CONTROL OF FLOW PAST AN AIRFOIL SECTION USING

ROTATING CYLINDERS

by

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Approval Signatures

We, the undersigned, approve the Master’s Thesis of Argin Nazari.

Thesis Title: Control of Flow past an Airfoil Section Using Rotating Cylinders

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Dedicated to my family
Abstract

The flow past a NACA 0024 airfoil with a leading edge rotating cylinder is simulated numerically using the ANSYS CFX software. To delay the boundary layer separation from the airfoil surface, different configurations for the airfoil and the cylinder were used. A leading edge rotating cylinder with some of its surface area exposed to the free stream velocity was positioned on the airfoil. The shear stress transport turbulence model was used for the analysis. The lift coefficient for the airfoil with the rotating cylinder was found to be considerably higher as compared to the original airfoil. The lift and pressure coefficients and the velocity profiles for this airfoil compared well with published experimental data. The detached eddy simulation turbulence model was used to analyze the flow field for the wake regions and vortices created from the flow separation. The results predicted by this model were accurate in terms of the airfoil drag coefficient and had lower computational costs that are usually associated with the standard large eddy simulation model. The flow over the same airfoil with an addition of a flap and a second rotating cylinder was also analyzed using the shear stress transport model. The use of rotating cylinders on the airfoil increased the lift coefficient and the stall angle by delaying the flow separation. For the case with a leading edge rotating cylinder, the effect of the momentum injection from the cylinder rotation increased the lift coefficient by 60% and the stall angle by approximately 80% as compared to the original airfoil. For the airfoil with two rotating cylinders the stall angle was increased by 90% with the use of rotating cylinders as a moving surface.

Search Terms: Rotating cylinder, Airfoil, Boundary layer control, Turbulence, Computational fluid dynamics, Detached eddy simulation, Shear stress transport
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Nomenclature

Symbols

- $c$: Chord length (m)
- $C_D$: Drag coefficient = $D / (0.5\rho U_\infty^2 S)$
- $C_L$: Lift coefficient = $L / (0.5\rho U_\infty^2 S)$
- $C_P$: Pressure coefficient = $(P-P_\infty) / (0.5\rho U_\infty^2)$
- $D$: Drag (N)
- $k$: Turbulence kinetic energy per unit mass (m$^2$/s$^2$)
- $L$: Lift (N)
- $P$: Pressure (Pa)
- $P_\infty$: Free stream pressure (Pa)
- $Re$: Reynolds number = $(\rho U_\infty c) / \mu$
- $S$: wing area (m$^2$)
- $t$: Time (seconds)
- $U$: Horizontal velocity component (m/s)
- $U_c$: Cylinder circumferential speed (m/s)
- $U_\infty$: Free stream velocity (m/s)
- $x$: Horizontal distance measured from leading edge (m)
- $y$: Vertical distance measured from the upper surface of airfoil (m)

Greek letters

- $\alpha$: Angle of attack (°)
- $\delta$: Flap angle (°)
- $\varepsilon$: Turbulent dissipation rate (m$^2$/s$^3$)
- $\mu$: Dynamic viscosity (kg/m.s)
- $\nu$: Kinematic viscosity (m$^2$/s)
- $\xi$: Rotation ratio = $U_c/U_\infty$
- $\rho$: Density (kg/m$^3$)
- $\omega$: Specific dissipation rate (1/s)
### Acronyms

<table>
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<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
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<tr>
<td>DES</td>
<td>Detached eddy simulation</td>
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<tr>
<td>LES</td>
<td>Large eddy simulation</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds averaged Navier Stokes</td>
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<tr>
<td>SST</td>
<td>Shear stress transport</td>
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Chapter 1: Introduction

1.1. Background

In the field of aerodynamics, it is important to understand the flow behavior over an airfoil surface. This will pave the way for designing and using different techniques to improve the aerodynamic characteristics of an airfoil. According to Cengel and Cimbala [1], when the air flows over the airfoil, the velocity near the wall decreases and eventually becomes zero at the wall surface. This is because of the viscous effects near the wall of the airfoil and is illustrated as the no-slip condition. It is because of this condition that there is a velocity gradient in the direction perpendicular to the airfoil surface. This results in the formation of velocity profiles along the surface. The boundary layer is a region of flow in the vicinity of the wall surface where the viscous forces are considerable.

