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Experimental Study on Flow Separation Control of a Wing by Continuous Suction and Injection

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Abstract*- Active flow separation control techniques have been studied to improve aerodynamic performance of moving objects in fluids such as aircrafts, motor vehicles and turbine blades .The aim of this thesis is to control the flow separation of an airfoil by suction and injection on the upper surface. The presence of friction in the flow causes a shear stress at the surface of the body, which in turn contributes to the aerodynamic drag of the body, that is, skin friction drag. However, friction also causes another phenomenon called flow separation. From a fluid dynamist's point of view, the performance of an aircraft is essentially controlled by the development of the boundary layer on its surface and its interaction with the mean flow. This interaction decides the pressure distribution on the airfoil surface, and subsequently the aerodynamic loads on the wing. In order to obtain the highest levels of performance efficiency for mission varying aircraft, it is necessary to either:(a) alter the boundary layer behavior over the airfoil surface--flow control methods of interest(b) change the geometry of the airfoil real time for changing free stream conditions—adaptive wing technology. Alter the boundary layer behavior over the airfoil surface can be changed by suction and injection on the upper surface. The value of the aerodynamic efficiency needs to be maximization. For this case lift should be high and drag should be low, which increases aircraft efficiency. It is shown from the experiment that the flow separation occurs at 8˚ attack angle in regular surface airfoil and at 16˚ attack angle in surface with suction at 50% cord length from the leading edge and 20% cord length from trailing edge.*

Keywords: Flow separation control, Airfoil, Suction and Injection.

1. INTRODUCTION

All solid objects traveling through a fluid (or alternately a stationary object exposed to a moving fluid) acquire a boundary layer of fluid around them where viscous forces occur in the layer of fluid close to the solid surface. Boundary layers can be either laminar or turbulent. A reasonable assessment of whether the boundary layer will be laminar or turbulent can be made by calculating the Reynolds number of the local flow conditions. Flow separation occurs when the boundary layer travels far enough against an adverse pressure gradient that the speed of the boundary layer falls almost to zero. The fluid flow becomes detached from the surface of the object, and instead takes the forms of eddies and vortices. In aerodynamics, flow separation can often result in increased drag, particularly pressure drag which is caused by the pressure differential between the front and rear surfaces of the objects as it travels to the fluid. For this region mass effort and research has gone into the design of aerodynamic and hydrodynamic surfaces which delay flow separation and keep the local flow attached for as long as possible. When a real fluid flows past a solid boundary a layer of fluid which comes in contact with the boundary surface adheres to it on account of viscosity. Since this layer of fluid cannot slip away from the boundary surface it attains the same velocity as that of the boundary. In other words at the boundary surface there is no relative motion between the fluid and the boundary. If the boundary is stationary, the fluid velocity at the boundary surface will be zero. Thus at the boundary surface the layer of fluid undergoes retardation. This retarded layer of fluid causes retardation for the adjacent layer of the fluid, thereby developing a small region in the immediate vicinity of the boundary surface in which the velocity of flowing fluid increases gradually from zero at the boundary surface to the velocity of the mainstream. This region is known as boundary layer. The boundary layer develops, up to a certain portion of the plate from the leading edge, the flow in the boundary layer exhibits all the characteristics of laminar flow. This is known as laminar boundary layer. If the plate is sufficiently long, then beyond some distance from the leading edge the laminar boundary layer becomes unstable and then turbulent boundary layer is formed. This turbulent boundary layer may be formed by using external disturbance like passing outside a series of cylinder near the leading edge. The boundary layer thickness is considerable affected by the pressure gradient in the direction of flow. If the pressure gradient is zero, then the boundary layer continues to grow in thickness along a flat plate. With negative pressure gradient, the boundary layer thickens rapidly. The adverse pressure gradient plus the boundary shear decreases the momentum in the boundary layer, and if they both act over a sufficient distance they cause the fluid in the boundary layer to come to rest. In this position the flow separation is started. Also when the velocity gradient reaches to zero then the flow becomes to separate. So when the momentum of the layers near the surface is reduced to zero by the combined action of pressure and viscous forces then separation occur. So boundary layer separates under adverse pressure gradient as well as zero velocity gradients. Fluid flow separation can be controlled by various ways such as motion of the solid wall, slit suction, tangential blowing and suction, continuous suction and blowing by external disturbance, providing bumpy the surface, using oscillating camber such as piezoelectric actuator etc. Among them here the using of suction and injection to control flow the separation.

