Boundary Layer Control of Airfoil using Rotating Cylinder


Abstract: The requirement for improving the aerodynamic efficiency and delaying the formation of stall over the wing has been of prime importance within the field of aviation. The main objective of the project is to further improve upon these two parameters. The configuration used for analysis consists of a NACA 2412 airfoil of chord length 0.982m with a 64mm cylinder at the leading edge. Analysis is completed using ANSYS Fluent, with a freestream velocity of 10m/s. The aerodynamic characteristics of three configuration bare airfoil, Airfoil with static cylinder and Airfoil with rotating cylinder are tabulated and plotted. The comparison is then followed by pressure and velocity contours to visualize the flow over each configuration. The rotating cylinder configuration shows a improvement in the aerodynamics characteristics. The rotating cylinder configuration gives the most favourable result. This study has a potential application in high lift devices and can be used as stall delaying device.

Keywords: Boundary Layer, Flow Separation, Magnus Effect, Rotating cylinder.

I. INTRODUCTION

In the field of aerodynamics, it is important to know the flow behaviour over an airfoil surface. This can provide a path to style and use different techniques in improving the aerodynamic characteristics of an airfoil. The delay of boundary layer separation and also the improvement of the lift to drag ratio of an airfoil are always of great importance, not only to the look of the advanced aircrafts but also to the control of the boundary layer because the flow moves along the airfoil surface, it loses momentum and also the velocity values within the fluid layers along the perpendicular distance from the surface becomes zero, this continues down the airfoil until a degree where the flow cannot remain attached to the surface, this phenomenon is named as flow separation. The flow separation is related to the creation of vortices and reversed flows which contribute to a drastic call in the lift and a major increase within the drag force of the airfoil. A number of the methods to control this are blowing, suction, vortex generation and moving surfaces technique. The Magnus effect is an observable phenomenon that’s commonly related to a spinning object moving through the air or a fluid. The trail of the spinning object is deflected during a manner that’s not present when the article isn’t spinning. The deflection is explained by the difference in pressure of fluid on opposite sides of the spinning object. When a spinning body during a fluid flow creates a perpendicular force called the lift and an opposing force drag it’s called the Magnus effect. These forces working on the cylinder provides further lift forces for the airplane. The amount of drag and lift is varied by adjusting the rotating speed of the body.

Magnus Effect

A spinning object moving through a fluid departs from its straight path due to pressure differences that develops within the fluid as a results of velocity changes induced by the spinning body.

Fig 1. Flow over Rotating Cylinder

This force causes a deflection of the cylinder within the upwards direction. The deflections are often explained by the difference in pressure of fluid on opposite sides of the cylinder. When a cylinder body in a fluid creates a perpendicular force called the lift and an opposing force drag it's called the Magnus effect. These forces functioning on the cylinder provides a further lift forces for the airplane. The amounts of drag and lift are often varied by adjusting the rotating speed of the body.

Boundary Layer

As an object moves through a fluid, or as a fluid moves past an object, the molecules of the fluid near the article are disturbed and move round the object. Aerodynamic forces are generated between the fluid and also the object. The magnitude of those forces depend upon the form of the article, the speed of the article, the mass of the fluid going by the article and on two other important properties of the fluid; the viscosity and also the compressibility of the fluid.

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As the fluid moves past the object, the molecules right next to the surface stick on with the surface. The molecules just above the surface are stalled in their collisions with the molecules sticking to the surface. These molecules successively block down the flow just above them. The farther one moves, it is removed from the surface, the less the collisions suffering from the object surface. This creates a skinny layer of fluid near the surface during which the speed changes from zero at the surface to the free stream value removed from the surface.

**Flow Separation**

Flow separation is the detachment of a boundary layer from a surface into a wake. Separation occurs in flow that's slowing down, with pressure increasing, after passing the thickest part of a streamline body or passing through a widening passage, for instance, flow against an increasing pressure is understood as flow in an adverse pressure gradient. The flow gets separated when it has travelled far enough in an adverse pressure gradient that the speed of the flow relative to the surface has stopped and reversed the direction. The flow becomes detached from the surface, and instead takes the kinds of eddies and vortices. Much effort and research has gone into the look of aerodynamic surface contours and added features which delay flow separation and keep the flow attached for as long possible.

**Fig 3. Flow Separation over an airfoil**

When the boundary layer separates, its displacement thickness increases sharply, which modifies the outside potential flow and pressure field.

In this project we are employing a cambered airfoil NACA 2412. And the analysis is carried out in ANSYS Fluent CFD. All the CAD drawings are made in Design modeller of the ANSYS Fluent workbench for the computability and accuracy.
TABLE 1. GEOMETRICAL DIMENSIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-out cylinder (Diameter)</td>
<td>70</td>
</tr>
<tr>
<td>Fluid cylinder (Diameter)</td>
<td>68</td>
</tr>
<tr>
<td>(R1)</td>
<td></td>
</tr>
<tr>
<td>Rotating cylinder (Diameter)</td>
<td>64</td>
</tr>
<tr>
<td>(R2)</td>
<td></td>
</tr>
<tr>
<td>Horizontal distance from leading edge</td>
<td>50</td>
</tr>
<tr>
<td>Vertical distance from chord line</td>
<td>5.6</td>
</tr>
<tr>
<td>Chord length</td>
<td>982</td>
</tr>
</tbody>
</table>

C. Meshing

The mesh was generated using All Triangles method with body sizing to make the domain mesh finer. Edge sizing on the airfoil and the cylinder were used to capture the profile perfectly and to obtain accurate solutions. Connections were provided to the outer fluid domain and inner fluid domain to make the mesh into a single component.