The velocity gradient in the perpendicular direction to the wall surface is created because of one fluid layer exerting viscous force on the next fluid layer due to the no-slip condition. As the flow moves along the airfoil surface, it loses momentum and the velocity values in the fluid layers along the perpendicular distance from the surface become zero. This continues down the airfoil until a point where the flow can no longer remain attached to the surface. This is called flow separation. Flow separation is associated with the creation of vortices and reversed flows which contribute to a drastic drop in the lift and a significant increase in the drag force on the airfoil. Many techniques have been used to delay the flow separation from the airfoil surface. Some of these methods for boundary layer control are the blowing, suction, vortex generation and moving surfaces technique.

Rosenhead [2], Schlichting [4] and [5], Lachmann [3] and Chang [6] have discussed boundary layer control techniques. The blowing method uses a technique where a fluid with higher momentum is injected into the flow near the wall surface. The objective of this is to increase the velocity of the fluid near the wall surface to prevent flow separation. This can be achieved by having a device to blow air into the flow or by redirecting the flow from a higher pressure region to the airfoil surface.
In the suction method, flow separation is prevented by removing the fluid particles which have lost their momentum to move along the airfoil. This is usually done by having a slit opening on the airfoil where the flow is sucked in before it has the chance to get detached from the airfoil surface. The slit opening is usually connected to a vacuum so that the pressure difference directs the flow to the vacuum before separation takes place. The vortex generation method, however, does not prevent flow separation but it controls the flow after the separation has taken place. The moving surface method uses a movable surface such as a belt or a rotating cylinder to add extra momentum to the flow. This increases the velocity near the airfoil surface and therefore delays the flow separation. This research paper focuses on the use of rotating cylinders on the NACA 0024 airfoil. The lift coefficient increases and the stall angle are delayed by the use of moving surfaces.

1.2. Literature review

Al-Garni et al. [7] conducted a study where they experimentally analyzed the flow separation over a NACA 0024 airfoil with a leading edge rotating cylinder. Their results indicated an increase in the lift coefficient when the ratio of the cylinder speed to the free stream velocity \( \xi \), was increased. For \( \xi = 4 \), the maximum lift coefficient was 1.6 and the stall angle was approximately 30°. However, for \( \xi = 0 \) the maximum lift coefficient, \( C_L = 0.9 \) and the stall was at an angle of attack, \( \alpha = 10° \). The stall angle was increased from 10° to 30°, which is an increase of approximately 200% and the lift coefficient was increased by approximately 77% when \( \xi \) increased from 0 to 4. It is also important to mention that their results showed a significant increase in the lift coefficient between \( \xi = 2 \) and \( \xi = 3 \). This is in comparison with the change in the values of \( C_L \) from \( \xi = 3 \) to 4 where the increase in the lift coefficients were not very significant. Moreover, the stall angles for \( \xi = 1 \) and 2 were very close to each other with just a few degrees apart. For \( \xi = 3 \) and 4 the stall angle was at \( \alpha = 30° \), and the lift coefficients only started to drop slowly after the stall angle. For all the rest of the cases the drop in lift coefficients after the stall angle appeared to be at a faster rate. The drag coefficient [7] for \( \xi = 0 \) increased significantly starting from \( \alpha = 20° \) and reached a value of 0.8 at \( \alpha = 40° \). For \( \xi = 4 \), the drag coefficient curve continuously increased with approximately the same rate form \( \alpha = 10° \) and reached a value of 1.3 at \( \alpha = 40° \). Comparing the cases of \( \xi = 3 \) and \( \xi = 4 \), the drag coefficient values did not
show any significant changes for $0^\circ \leq \alpha \leq 40^\circ$. However for the case of $\xi = 1$, there was a slight drop in $C_D$ at $\alpha = 20^\circ$, after which it continued to increase at a very slow rate up to $\alpha = 30^\circ$. Beyond this angle of attack the drag coefficient started to increase at a much faster rate. The authors in [7] also measured and plotted the velocity profiles on the top surface of the airfoil for $\alpha = 0^\circ$ for $\xi =0$ and $\xi =4$. For $\xi =0$, at 60% chord length the velocity on the top surface of the airfoil started to decrease and it reached a value of zero velocity. At 100% chord length the velocity was approximately zero for up to $y = 10$ mm. In comparison to this, for $\xi =4$, the added momentum from the rotating cylinder increased the velocity near the top surface of the airfoil. The plots showed that even at 100% chord length the velocity is quite high compared to the case without the rotation. Moreover at 40% chord length the differences between the velocity profiles for $\xi =0$ and $\xi =4$ pointed out the effect of the added extra momentum from the rotating cylinder. The authors in [7] also plotted the turbulence intensity for $\alpha = 0^\circ$ for $\xi =0$ and $\xi =4$. Their plots for the turbulence intensity indicated that at sections of 80% and 100% chord length, the turbulence intensity was higher for the case of $\xi =0$ compared to the case with the rotation. For the case of no rotation, the turbulence intensity reached up to a maximum value of 20% while for the case of rotation, this value was close to 15%. The authors in [7] also performed a flow visualization experiment for $\alpha = 10^\circ$, $20^\circ$ and $30^\circ$ with different configurations of $\xi$. The results showed that as the value of $\xi$ increased, the flow separation was delayed further down the airfoil.

