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EFFECT OF LOWER SURFACE MODIFICATION ON AERODYNAMIC CHARACTERISTICS OF AN AIRFOIL

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Abstract*- This paper investigates the aerodynamic characteristics of a conventional airfoil and a stepped airfoil with backward facing step and compare them. A step was introduced at 55% of chord, with a depth of 5.5% of chord extending till the trailing edge of a NACA 4415 airfoil. Computational studies were conducted for both conventional airfoil and stepped airfoil to compare the aerodynamic performances. Experimental studies of scaled wing model with the same airfoil were conducted in a wind tunnel to validate some of the numerical results obtained for the cases of base and stepped airfoils. The results produced show that increase in coefficient of lift (C_l) and increase in lift to drag ratio (L/D) over conventional airfoil values could be obtained using stepped airfoils.*

Keywords: Aerodynamic Characteristics, Conventional Airfoil, Stepped Airfoil, Coefficient of Lift, Lift to Drag Ratio.

1. INTRODUCTION

An airfoil or aerofoil is the shape of a wing, blade or sail. An airfoil-shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. A wing is combination of large number of airfoil, so when air flows over airplane wing it causes airplane to lift. That's why airfoil size and shape playing an important role on airplane flying and so effective airfoil design and still its modification work is going on. People have been constantly researching on improving the quality of flow over the aircraft so as to enhance the overall performance in terms of lift, drag and stability characteristics as the advent of successful aviation in commercial, defense and experimental research sectors. A passive flow control technique which is used in this study is to modify the geometry of a conventional airfoil by introducing backward facing steps, which forms a relatively new family of airfoil designs popularly known as "KF (Kline-Fogleman) airfoils". Introduction of a step could be greatly effective in changing the overall flow quality in the step cavity. The flow transformation could be understood as due to rotation of the flow promoted by the introduction of the step along a length of an airfoil edge which otherwise had been continuous. Stepped airfoils use the concept of trapped vortex cavities. Figure 1 compares the flow over a conventional with that over a modified airfoil with a step.

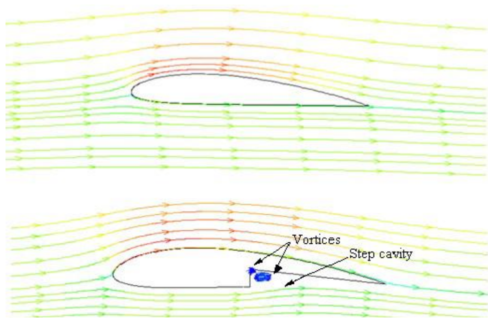


Fig.1: Comparison of flow over conventional airfoil and stepped airfoil

A breakthrough concept in airfoil design was introduced by Richard L.Kline and Floyd F.Fogleman with their stepped airfoils developed in early 1960s. This opened a new chapter in the aerodynamics with the break-through design of high performance airfoils with extended stalling capabilities and improved lift and drag characteristics. The object of this design was described by *The Ultimate Paper Airplane*[1] by Richard L.Kline & F.Fogleman and it was to develop an improved airfoil with enhanced lift, drag and stability characteristics and adaptability over a wide range of speeds, achieved by the generation of vortical flow that alters the flow field resulting in favorable effects. Several other articles published later had also stated that Kline-Fogleman (KF) airfoils were capable of combining the best features of conventional airfoils i.e. better lift with thick ones and higher speeds with thinner ones and further that they worked extremely well for achieving higher lift as well as forward speed. These statements are supported by the world record that Dick Kline still holds for the farthest flying paper plane equipped with stepped airfoils. In an email that Kline sent to an RC modeling group on issues concerning KF airfoils, he highlighted the advantages of KF airfoils. Most noteworthy ones being the capability of KF airfoils to handle a wide range of speeds; the much greater range for its center of gravity which its case could be moved as much as 40% chord location from the leading edge thus allowing it to carry a heavier load; better air penetration based on the flight experiences of model planes built with KF airfoils; high strength to weight ratio; great stability and control.

Some of the earliest citations of airfoils with vortex trapping cavities were made in a paper by Ringleb F.O.[2] (1961). W.A.Kasper[3] claimed the first successful use of a trapped vortex in a flight experiment in the seventies using a concept so-called as Kasper wing. The Kasper-wing produced vortex shedding as against a steady trapped vortex thus resulting in lift enhancement was verified by the experimental studies undertaken by Kruppa[4] (1977). By the researchers of Saab-Scania (1974) using a wing with a vortex cavity, some promising results were obtained as reported by Kruppa in his paper.