D. Mesh Independency Test

The way to check if the solution is independent of grid or not
to create a grid with more cells to compare the solutions of
the two models. By refining the grid and checking for drag
coefficient we find that for about 110000 cells the values
don’t vary substantially affecting the output. This is chosen to
improve the accuracy and reduce the computation time.

![Fig 10. Mesh Independence test for rotating cylinder](image)

**E. Validation of the software**

First step in checking the software is by comparing the results
obtain to the results published by the research papers that we
are using for reference. The error between the results obtained
and the research papers should be the within 10%
tolerance. This ensures that results obtained by the software
and the methodology is accurate and reliable for the project.
The following table gives the insight of the validation that
was performed on the NACA 2412 airfoil.

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>CL(Reference)</th>
<th>CL(obtained)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.204</td>
<td>0.204</td>
<td>0</td>
</tr>
<tr>
<td>2°</td>
<td>0.416</td>
<td>0.403</td>
<td>3.12</td>
</tr>
<tr>
<td>4°</td>
<td>0.625</td>
<td>0.592</td>
<td>5.28</td>
</tr>
<tr>
<td>6°</td>
<td>0.824</td>
<td>0.757</td>
<td>8.13</td>
</tr>
<tr>
<td>8°</td>
<td>0.972</td>
<td>0.887</td>
<td>8.74</td>
</tr>
<tr>
<td>10°</td>
<td>1.157</td>
<td>1.051</td>
<td>9.16</td>
</tr>
<tr>
<td>12°</td>
<td>1.201</td>
<td>1.103</td>
<td>8.15</td>
</tr>
<tr>
<td>14°</td>
<td>1.255</td>
<td>1.039</td>
<td>15.1</td>
</tr>
<tr>
<td>16°</td>
<td>1.191</td>
<td>1.093</td>
<td>8.22</td>
</tr>
</tbody>
</table>

![Fig II. Validation Curve](image)

**F. Setup/ Analysis**

Spalart Allmaras Turbulence model was used with mesh
motion in cell zone conditions. Inlet velocity of 10m/s was
given for the analysis. The cylinder rotation was varied to
optimal value of about 11000rpm (3.7 times the freestream
velocity) in the clockwise direction. The step size was 0.0001
to obtain solution with maximum accuracy. Lift and Drag
coefficients were plotted at the airfoil and the cylinder
location. The convergence condition was set to 0.0001 to
maximize the accuracy of the solution obtained. The
reference values were computed from inlet and hybrid
initialization was used. Solution animation was used to study
the flow behaviour around the geometry. A internal
connection was given to outer fluid domain and inner fluid
domain to make them as a single unit.

**G. Optimising the cylinder location and size**

Cylinder with 109mm at 0.2c was initially designed but this
configuration had very high drag. In the second iteration
44mm cylinder at 0.025c was analysed. But this
configuration didn’t provide adequate lift as per the
requirement and hence was discarded. The final
configuration that we affixed on was 64mm cylinder at 0.050c of the chord length which had favourable
aerodynamic characteristics.

**III. RESULTS AND DISCUSSIONS**

The lift, drag, and efficiency values of each of the
configuration (bare airfoil, airfoil with static cylinder, airfoil
with rotating cylinder) was tabulated at various angles of
attack. The following table gives the comparison between
them. Table III shows that the least performing configuration
is the one with static cylinder. This is due to the fact that the
cylinder produces a lot of drag. As the cylinder starts to rotate
we observe that the performance increases. At low angles of
attack the efficiency of this configuration is much higher than
the bare airfoil configuration. We also observe an increase in
lift coefficient with the rotating cylinder. The cylinder
provides an additional lift to the airfoil. The part of flow from
the pressure surface gets redirected to the suction surface due
to the spinning motion of the cylinder thereby energizing the
boundary layer on the suction surface.

The corresponding graphs of angle of attack versus
respective aerodynamic characteristics is shown in the
figures below.