Hassan and Sankar [8] conducted a study where they performed numerical and experimental analyses on NACA 0012 and NACA 63-218 airfoils with a leading edge rotating cylinder. In their research they introduced a variable $\beta$ which is the related Mach number for the leading edge rotating cylinder. Therefore, the higher the value of $\beta$, the higher the speed of the cylinder, which in turns adds more momentum to the flow near the airfoil surface. The numerical and experimental results showed that the lift coefficient for the NACA 63-218 airfoil increased from approximately 0.9 to 2.2 when $\beta$ was increased from 0.0 to 0.21 for $\text{Re} = 2.9 \times 10^6$. For $\beta = 0.0$, the lift coefficient reached the maximum value of 0.9 at $\alpha = 10^\circ$, after which it started to drop to approximately 0.7 at about $\alpha = 12^\circ$. After this point, both the experimental and numerical results showed an increase in the lift coefficient up to $\alpha = 20^\circ$. Both cases of
\( \beta = 0.12 \) and \( \beta = 0.21 \) showed similar trends of increasing lift coefficient up to the stall angle followed by a drop and then a slight increase afterwards. Also, all three cases of \( \beta \) produced positive lift coefficients for \( \alpha = 0^\circ \). Moreover, the graphs of \( \beta = 0.0 \) and \( \beta = 0.12 \) were overlapping for \( 0^\circ \leq \alpha \leq 10^\circ \) while the graph of \( \beta = 0.21 \) showed an increase in the lift coefficient values for \( 0^\circ \leq \alpha \leq 40^\circ \). The results [8] of \( C_P \) plots showed a decrease in the \( C_P \) values on the top surface of the airfoil as \( \beta \) was increased. For NACA 0012 at \( \alpha = 10^\circ \), the results showed the lowest \( C_P \) value of -1.8 for \( \beta = 0.4 \) for \( Re = 3.45 \times 10^6 \). This occurred at a position of approximately 6% chord length from the leading edge of the airfoil. This was due to the rotating cylinder adding an extra momentum to the flow. Also for \( \beta = 0.25 \), the maximum negative \( C_P \) was approximately -1.6. Similarly, the authors [8] also plotted the results for the \( C_P \) values for NACA 0012 at \( \alpha = 5^\circ \). For \( \beta = 0 \), the lowest \( C_P \) value was about -1.2 and for \( \beta = 0.4 \) the \( C_P \) value decreased to about -1.8. The decrease in the value of \( C_P \) was considerably high when \( \beta \) was changed from 0.3 to 0.4. Moreover, the authors also plotted the velocity vectors for NACA 0012 at \( \alpha = 15^\circ \) for \( Re = 8 \times 10^4 \). Their results clearly showed that as \( \beta \) was increased, the flow separation from the airfoil was delayed. For \( \beta = 0 \), the separation occurred very close to the leading edge of the airfoil while for \( \beta = 0.30 \) the separation took place much further down the airfoil. The authors [8] concluded that for subcritical flows, the effect of the rotating cylinder as a moving surface was to decrease the separated region on the top surface of the airfoil. This was done by delaying the flow separation. Hence it resulted in an increased lift coefficient. For supercritical flows, however, the drastic increase in the drag coefficient did not justify the increase in the lift coefficient values.