2. METHODOLOGY

To control the flow, passive or active devices are used. Passive control devices are those, which are not energy consumptive. They mainly affect the flow by the geometry of the airfoil. In contrast, active control devices use energy such as surface suction or injection. The boundary layer suction is to prevent separation of either of laminar or turbulent layers. The suction removes the retarded air close to the surface, it will remove the cause of separation, and this aspect leads to its use to obtain high lift coefficients from various airfoil configurations. The suction of air from the boundary layer flow into the surface of the body, causes the tired air near the surface being removed and a new boundary layer is started to reform downstream of the suction point with a consequent reduction in drag (Schertz, J.A., 1984). Generally, in surface injection, a secondary fluid is injected through miniature openings or slots on the surface. In this separation control, which is due to the complete loss of energy of the air flowing immediately adjacent to the surface, is to energize this tired air by means of blowing a thin, high speed jet into it and improve efficiency that means reduce total consumption of energy by increase lift with decreasing drag force.

In order to study the effect of suction and injection, four inclined internal slots and holes are created in the airfoil. Fluid is sucked from the leading edge slot by a single cylinder piston mechanism through a circular pipe from main flow by suction. The low energy fluid in the boundary layer is removed by suction before it can separate. For injection the sucked air in suction process is used. For this fluid is injected at the trailing edge slot by the single cylinder piston mechanism through a circular pipe to main flow by injection. The low energy fluid in the trailing is energized by injection. So the sucked air is directly used to the separation point of the trailing edge and create a new boundary layer which control the flow separation.

The experiment is conducted with a model wing constructed with a base profile of a NACA 4220. Each model has a recess cut in the upper surface, into which a sub-sonic flow separation control mechanism that could generate suction and injection fluid flow over an airfoil. The data of pressure difference was taken by the digital manometer. The pressure co-efficient is measured by following equation-

Co-efficient of Pressure, $C_p = \dfrac{P - P_\infty}{q_\infty}$

$$C_p = \frac{P - P_\infty}{\frac{1}{2}\rho_\infty U_\infty^2} \quad \text{---------------------------} \quad 1$$

From above equation, the value of Cp is found and Lift and drag co-efficient are calculated by integrating the pressures over of the wing.

Co-efficient of Lift,

$$C_L = \frac{1}{c}\int_0^c (Cp_l - Cp_u)dx \quad \text{----}\ 2$$

Co- efficient of Drag,

$$C_D = \frac{1}{c}\int_0^c (Cp_l - Cp_u)dy \quad \text{----------}3$$

In the case with suction and injection seven different angles of attack, 0, 4, 8, 10, 12, 15, and 20 are taken into consideration and three different fluid flow velocities are 2.98 m/s, 3.48 m/s, 4.47m/s.

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3. EXPERIMENTAL SET-UP AND PROCEDURE

The experiments were conducted using 36×36×100 cm subsonic wind tunnel. Figure 1 shows a photograph of the experimental set up. A small sized model is appropriate to examine the aerodynamic characteristics for the experiments. If we desire to examine the aerodynamic characteristics of a large model, a large scale wind tunnel facility is necessary for testing or the inflatable wing must be drastically scaled down to match the usual wind tunnel size violating the Reynolds number analogy requirements. Furthermore, it would be difficult to support the inflatable wing a desirable attitude in these wind tunnel experiments. Since the vertical part of the aerodynamic force produces the lifting force necessary to suspend the load. The main interest is to examine the aerodynamic characteristics of the model. The model was placed in the middle of the test section supported by a frame. The frame is constructed by four 5mm diameter threaded iron rod, bolts, a flat plate and two bars with angle measuring system. The four threaded rods placed the plate tightly inside the wind tunnel. This plate holds the two bars, and these bars hold the model tightly inside the wind tunnel. One bar has an extended part which is used to measure the angle of attack of the model. The surface of the model is drilled through 2 mm diameter holes and small sizes pressure tubes are placed inside the drilled holes. One end of the vinyl tubes are attached to each pressure tube and the other end are connected to a digital manometer for measurement of the surface pressure of the model at different points. A single cylinder piston mechanism is connected with airfoil through circular pipe at the leading and trailing edge slot to execute suction and injection.