The bare airfoil and the rotating cylinder configuration gives
the best results as observed from the graph. The
$C_L$ distribution of the three configurations remain the
same but the $C_L$ of the static cylinder starts dropping as the
angle of attack is increased. The $C_D$ of the airfoil and rotating cylinder remains identical
up to 8° of angle of attack. The drag increases slightly on the
rotating cylinder configuration due to the addition of
cylinder.
### Table III. Comparison of Aerodynamic Performance

<table>
<thead>
<tr>
<th>Angle of Attack</th>
<th>Bare Airfoil</th>
<th>Airfoil with Static Cylinder</th>
<th>Airfoil with Rotating Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_L$</td>
<td>$C_D$</td>
<td>L/D</td>
</tr>
<tr>
<td>0°</td>
<td>0.204</td>
<td>0.0126</td>
<td>16.19</td>
</tr>
<tr>
<td>4°</td>
<td>0.571</td>
<td>0.0151</td>
<td>37.80</td>
</tr>
<tr>
<td>8°</td>
<td>0.880</td>
<td>0.026</td>
<td>33.84</td>
</tr>
<tr>
<td>12°</td>
<td>1.080</td>
<td>0.054</td>
<td>20</td>
</tr>
<tr>
<td>16°</td>
<td>1.170</td>
<td>0.131</td>
<td>8.93</td>
</tr>
</tbody>
</table>

### Fig 12. (a) Angle of Attack v/s Coefficient of Lift Distribution. (b) Angle of Attack v/s Coefficient of Drag Distribution. (c) Angle of Attack v/s Efficiency.

The static airfoil has the highest L/D ratio of 37.8 at an angle of attack of 4°, this is surpassed by the rotating cylinder configuration which has a maximum value of 39.93 at the same angle of attack. The static cylinder configuration has a very low L/D ratio, due to the cylinder rotation with an angular velocity of 11000rpm the L/D ratio increases by about 2.5 times.

The Lift coefficient of the static cylinder configuration drops rapidly after 8°. The Lift coefficient of the cylinder with rotation is slightly higher than the bare airfoil at all angles of attack. Therefore it is evident from the data obtained and tabulated that the rotating cylinder configuration enhances the lift producing capabilities of an airfoil at all angles of attack.

### A. Pressure contours

The pressure contours of the bare airfoil and rotating cylinder configuration at various angle of attack is shown in the following figures. The rpm is kept constant at 11000 for all angles of attack.
The pressure contours are compared between the airfoil and the rotating cylinder configuration at an angle of attack of 4°. The high pressure acting at the leading edge is similar in both cases but the low pressure values at the suction side is lower in the rotating cylinder configuration as compared to the bare airfoil.

Fig 13. Pressure contours at 4° angle of attack (a) Bare airfoil. (b) Rotating cylinder

The pressure contours are compared between the airfoil and the rotating cylinder configuration at an angle of attack of 8°. The high pressure acting at the leading edge is similar in both cases but the low pressure values at the suction side is lower in the rotating cylinder configuration as compared to the bare airfoil.

Fig 14. Pressure contours at 8° angle of attack (a) Bare airfoil. (b) Rotating cylinder

The pressure contours are compared between the airfoil and the rotating cylinder configuration at an angle of attack of 12°. The pressure difference between the pressure surface and suction surface is visibly higher in the rotating cylinder configuration when compared to the bare static airfoil. This explains the reduction in drag in the rotating cylinder configuration.

Fig 15. Pressure contours at 12° angle of attack (a) Bare airfoil. (b) Rotating cylinder
The pressure contours are compared between the airfoil and the rotating cylinder configuration at an angle of attack of 16°. The pressure at the leading edge is significantly higher in the rotating cylinder configuration compared to bare static airfoil, this can explain the significant reduction in drag compared to static cylinder configuration.

B. Velocity Contours

The velocity contours of the bare airfoil and rotating cylinder helps in understanding the flow separation point and drag over the surface. The following figures shows the configuration at different angle of attack. The speed of the rotating cylinder is 11000rpm.

The significantly higher velocity in Fig 17(b) is due to the fact that cylinder rotation causes a high velocity in the clearance between the cylinder and at the airfoil, due to the shape of the cylinder at the leading edge the velocity downstream is lower than the airfoil, but when the cylinder rotates with an angular speed, the velocity on the suction side is increased.

The flow around the upper surface of the cylinder is smoother when compared to the bare airfoil but near the trailing edge, the flow velocity of rotating cylinder configuration is lower compared to the bare airfoil.
The velocity contours are compared between the airfoil and the rotating cylinder configuration at an angle of attack of 12°. The rotating cylinder configuration has higher velocity at the leading edge but deteriorates towards the trailing edge when compared to the bare airfoil.

This velocity contour shows the airfoil stalling, the lift coefficient decreases with a further increase with angle of attack. In fig 20(b), the wake starts forming on the suction surface of the airfoil, this occurs because the slit of the configuration becomes tangential to inlet velocity, thereby increasing drag.

IV. CONCLUSION

The concept of energizing and controlling of the boundary layer is understood by employing a rotating cylinder at the leading edge of the cambered NACA 2412 airfoil. The boundary layer on the suction surface gets energized by the action of rotating cylinder and potentially delaying the stall and boundary layer separation. The CFD analysis gave us the insight on how a rotating cylinder energizes the boundary layer and increases the aerodynamic performance. From the above results we observe an increase in the lift coefficient and thereby an increase in the efficiency of the airfoil. Further this analysis can be improved by employing blades of different shape and size to increase the performance. This has a potential employing as a high lift device. In conclusion the rotating cylinder produces improved lift, thereby potentially increasing take-off performance or whenever an increased lift is required.

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