Thouault et al. [9] performed a numerical analysis for a rotating cylinder using transient RANS modeling methods. They used the ANSYS CFX software for their analysis. The rotating cylinder was equipped with end plates, where the ratio of the end plate diameter to the rotating cylinder diameter was 2. The shear stress transport (SST) turbulence model was used for the flow analysis. The authors also performed a grid independence test to ensure the accuracy of their results. They plotted the numerical lift and drag coefficients for the rotating cylinder against the experimental results. The numerical results were compared with the experimental data for \( 0^\circ \leq \alpha < 3.4^\circ \). The lift coefficient values agreed well with the experimental data. However, the
drag coefficient values were close to the experimental data in the range of $1^\circ < \alpha < 2^\circ$. Both experimental and numerical lift coefficients increased as $\alpha$ was increased. At $\alpha = 2.5^\circ$, the experimental $C_L = 7$ and the numerical $C_L = 7.4$. However the drag coefficient for $\alpha > 2^\circ$ and $\alpha < 1^\circ$ showed a considerable difference for the numerical and experimental results. The authors [9] also investigated the effects of adding more discs along the rotating cylinder on the lift and drag coefficients. The ratio of the end disc diameters to the rotating cylinder diameter was increased to 3. They introduced a variable, $s$, which defined the ratio of the spacing of the discs along the cylinder. They defined the variable $b$ as the distance between two end discs and the variable $D$ as the rotating cylinder diameter. The reference case was considered to be the rotating cylinder without the end discs. It was found that the reference case had the highest lift coefficient. However, for the case with $s = 1.27$, the lift coefficient was the lowest. Also it is important to mention that their results proved that adding more discs did not have any effect on the lift coefficient for $\alpha < 2^\circ$. The drag coefficients for $s = 1.27$ and $s = 0.63$ were lower in comparison to the other cases with $\alpha > 2.5^\circ$. At $\alpha = 3^\circ$ for $s = 1.27$ the $C_D = 2.6$, while for the reference case the $C_D = 2.9$ for the same angle. Moreover, for $\alpha < 2.5^\circ$ the reference case produced the lowest drag coefficient. The lift-to-drag ratio was highest for the reference case for $\alpha < 2.7^\circ$. The case with $s = 2.53$ had the highest lift-to-drag ratio for $\alpha > 2.7^\circ$.