Fig. 1 Photograph of Experimental Set-up

4. RESULTS AND DISCUSSION

Pressure coefficients for the no control condition and test condition are shown in figure 2 to 7. Data at the test condition are shown here in dimensionless form according to eqns. 1. The effect of the pressure co-efficient on the upstream of the slot is considerable. Downstream of the slot, the separation point is not significantly affected but the pressure in the vicinity of separation reduces. Just downstream of separation, there is a relatively sharp pressure drop, followed by a pressure recovery that crosses over the no control line with reattachment occurring further upstream. This results in a curious situation where control appears to promote separation close to the control location while simultaneously shortening the reattachment length. The pressure coefficient distributions around the airfoil NACA 4220 when the angle of attack changing from 0 degrees to 20 degrees**.** When the angle of attack is relatively small (i.e., < 8 degrees), the pressure near the nose of the NACA 4220 airfoil was found to decrease quickly along the upper surface of the airfoil, and reached its negative pressure coefficient peak rapidly, then, the static pressure was found to recover over the upper surface of the airfoil gradually and smoothly up to the trailing edge of the airfoil, which is a typical behavior of the static pressure distribution over the upper surface of an airfoil without any flow separation. Over the separated region, the turbulent pressure fluctuations associated with control are significantly larger than those of the no control case. It is interesting to note that fluctuating turbulence peaks occur slightly upstream of reattachment for both the no control and control cases. The coherent fluctuations peak in the vicinity of $C_{p,min}$ and then decay rapidly and approximately linearly, where the contributions of the coherent and turbulent fluctuations are almost same which has been shown figure 2 to 3. Thus, the region in which separation is promoted is associated with amplification of the coherent pressure wave; the region of pressure recovery is associated with its dissipation.

