used to reduce the flow separation for improving lift and drag co-efficients. To reduce the flow separation, boundary layer is energized using either leading edge slot or dimple effect. The present study highlights the flow separation problem and delaying it. It is observed that the lift co-efficient increases by reducing flow separation.

II. RESEARCH METHODOLOGY

In this research, the design is modeled in CATIA V5R20 and analysis is carried out using ANSYS CFX. Lift and drag coefficients are through computational analysis. Wing section with a span of 3 m is considered using NACA-0012. Initial computation is done using plain wing; results are taken as reference values in order to compare with the different shapes of cavities in wing. Square and triangular shapes are considered as cavities for the present research work. Initial analysis is done to predict the flow separation points which are placed just ahead of that point to delay the separation. Computational analysis is for the wing section of 3 m span length and angle of attack is varied between 0 and 25 degrees. Domain length is considered as 20 times the chord length of the airfoil section. Then, dimples are introduced at top surface of airfoil from the leading edge at a distance of 0.1 m. The dimples of square size have length of 0.1 m while the triangular dimples have a length of 0.1 m with its height 0.1 m. In triangle dimple, one of its sharp edges is facing trailing edge. Totally, two dimples are introduced on top surface of the airfoil. Both square and triangle dimples having same depth as 0.06 m.

Fig. 1 shows the NACA-0012 airfoil without dimples which is imported model from CATIA V5R20. Fig. 2 shows two triangle cavities present on top surface of the airfoil. Fig. 3

shows two rectangle cavities present on top surface of the airfoil.

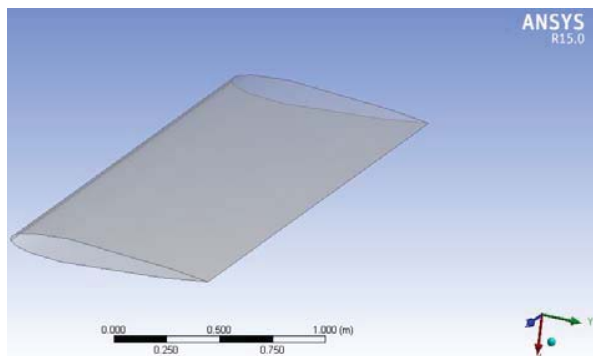


Fig. 1 Wing of NACA-0012 without dimple

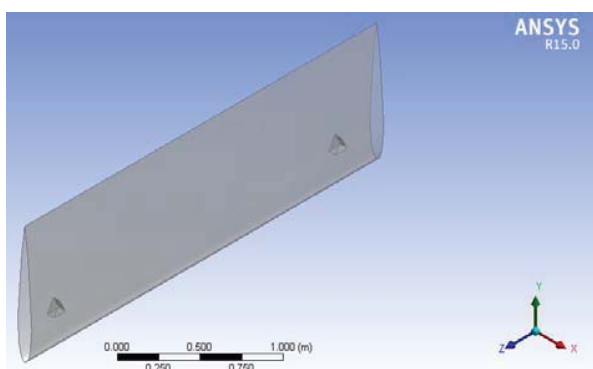


Fig. 2 Triangle cavity pattern over the wing section

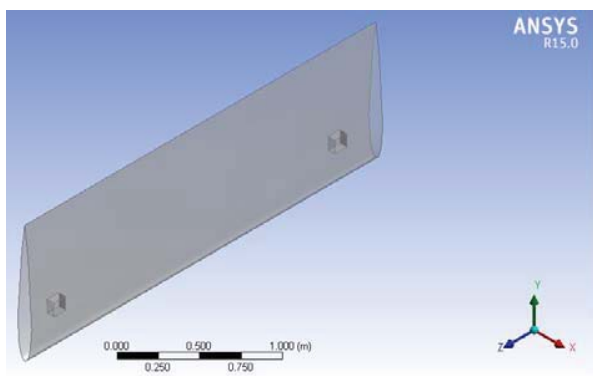


Fig. 3 Square cavity pattern over the wing section

III. COMPUTATIONAL ANALYSIS

This section will discuss about the boundary conditions used for this current analysis. Velocity inlet is used at the inlet of the boundary with the free stream velocity of 30 m/s, for constant Reynolds number. Wing section is considered as solid wall with no-slip boundary condition. Turbulent model, k- ω is employed with standard wall functions.

Computational analysis is carried out in order to predict the values of lift and drag co-efficient of wing section at 30 m/s free stream velocity. After that, normal and axial forces are derived from ANSYS CFX post. The lift and drag forces are calculated by:

$$L = N \cos \alpha - A \sin \alpha$$

$$D = A \cos \alpha + N \sin \alpha$$

where, L represents lift force; D represents drag force; α represents angle of attack; A is force measured along axial direction; N is force measured along normal direction.