Modi and Deshpande [10] performed experiments to investigate the effect of a rotating cylinder on the leading edge of a Joukowski airfoil. A 37 mm diameter rotating cylinder was positioned on the leading edge of a 370 mm chord airfoil. The $C_p$ plots indicated much lower pressure on the top surface of the airfoil when the ratio of the cylinder’s circumferential speed over the free stream velocity increased. Their results [10] for $\alpha = 15^\circ$ showed that the lowest $C_p = -3$ for $U_c/U_\infty = 2$, and for $U_c/U_\infty = 0$ the $C_p = -1.4$. Similarly, for $\alpha = 30^\circ$, the lowest $C_p = -2.8$ for $U_c/U_\infty = 3$, and for $U_c/U_\infty = 0$ the $C_p = -1.7$. Therefore for both angles of attack, the lift coefficient increased with the use of rotating cylinders. At $x/c = 0.1$, for $\alpha = 15^\circ$ and $U_c/U_\infty = 2$, the $C_p$ values showed the effect of the rotating cylinders adding an extra momentum into the flow. The authors [10] also plotted the $C_L$ graph for different speed ratios. The maximum $C_L$ value of 1.55 was recorded for the case of $U_c/U_\infty = 3$. The stall angle for this ratio was approximately $\alpha = 35^\circ$. This is in comparison to the stall angle of $\alpha = 10^\circ$.
and $C_L=0.9$ for the original airfoil. The results [10] showed an increase of about 70% in the lift coefficient and an increase of about 250% in the stall angle. It is important to note that the original airfoil produced a higher lift coefficient compared to the airfoil with $U_c/U_\infty=0$. This is because the original shape of the airfoil was distorted when incorporated with the rotating cylinder. The lift coefficient for the original airfoil was approximately 0.9 while the $C_L$ for the case of $U_c/U_\infty=0$ was recorded to be approximately 0.76. For all the cases of speed ratios, except the case for $U_c/U_\infty=3$, the lift coefficient values increased after their corresponding stall angles for up to $\alpha = 40^\circ$. After this point the value of $C_L$ dropped as $\alpha$ was increased to $90^\circ$. The authors [10] also plotted the $C_D$ values against $\alpha$ for different cases of speed ratios. The drag coefficient values in the range of $50^\circ \leq \alpha \leq 90^\circ$ produced interesting results. In this range, the effect of the rotating cylinder decreased the drag coefficient. At $\alpha = 70^\circ$, the drag coefficient was approximately 1.4 for $U_c/U_\infty=0$. But for the same angle, the drag coefficient for $U_c/U_\infty=4$ was approximately 1.15. The authors [10] also concluded that at lower angles of attack of $\alpha \leq 8^\circ$, the effect of the rotating cylinder was to decrease the drag coefficient. They [10] also investigated the $C_L/C_D$ graph for up to $\alpha = 90^\circ$. For $U_c/U_\infty=3$, the maximum $C_L/C_D=16$ at about $\alpha = 7^\circ$ while for the no rotation case, the maximum $C_L/C_D=6$ at about the same angle as the case with rotation.

Modi et al. [11] investigated the lift coefficient of an airfoil with rotating cylinders. They used both splined and smooth cylinders and compared their effects on the lift coefficient of the airfoil. They concluded that the lift coefficient increased when the ratio of the cylinder speed to the free stream velocity increased. However, the increase in the lift coefficient was significantly more when the splined cylinders were used. Thom and Sengupta [12] compared the effects of the surface texture of three rotating cylinders on the resulting torque coefficient. They used sanded, wooden and smooth cylinders and the results showed that the sanded surface produced the highest torque coefficient while the smooth cylinder produced the lowest. Thom [13] also compared the lift and drag coefficients of rotating cylinders with different end shapes. He used square and rounded ends on rotating cylinders. He concluded that the rotating cylinder with square ends produced higher lift coefficient than the rounded end cylinder. But the square ended cylinder also produced higher drag coefficient values. Modi [14] investigated the use of one and two rotating cylinders on 15%
Joukowski airfoils. He compared the lift coefficients of the airfoils having different locations for the rotating cylinders. The original airfoil without rotating cylinders produced a maximum $C_L = 0.9$ with a stall angle at $\alpha = 10^\circ$, while the airfoil with one leading edge rotating cylinder produced a maximum $C_L = 2.0$ at $\alpha = 28^\circ$. The airfoil with one trailing edge rotating cylinder produced a maximum $C_L = 1.7$ but the stall angle was found to be at $\alpha = 8^\circ$. The maximum $C_L = 2.6$ and the stall angle was at $\alpha = 20^\circ$. The results improved when he repositioned the two rotating cylinders, with one cylinder placed at the leading edge and one placed approximately at 50% of the chord length. The maximum $C_L = 2.75$ and the stall angle was at $\alpha = 40^\circ$.

Mokhtarian et al. [15] investigated the effect of the shape of the rotating cylinder on the lift coefficient of the airfoil. He used a scooped cylinder on the airfoil leading edge and proved that the resulting lift coefficient was increased for low cylinder speeds. This was due to the cylinder being able to push more air towards the upper surface of the airfoil. However at higher cylinder speeds, the effect of the scooped shaped cylinder appeared to diminish and the lift coefficient was found to be almost the same as the original cylinder shape. Modi et al. [16] investigated the lift and drag coefficients on a NACA 63-218 airfoil. They used two cases of airfoils, a leading edge rotating cylinder and another with including a flap rotating cylinder. For both cases, the lift-to-drag coefficient ratio increased when the cylinder rotation was present as compared to the cases without the rotation. However, they concluded that the increase in the lift-to-drag coefficient became very small for velocity ratios of greater than 2. They [16] performed wind tunnel experiments to investigate the effect of the size of the gap between the cylinder and the airfoil. They concluded that the smaller the size of the gap between the two surfaces of the airfoil and the cylinder, the more effective is the added momentum from the cylinder on the flow.