In 1994, Demeter G.Fertis[5] scientifically proved the benefits of KF airfoils through experiments and flight testing. He compared the results obtained for the stepped airfoil with those for conventional NACA 23012 airfoil and confirmed that the airfoils developed by Kline and Fogleman were potential designs to obtain better lift characteristics over a broad range of angles of attack, improve or eliminate stall at all possible operational airspeeds, increase lift to drag ratios over a wider range of operational angles of attack and be adaptable for both fixed and rotary wing aircraft. This set the direction for a new domain in flow control research, which till then involved focusing on use of flow control techniques on conventional airfoils.

Stephen Witherspoon[6] and Fathi Finaish (1996) conducted aerodynamic studies on stepped airfoils for different configurations defined by the step lengths, depths, and the location of steps on airfoil chord. Steps on NACA 0012 and 23012 airfoils showed that higher lift coefficients were obtained with lower surface step.

BAE SYSTEMS [7], through their "AEROMEMS" research program (2000) concluded that MEMS based fully developed flow control system could result in a timeframe of 10-15 years. Research and Development work was intensified with the launch of "AEROMEMS II" program that focused on extensive wind-tunnel and flight testing of MEMS applications for flow control on a commercial scale. Quality research was also conducted with the initiatives taken at the Air Force Research Laboratory's Air Vehicle Directorate (AFRL/VA), NASA, DARPA apart from the support rendered by technical organizations such as AIAA through The Fluid Dynamics Technical Committee (FDTC) and ASME through The Fluid Dynamics Technical Committee (FDTC).

Research at UCLA/Caltech by Ho[8] and Tai, 2001 involved flight testing of a smart skin attached to an UAV, integrated with several shear stress sensors and balloon actuators distributed over the skin. It was aimed at controlling the pitching, rolling and yawing moments by controlling the position of leading-edge vortices, achieved by micro-actuators coupled with a delta wing boundary layer. T. Crittenden, A. Glezer, E. Birdsell and M. Allen used MEMS-based sensing devices and pulse jets integrated into the flow boundary to achieve aerodynamic control.

W.W.H. Yeung[9] (2006) conducted flow visualization studies of corrugated airfoils using steps to compare them with conventional Joukowsky airfoil incorporating a backward facing step based on conformal mapping calculations. The results were in favor of the corrugated airfoils confirming that stepped airfoils produced better lift characteristics due to the formation of vortices. Triple corrugated airfoils produced as much as 10 % more than their conventional counterparts for the same camber, thickness and angle of attack.

Fabrizio De Gregorio and Giuseppe Fraioli[10] (2008) conducted an experimental study of flow control using a trapped vortex cavity on a high thickness airfoil with an objective to apply the results obtained to blended wing designs. Data from PIV measurements showed that passive Trapped Vortex Control (TVC) flow control is neither an effective separation control mechanism nor capable of confining the vortex, and controlling the vortex shedding. On the other hand, active flow control is capable of controlling flow separation.

Masoud Boroomand and Shirzad Hosseinverdi[11] (2009) numerically investigated the turbulent flow around a NACA 2412 airfoil with backward facing steps at high Reynolds number with the objective of enhancing the aerodynamic performance by trapped vortex lift augmentation. All the results obtained through their study were in total agreement with those obtained by Stephen Witherspoon and Fathi Finaish (1996) through their study of NACA 0012 airfoil with a step. Conclusions from their study conducted in 2009 include increase in drag for all stepped airfoil configurations; increase in lift coefficients and lift to drag ratios at some angles of attack for upper step configurations; positive effect shown by lower step configurations on delaying the stalling angle.

2. COMPUTATIONAL MODELING

The numerical studies were conducted using a commercially available computational fluid dynamics package to simulate flow around the airfoils. To solve this problem numerically following equation are used by FLUENT CFD software.

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho V) = 0 \qquad (2)$$

Where ∇ is the gradient operator.