The coefficient of lift and coefficient drag are then calculated by

$$C_L = (L) / (0.5 * \rho * V^2 * S)$$

$$C_D = (D) / (0.5 * \rho * V^2 * S)$$

where, C_L represents coefficient of lift; C_D represents coefficient of drag; ρ represents density of air; V is the velocity of air; S is the wing area.

IV. RESULTS AND DISCUSSION

Here, the discussion is about how coefficient of lift and coefficient drag varies when angle of attack is changed. Initially the work was done for plain airfoil to find out the stalling angle.

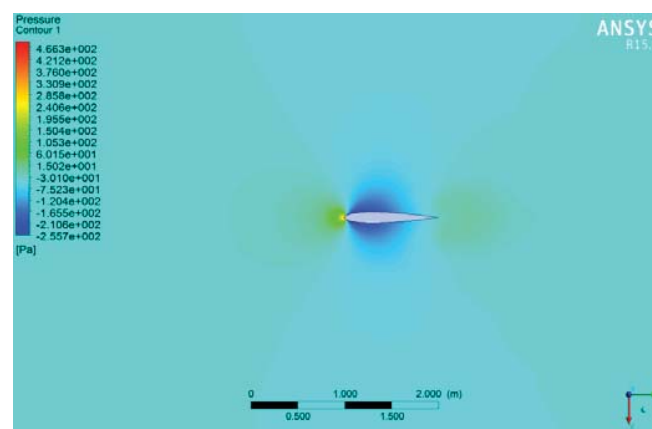


Fig. 4 Pressure contour at zero angle for attack in plain airfoil

Fig. 4 shows the pressure distribution of the plain NACA0012 airfoil. The figure shows clearly at zero angle of attack the maximum pressure is located at the leading edge of the airfoil. At zero angle of attack, the top and bottom surface of the airfoil undergoes the even pressure distribution. Otherwise it may be seen that there is no pressure difference in NACA0012, results in not able to produce lift at this angle of attack.

Fig. 5 shows the coefficient of lift and coefficient of drag for various angle of attack for plain airfoil. In this plain airfoil, analysis is done for 0, 10, 15, 16 and 25 degrees. For ten-degree angle of attack, coefficient of lift and coefficient of drag is 0.95 and 0.02, respectively. In plain airfoil, maximum coefficient of lift is produced at 15 degrees at a value of 1.17, at the same angle of attack coefficient of drag is 0.04. At 16 degrees, this plain airfoil goes to stall.