Buerge [17] used a Clark Y airfoil and a rotating cylinder positioned not on the airfoil but below it, near the trailing edge. The combined lift coefficient of the airfoil and the cylinder increased by approximately 200% compared to the lift coefficient of the airfoil itself. Modi et al. [18] used two rotating cylinders at the front and back of a flat plate. They produced the drag coefficients for different ratios of cylinder speed to the free stream velocity for $0 \leq \alpha \leq 90^\circ$. They concluded that the rotating cylinders reduced the drag coefficient of the plate as the velocity ratio
increased. At $\alpha = 90^\circ$ the $C_D = 0.5$ for the velocity ratio of 3, while for the same $\alpha$, the $C_D = 1.85$ for the case with no rotation. Therefore, a significant decrease in the drag coefficient was achieved. Badalamenti and Prince [19] investigated the effect of different sizes of end plates on the lift and drag coefficients of a rotating cylinder. The percentage change in the lift coefficient increased when the ratio of the velocities increased. At a velocity ratio of 5.5 there was a 200% increase in the lift coefficient for the case where the end plates had a diameter three times larger than the cylinder. This is in comparison to a 10% increase in the lift for the case with a diameter ratio of 1.10 for the same velocity ratio. It is to note that for the cases up to the diameter ratio of 1.5, the percentage change in the lift for each case remained constant for velocity ratios greater than 5. For the cases with diameter ratios of 2 and 3, the percentage changes in the lift were the same for velocity ratios less than 3. The highest lift-to-drag ratio was recorded for the case with a diameter ratio of 3. This occurred at the velocity ratio of 2.2 where the lift-to-drag ratio was 6.5. For the case with no plates, the highest lift-to-drag ratio was 2.7 at a velocity ratio of 2. Calderon and Arnold [20] conducted a study on flap rotating cylinders to increase the lift coefficient on an airfoil. They were able to increase the lift with very low power input for the rotation of the cylinders.

Weiberg and Gamse [21] and Weiberg and Dickinson [22] performed experiments on a specific plane with a flap rotating cylinder. When the $U_c/U_e$ ratio was increased they recorded a decrease in the separated region over the flap. An interesting study was also done by Do et al. [23] for flows over airfoils. Tennant et al. [24] positioned a rotating cylinder on the trailing edge of a symmetrical airfoil and recorded a high lift coefficient of 1.2 at $\alpha = 0^\circ$ for $U_c/U_e = 3$. Sahu and Patnaik [25] conducted a numerical analysis to study the effect of a rotating cylinder positioned on the leading edge of a NACA 0012 airfoil. They plotted the mean lift coefficient against the angle of attack. They used the SST, Realizable k-ε and Spalart Allamaras turbulence models and compared the results to published experimental data. The SST predicted the most accurate results. They also plotted the streak lines for the airfoil with and without the rotating cylinder and investigated the wake regions and vortices created in the field past the airfoil. They concluded that the size of the vortices was reduced with the use of rotating cylinders. Many numerical and experimental studies
have been conducted by Sinha et al. [26], Ashutosh et al. [27] and Saatchi et al. [28]. A detailed review and discussion of many studies in this field is provided by Seifert [29]. Johson et al. [30] analyzed the effect of a rotating cylinder along with the use of a flap. Sayers [31] investigated the effect of a rudder leading edge rotating cylinder. Brooks [32] analyzed experimentally the effect of a leading and a trailing edge rotating cylinder on a hydrofoil. Kothari and Anderson [33] and Viswanath [34] also investigated the effects of a rotating cylinder on an airfoil. Shmilovich and Yadlin [35], [36] and Lin et al. [37] investigated methods for delaying the separation of the flow. Ahmed et al. [38] investigated the effect of a leading edge rotating cylinders on the lift coefficient of an airfoil. In the table below the specific details of works of some of the prominent authors in this field are summarized.