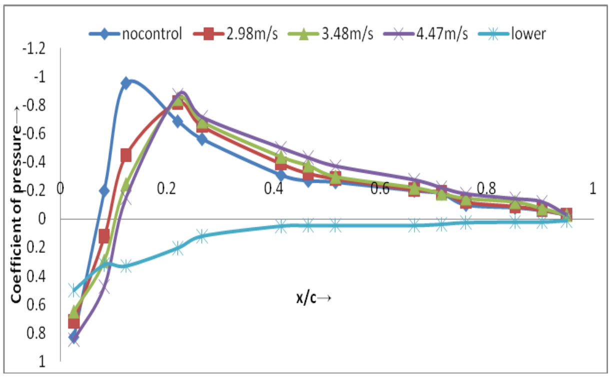

Figure 2: Pressure coefficient C_p distribution along the cord at α = 4 degree

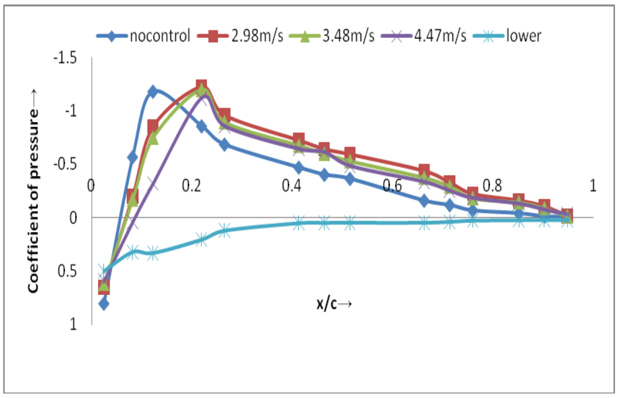

Figure 3: Pressure coefficient C_p distribution along the cord at α = 8 degree

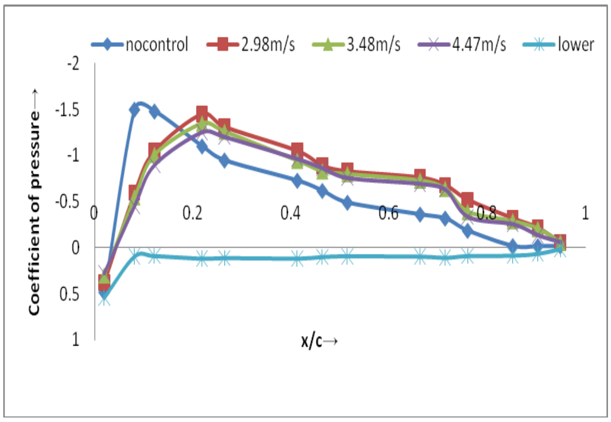

Figure 4: Pressure coefficient C_p distribution along the cord at α = 10 degree

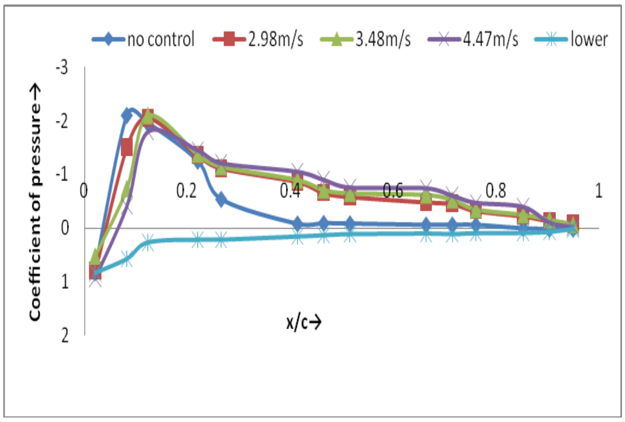

Figure 5: Pressure coefficient C_p distribution along the cord at $\alpha = 12$ degree

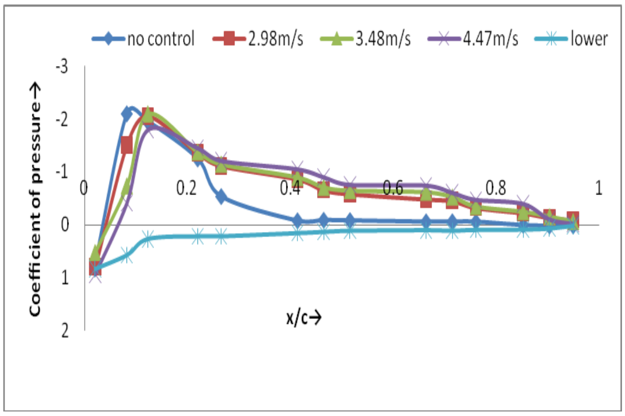

Figure 6: Pressure coefficient C_p distribution along the cord at $\alpha = 15$ degree

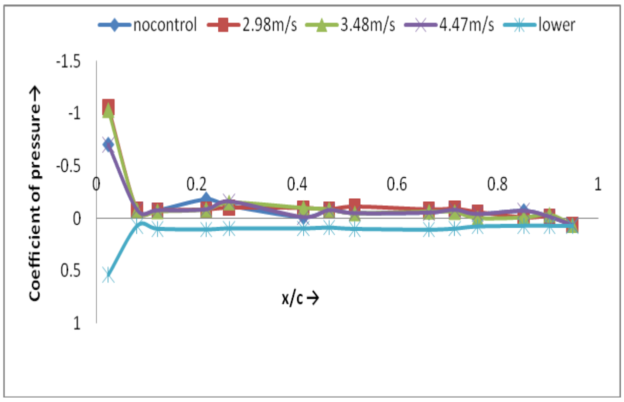

Figure 7: Pressure coefficient C_p distribution along the cord at $\alpha = 20$ degree

As the angle of attack increased to 8 ~ 10 degrees, one distinctive characteristic of the pressure coefficient profiles along the upper surface of the airfoil is the region of nearly constant pressure at $0.08 < x/c < 0.2$. Such region in the pressure coefficient profiles would indicate the separation of the laminar boundary layer from the airfoil upper surface (i.e., flow separation occurred). The sudden increase in static pressure following the "plateau" serves to indicate the rapid transition of the separated laminar shear layer to turbulent flow, which would lead to the reattachment of the separated boundary layer and formation of a laminar separation bubble. The static pressure profile was found to recover gradually and smoothly at downstream region of $x/c > 0.25 \sim 0.30$, which is as the same as those cases with smaller angle of attack and no flow separation. It indicates that the reattachment point, where the separated boundary layer reattach to the airfoil upper surface (i.e., the rear end of the separation bubble) would be located in the neighborhood of $x/c \approx 0.25 \sim 0.30$.The angle of attack becoming bigger than 15 degrees, the maximum absolute value of the pressure coefficient on airfoil upper surface near the leading edge was found to be only about 1.0, which is much smaller than that with smaller angle of attack (about 4.0). The static pressure over the entire upper surface of airfoil was found be nearly constant, i.e., the nearly constant pressure region was found to extend to the trailing edge of the airfoil, which indicates the separated shear layer fails to reattach to the airfoil upper surface, and flow separation would occur over entire upper surface of the airfoil, so the airfoil is found to stall completely as the angle of attack becoming greater than 15 degree.