Momentum equation:

Navier–Stokes equations

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\lambda \nabla . V + 2\mu\frac{\partial u}{\partial x}\right) +$$

$$\frac{\partial}{\partial y}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})] + \rho F(x)$$

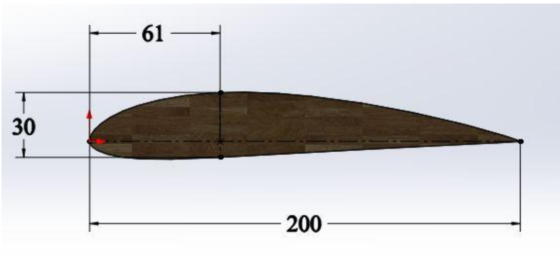
$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho uv)}{\partial x} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial y}(\lambda \nabla . V + 2\mu\frac{\partial u}{\partial y}) + \frac{\partial}{\partial x}[\mu(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y})] + \rho F(y) \quad (3)$$

Equation of state:
The classic equation of state for an ideal gas

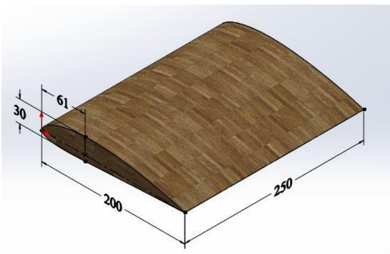
$$P = \rho RT \quad (4)$$

All of the computational work was done using commercial software packages. Main bodies of airfoils and the modified airfoils were created by using SOLIDWORKS. Then the bodies were imported into ANSYS "FLUENT", a finite volume method based CFD tool, which was used for the entire numerical analysis.

The problem was set up as a three dimensional flow problem in single phase. The Cartesian co-ordinate axes were fixed at the leading edge of the airfoil in each case. Length of the airfoil was 200mm in each case. For stepped airfoil, step was introduced at 55% of chord, with a depth of 5.5% of chord extending till the trailing edge. In figure all dimensions are in millimeter.

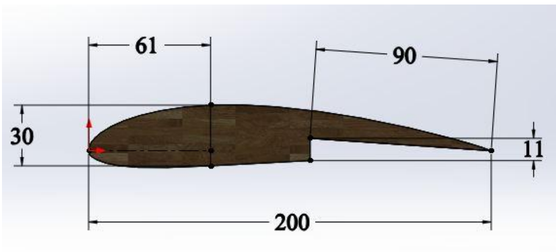


(a)



(b)

Fig.2: Designed NACA 4415 airfoil and wing



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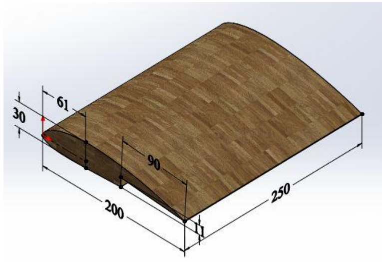


(b)

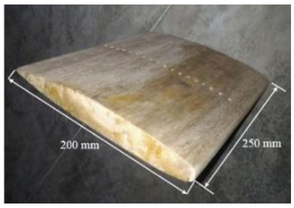
Fig.2: Designed NACA 4415 airfoil and wing with step

The flow was modeled as steady, incompressible in the flow domain. The fluid chosen was air at standard atmospheric conditions. The inlet was set as "Velocity Inlet" which includes all the front of the flow domain. All the exit boundaries combined were set as "Pressure Outlet". All the airfoil edges together were set as "Wall" with no-slip condition. The convergence criteria was set at 1e-06 for residuals, continuity, x and y velocities uniformly. The flow solver used the SIMPLE algorithm for pressure-velocity coupling. Pressure was set as second order, Momentum, and Modified Turbulent Viscosity were set as Second Order Upwind.

3. EXPERIMENTAL DETAILS

This approach required building a test wing model using a conventional NACA airfoil and redesigning it to obtain the modified airfoil configurations to be tested. Force data including lift and drag were recorded during the tests. Experimental studies were conducted to complement the results obtained by the computational studies. All the experimental studies were conducted in the Aerodynamics and Aerial Robotics lab in the Department of Mechanical Engineering at the Khulna University of Engineering & Technology (KUET).

The wing model used for wind tunnel testing was built according to NACA 4415 airfoil with a lower surface step configuration located at 55% of chord with a depth of 5.5% of chord extending till the tailing edge. Models geometry and dimensions are shown in figures.