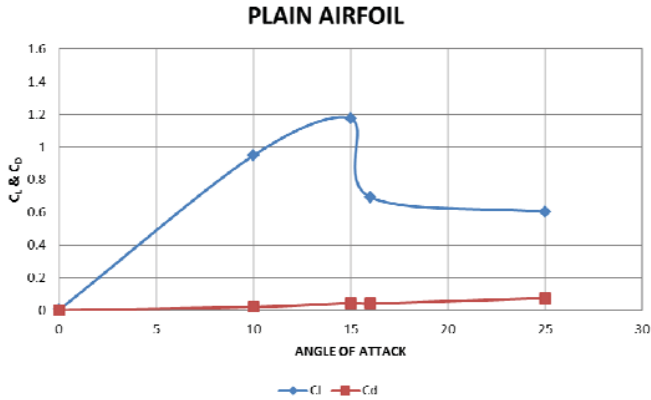


Fig. 5 C_L and C_D for plain NACA0012 airfoil

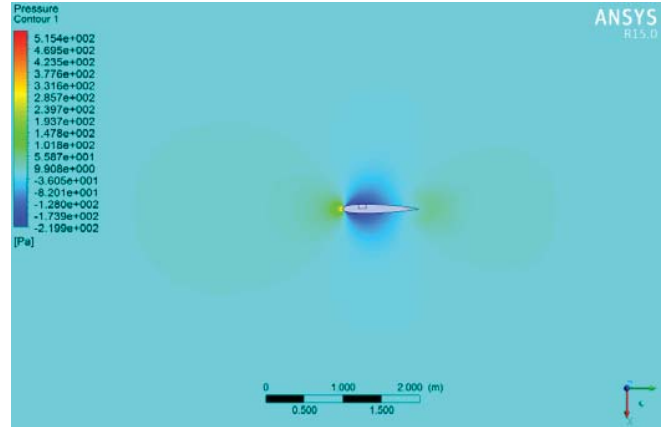


Fig. 8 Pressure contour at zero angle of attack for square dimple airfoil

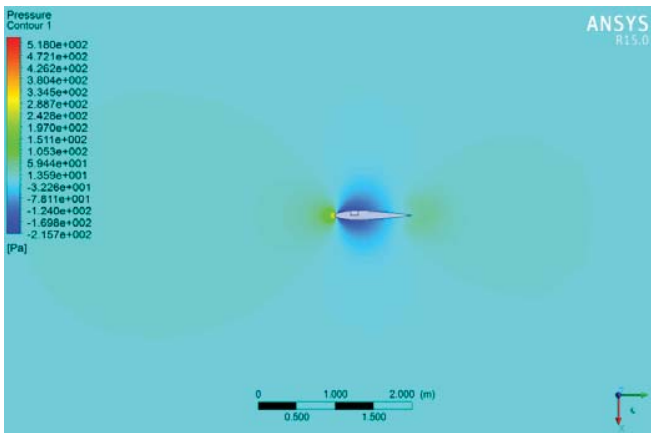


Fig. 6 Pressure contour at zero angle of attack for triangle dimple airfoil

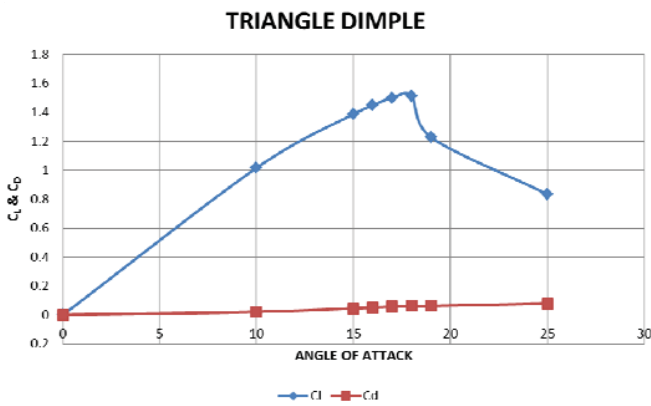


Fig. 7 C_L and C_D for triangular dimple airfoil

The behavior of an airfoil after stalling is characterized by lift and coefficient of drag values are 0.60 and 0.07 respectively. After the stall coefficient of lift, it only gets reduced.

Fig. 6 shows the pressure distribution over the airfoil at zero angle of attack for triangle dimple. It has the maximum pressure at leading edge of the airfoil when compared to plain airfoil.

As shown in Fig. 7, triangle dimples used on airfoil show the coefficient of lift and coefficient of drag for various angles of attack. In this airfoil, we get increasing in lift and increasing stalling angle. In this triangle, we did analyses for 0, 10, 15, 16, 17, 18, 19, and 25 degrees.

In the triangular dimple airfoil, at zero angle of attack, coefficient of lift value as 0.00 and 0.01 as coefficient of drag. For ten-degree angle of attack, coefficient of lift and coefficient of drag are 1.01 and 0.02, respectively. At fifteen-degree angle of attack, the lift coefficient is 1.38 and drag coefficient is 0.05. At 16-degree angle of attack, the lift coefficient and drag coefficient are 1.44 and 0.05, respectively. This numerical value shows clearly that the introduction of triangular dimple in this pattern increases the lift coefficient and stalling angle when compared to the base airfoil. This simulation work was continued until to reach the stalling angle. For seventeen-degree angle of attack, the value of lift coefficient and drag coefficient are 1.49 and 0.05, respectively. In this triangular dimple airfoil, coefficient of lift is 1.51 and coefficient of drag is 0.06 at 18 degrees. At 19 degrees, this triangular dimple airfoil goes to stall. At twenty-five-degree angle of attack, it has the lift and drag coefficient as 0.83 and 0.07 respectively.

Fig. 8 shows the pressure contour for square dimple airfoil at zero angle of attack. This shows the wing with cavities has the maximum pressure at leading edge of the airfoil when compared to plain airfoil and triangle dimple airfoil.

Fig. 9 shows the lift coefficient and drag coefficient for various angles of attack for square dimple airfoil.

Finally, we discuss about, square dimple airfoil and its results. In this square dimple airfoil, we done analysis for 0, 10, 15, 16, 17, 18, 19, and 25 degrees. At zero angle of attack, coefficient of lift value as 0.00 and 0.01 as coefficient of drag. For ten-degree angle of attack, coefficient of lift and coefficient of drag are 1.02 and 0.02, respectively. At fifteen-degree angle of attack, it has the lift coefficient as 1.39 and drag coefficient as 0.05. At 16-degree angle of attack, it has the lift coefficient and drag coefficient of 1.46 and 0.05 respectively. In square dimple, the coefficient of lift increases. Numerical value shows at 16 degrees, this square dimple has

the maximum lift coefficient for this pattern when compared to plain airfoil and triangle dimple airfoil. This 16-degree is not stalling angle for this square dimple airfoil. So we continue our computational work to find stalling angle. For 17-degree angle of attack, it has the lift coefficient and coefficient of drag as 1.49 and 0.062 respectively. Square dimple has the maximum coefficient of lift of 1.52 and coefficient of drag as 0.06, this is achieved at a value of 18 degrees. At 19 degrees, this airfoil goes to stall. Next, we continue our work after the stalled angle has the lift coefficient and drag coefficient as 0.91 and 0.81 respectively. Therefore, before the stalling angle lift coefficient for plain airfoil is 1.17 at fifteen-degree angle of attack, for triangle dimple airfoil has 1.51 at eighteen-degree angle of attack and for square dimple airfoil has 1.52 at 18 degrees. These values show that the pattern leads to increase in lift coefficient as well as increasing in stalling angle.