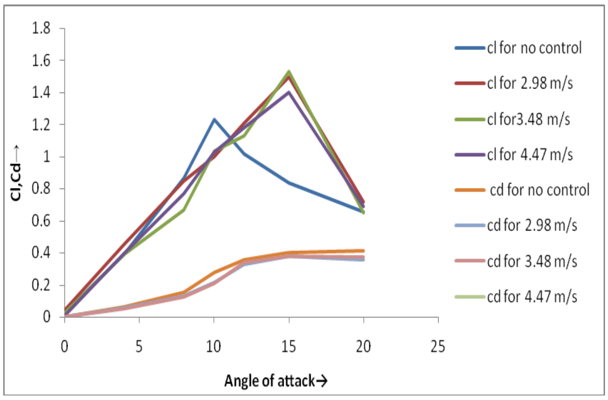

Figure 8: Lift Coefficient C_L, Drag Coefficient C_D Vs Angle of attack

Lift coefficients and drag coefficients were calculated by integrating the pressures from the equation 2 and 3 over the upper pressure sides of the wing. The results are shown in the graph figure 4.8 for the regular surface and control surface for three different velocities. For all the velocities the nature of the lift curve is almost similar.
From the figure 8 it has been seen that the lift co-efficient increases with increasing angle of attack and after certain time lift co-efficient decreases with increasing angle of attack. The lift co-efficient curve is almost straight line for each frequency up to 5 degree angle of attack. Here flow is fully attached with wing surface. After 5 degree angle of attack a slight deflection is created and again increases lift co-efficient rapidly and reach its maximum point at surrounding 15 degree angle of attack. After the maximum point of lift co-efficient at angle of attack of 15 degree, the values of C_L get decreasing. The point from which the value starts to decrease is called stall. The separation of the boundary layer explains why aircraft wings will abruptly lose lift at high inclination to the flow. This condition is called a stall. After stall point a dead flow region is created and flow is unable to re-attach with wing surface. Here flow is separated from the upper pressure surface.
As a result the static pressure is started to increase drag force and decrease lift force. The increasing rate of lift

co-efficient is higher from angle of attack 8 to 15 degrees than from angle of attack 0 to 5 degree. It is clearly said that by using flow separation control by suction and injection, fluid flow is re-attached from 8 to 15 degree and thus lift co-efficient is increased. In case of no control curve (Fig: 8) the lift co efficient is lower that the other control curves and the lift efficient curve is continuously increasing with increase of velocity.

For regular surface and controlled surface with different velocities the drag coefficients curves are near similar to each other. From the figure 8 the drag coefficient is increased with the increase of angle of attack. After the angle of attack 15 degree, flow is separated from the upper surface and creates a vortex. Consequently static pressure and drag force are increased with the decrease of lift force. Here flow is fully separated from wing surface. It is observed finally from the figure 4.8 that the curve for standard value of C_L against angle of attack for regular surface is always lower than controlled surface and the curve for standard value of C_D against angle of attack for regular surface is always upper than the controlled surface. So from figure 4.8 the lift co- efficient for controlled surface is increases with angle of attack higher than the regular surface lift co- efficient and drag co- efficient is decreases with angle of attack than the regular surface drag co-efficient. From figure 8 it was seen that the maximum C_L lift co-efficient is obtained at angle of attack 14 degree, simultaneously significant amount of drag reduction is observed. Due to this condition it can be said that it follows energy conservation law.

5. CONCLUSION

An experimental study has been accomplished to determine the effects of suction and injection in the aerodynamic characteristics of a specific airfoil NACA 4220. The purpose of this project was to develop a flow separation control mechanism that could remove retarded air by suction and energize the tired air by injection using single cylinder buster to increase the lift force of airfoil. It is concluded that the suction and injection can significantly increase the lift coefficient and decrease the skin friction. The design mechanism shows that uniform and more powerful fluid flow could be generated along the slot of the airfoil. The device is an excellent candidate to control flow separation, where the required frequency is changing with aircraft speed and angle of attack. As friction drag at the turbulent boundary layer is far greater than that at the laminar boundary layer, the basic idea of friction drag reduction is focused on delaying the occurrence of transition, expanding the range of laminar flow at the object surface, and reduces friction drag at the turbulent boundary layer. In the specific case studied here, flow separation occurs at 8^0 angle of attack in regular surface but for controlled surface with suction and injection flow separation occurs after 15^0 angle of attack. This study can be a benchmark for the future numerical and experimental studies. Significant improvement was obtained in the lift coefficient for moderate to high angles of attack. But the effect decreases with the further increase of angle of attack, possibly due to less effective interaction between the disturbance and the shear layer.

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