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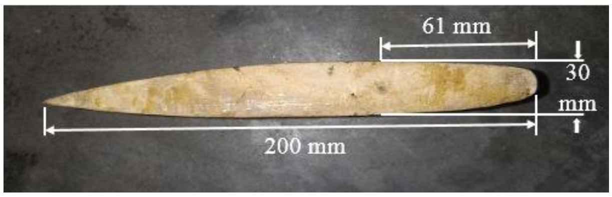
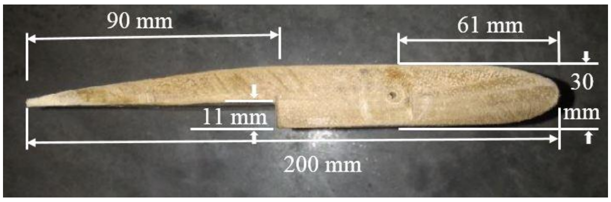


(b)
Fig.4: Constructed base wing

(a)



(b)

Fig.5: Constructed wing with step

4. RESULTS AND DISCUSSIONS

Through computational and experimental approaches, useful results were found for airfoil configuration comprising of conventional NACA airfoil and the corresponding modified airfoil with step introduced on the lower surface. Results are presented for airfoils by varying some geometric and aerodynamic parameters with the discussion of results. Pressure distribution and aerodynamic characteristics associated with the conventional and modified NACA 4415 airfoil configurations are discussed.

4.1 Computational Results

Results showing the flow field developments are presented as velocity vector, static pressure contour using FLUENT. Further, aerodynamic characteristics such as lift, drag coefficients, lift to drag ratio are also presented as obtained from the resulting pressure and shear stress distributions at different angle of attack. Conventional NACA 4415 airfoil and the modified airfoil configuration were studied for a given set of inlet conditions. Step was introduced at 55% of chord, with a depth of 5.5% of chord extending till the trailing edge of a NACA 4415 airfoil. Table 1 enlists the various cases investigated numerically as a part of this project.

Aerodynamic characteristics including lift, drag coefficients directly result from the pressure distributions around the conventional and modified airfoil. Figure 6 shows the comparison of lift coefficient for conventional and modified airfoil at different angle of attack. Figure 7 shows the comparison of drag coefficient for conventional and modified airfoil at different angle of attack. Figure 8 shows the comparison of lift to drag ratio for conventional and modified airfoil at different angle of attack.

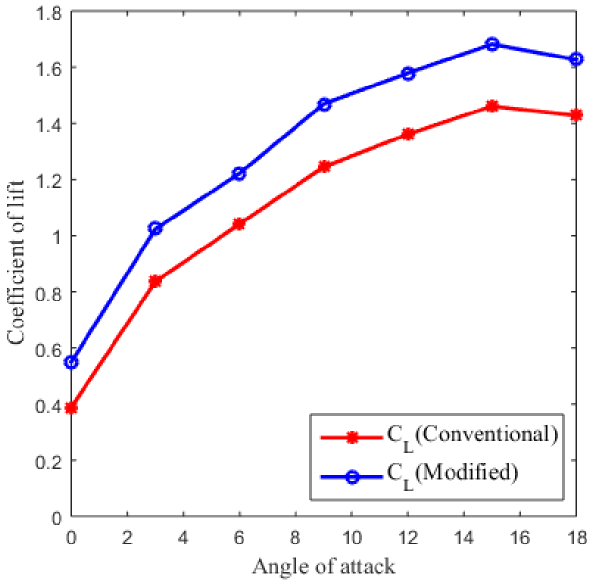


Fig.6: Comparison of lift coefficient for conventional and modified airfoil at different angle of attack

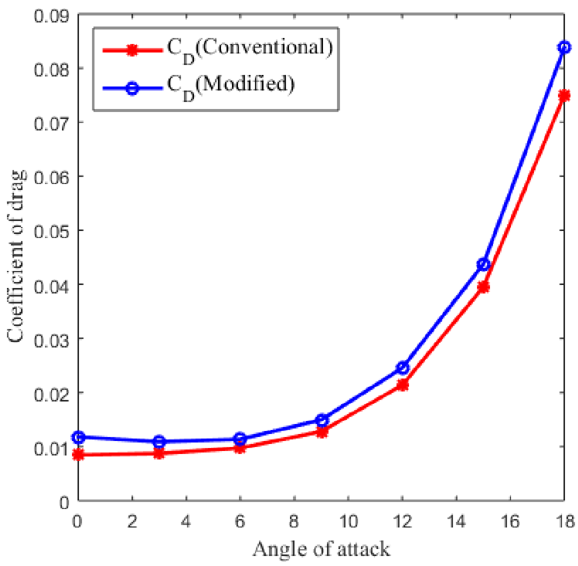


Fig.7: Comparison of drag coefficient for conventional and modified airfoil at different angle of attack

From figure 6 it has been seen that coefficient of lift has been increased for modified airfoil over conventional airfoil. For both conventional and modified airfoil lift has been increased from 0 to 15 degree angle of attack. At 15 degree angle of attack the lift increment is maximum. After 15 degree angle of attack lift comparatively decreased.