Even though the lift coefficient is increased, the coefficient of drag was not reduced. The drag coefficient continued to increase for increasing angle of attack for plain, triangular dimple and square dimple.

Fig. 10 shows, for ease of comparison, the lift for plain airfoil, triangle dimple airfoil and square dimple airfoil for various angle of attack.

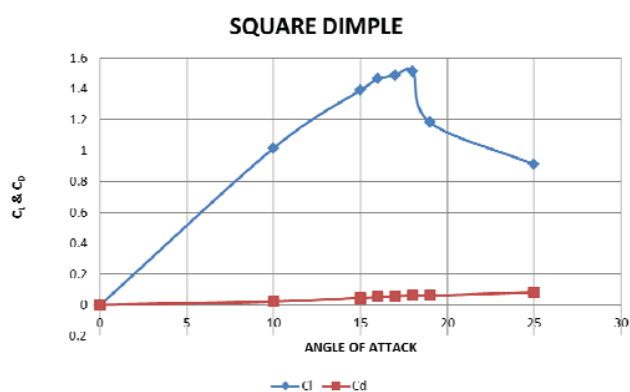


Fig. 9 C_L and C_D for square dimple airfoil

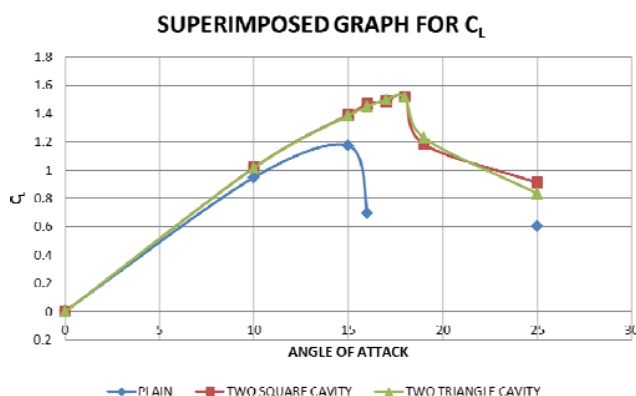


Fig. 10 C_L for plain, triangle and square dimple airfoil

The graphs shown are superimposed here values of coefficient of lift and coefficient of drag for a plain, triangle and square dimple.

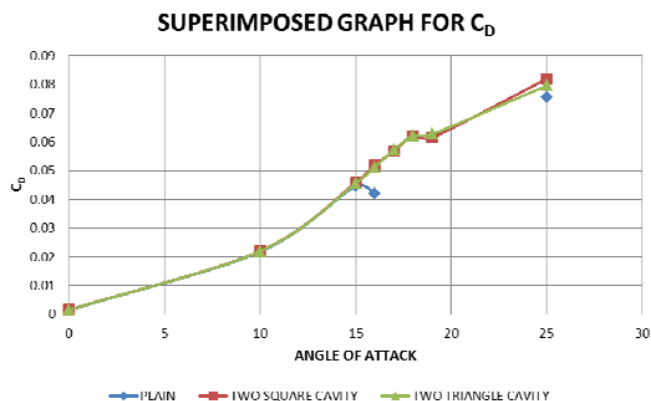


Fig. 11 C_D for plain, triangle and square dimple airfoil

Fig. 11 shows the coefficient of drag for plain airfoil, triangle dimple airfoil and square dimple airfoil for various angle of attack. It is clearly evident that dimples placed on wings are experiencing increase in lift coefficient and stalling angle than that of base model.

V. CONCLUSION

Computational results show an increase in lift. Introduction of dimple is an effective controlling method to increase in stall angle and lift coefficient. The following are the conclusions based on present study:

- For plain airfoil, maximum lift coefficient was 1.17, triangular dimple airfoil has 1.51, and square dimple airfoil has 1.52.
- With the help of dimple, maximum lift coefficient for triangular dimple has increased by 28.97% and square dimple has increased by 29.05%.
- For plain airfoil maximum stall angle was 15 degrees, triangular dimple airfoil has 18 degrees, and square dimple airfoil has 18 degrees.
- Effect of area of depth will be analysed in detailed to arrive at the optimum size/shape/orientation.
- The scale of turbulence should be varied and size/shape of the dimples can be changed and analyses need to be carried out.

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