It's noticeable from figure 7 that the drag coefficient for modified airfoil has been increased over conventional airfoil. Drag has been increased for modified airfoil from 0 degree angle of attack. With increasing of angle of attack drag also has been increased.

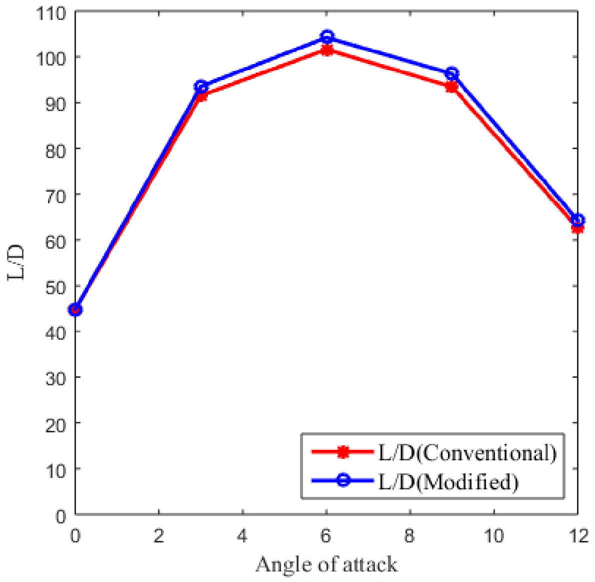


Fig.8: Comparison of drag coefficient for conventional and modified airfoil at different angle of attack

From figure 8 it has been seen that the lift to drag ratio is higher for modified airfoil than the lift to drag ratio of conventional airfoil. The maximum lift to drag ratio for modified airfoil is at 6 degree angle of attack. As drag is increased with increase of angle of attack, drag to lift ratio decreased at higher angle of attack. Though there is an increase in coefficient of lift over the base airfoil cases for all the stepped airfoil cases, there is rise in coefficient of drag as a consequence of the use of step. The contributions to the higher lift to drag ratios come from the significant increments in coefficient of lift for the modified airfoil cases.

4.2 Experimental Results

This section deals with the results and discussion of the experimental data obtained through the wind tunnel testing of a NACA 4415 airfoil based wing-model. Both conventional and modified wing model were tested in wind tunnel to validate some of the computational results. The experimental part deals with the measurements of upper and lower surface pressure of wing model to calculate the corresponding pressure coefficients. From coefficient of pressure coefficient of lift was measured at some angle of attack to compare with computational result.

Aerodynamic pressure acting on the upper and lower surface of base and modified wing model were recorded during the wind tunnel testing by pressure measuring sensor. The pressure data were processed to obtain lift coefficient. A comparison of coefficient of lift for computational and experimental process was done. Figure 9 and figure 10 shows the pressure distribution of base and modified wing respectively at different angle of attack. It has been seen that the pressure for modified wing has been increased almost from middle of chord length. The step of modified wing was made at 55% of the cord length. Due to this step a variation of pressure have been introduced.

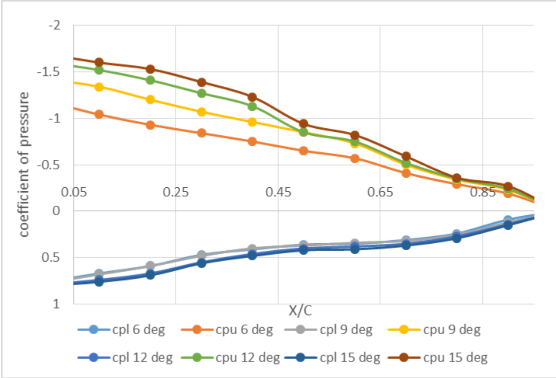


Fig.9: Pressure distribution of base wing at different angle of attack

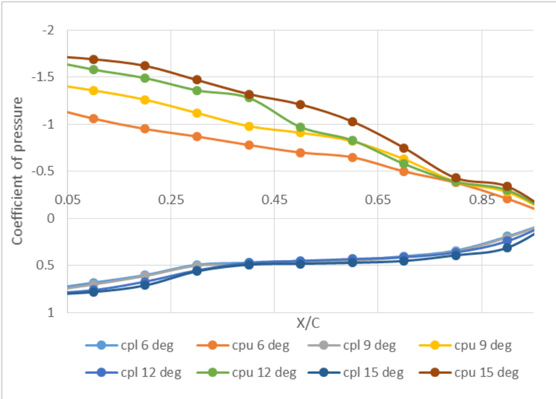


Fig.10: Pressure distribution of modified wing at different angle of attack

As no drill was made possible at the leading and tailing edges, pressure coefficient at those point could not be calculated. The area bounded by upper and lower curves in figure 9 and 10 indicates the lift coefficient. From the comparison of those figures it has been seen that the area almost from the mid chord has been increased for modified wing, which indicates the increase in lift coefficient.

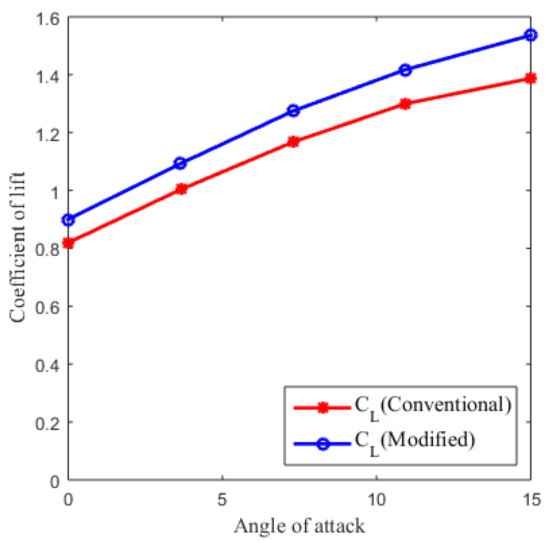


Fig.11: Experimental coefficient of lift for base and modified wing at different angle of attack

After calculating coefficient of pressure from upper and lower surfaces pressure for base and modified wing at different angle of attack, coefficients of lift were calculated. Figure 11 shows a comparison of lift coefficient for base and modified wing at some different angle of attacks which were found through experiment. It has been seen that lift coefficient has been increased for modified wing which is similar with computational result.

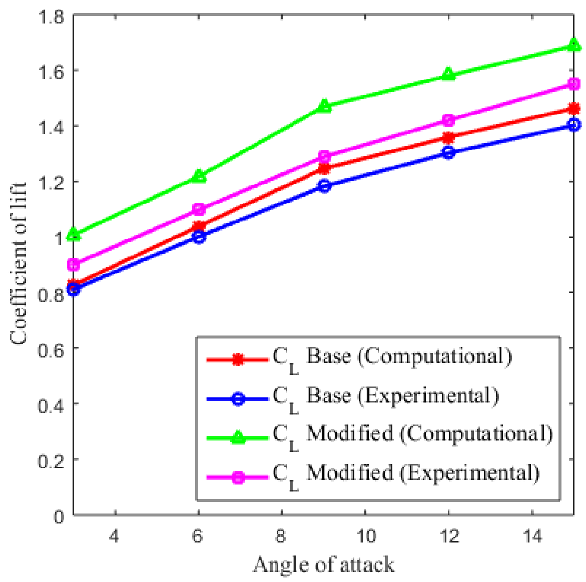


Fig.12: Comparison of computational and experimental lift coefficient for base and modified wing at different angle of attack

5. CONCLUSIONS

This paper investigates the aerodynamic characteristics of airfoil by modifying the geometry. A backward facing step was introduced to conventional NACA 4415 airfoil. From result it had been seen that airfoil with a backward facing step on the lower have the potential to enhance the aerodynamic characteristics by increasing the lift coefficients and lift-to-drag ratio. A step was introduced at 55% of chord with a depth of 5.5% of chord extending till the trailing edge of a NACA 4415 airfoil which was used for all airfoil cases studies. For all the cases velocity was 35.5m/sec. Results obtained show that the lift coefficient was higher by as much as 15.75% for modified airfoil at 15 degree angle of attack. Drag coefficient data indicated that with the introduction of a step, drag was increased. This observation was consistent in all the modified airfoil cases studied. Results shows percentage of increase in drag coefficient was 10.57% for modified airfoil at 15 degree angle of attack. The lift to drag ratios were higher for all the stepped airfoil cases studied. At 6 degree angle of attack maximum lift to drag ratio was obtained. Percentage of increase in lift to drag ratio was 2.69% for modified airfoil. Research still needs to be carried out and an open door to unexplored areas waits for better ideas and potential applications of stepped airfoil.

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