**Table 1: Summary of research done by some prominent authors in the field**

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of work</th>
<th>Investigations</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thouault et al. [9]</td>
<td>Rotating cylinder with end plates</td>
<td>$C_L$, $C_D$</td>
<td>2010</td>
</tr>
<tr>
<td>Modi et al. [11]</td>
<td>Lift generated by splined and smooth rotating cylinders</td>
<td>$C_L$</td>
<td>1998</td>
</tr>
<tr>
<td>Modi et al. [18]</td>
<td>Reduction in drag with the use of rotating cylinders</td>
<td>$C_D$</td>
<td>1991</td>
</tr>
<tr>
<td>Shmilovich &amp; Yadlin [36]</td>
<td>Flow control for high lift systems</td>
<td>Performance of high lift wing investigated</td>
<td>2009</td>
</tr>
<tr>
<td>Lin et al. [37]</td>
<td>Control of flow separation by different airfoil surface structure</td>
<td>$C_L$</td>
<td>2013</td>
</tr>
<tr>
<td>Ahmed et al. [38]</td>
<td>Control of flow separation using rotating cylinder</td>
<td>$C_L$, $C_D$, $C_P$</td>
<td>2014</td>
</tr>
</tbody>
</table>
1.3. Research objectives

The main objective of this research is to control the boundary layer on the top surface of the airfoil by incorporating rotating cylinders in the geometry of the airfoil so that there would be an increase in the lift coefficient of the airfoil. Also another objective of this research is to decrease the drag coefficient at lower angles of attack and to delay the sudden increase in the drag coefficient that usually takes place after the stall. This is done by using rotating cylinders and delaying the flow separation. First a rotating cylinder is used at the leading edge of the airfoil to achieve this objective. And next an airfoil with two rotating cylinders is used for the analysis. The first cylinder is at the leading edge and the second cylinder is positioned on the flap.

1.4. Significance of research and problem statement

Control of boundary layer is of utmost interest in the field of aerodynamics. It is mainly due to the fact that delaying the boundary layer separation enhances the aerodynamic properties of the airfoil. A leading edge rotating cylinder will delay the flow separation by decreasing the relative motion of the free stream velocity to the fixed airfoil surface. It also adds an extra momentum to the flow which in turn increases the velocity even more at the upper surface of the airfoil. This delays the separation of the boundary layer. A separated boundary layer creates vortices with reversed flows, which increase the drag coefficient of the airfoil. Therefore by delaying the separation, the drag coefficient does not increase as significantly as for the cases with flow separation. For lower angles of attack the effect of the rotating cylinders is to decrease the drag coefficient of the airfoil. When the boundary layer remains attached to the airfoil surface, the lift coefficient and the stall angle increase drastically. Also the lift to drag coefficient ratio increases with the use of rotating cylinders. A real life application of this would be the example of a plane taking off on a runway. The wing tips usually are not able to produce the same amount of lift during takeoff as they do during the flight. This is because, before takeoff the wing tips usually have negative angle of attacks and therefore the lift generated in these regions is much lower as compared to the parts of the wing closer to the fuselage. Use of moving surfaces on the wing tips during takeoff could prove to be useful in terms of boundary layer control and an increased lift coefficient. This could also result in lower fuel consumption during takeoff.
1.5. Research methods and theoretical formulations

ANSYS CFX software was used for the simulation of the results in this research. The turbulence models used in this research were the shear stress transport (SST) and the detached eddy simulation (DES) models. However, the two equation models such as the standard k-ω and k-ε turbulence models are also discussed in terms of their shortcomings as compared with the more advanced models. In this section, the governing equations for each of these turbulence models will be discussed from ANSYS CFX – Solver Theory Guide [39].

The k-ε model works well with flows away from the wall and uses wall functions in the viscous sub layer region of the boundary layer and therefore irrespective of the fine grid used in this region, it fails to predict the flow separation.

The continuity equation is written as [39]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j) = 0$$  \hspace{1cm} (1)

The momentum equation is written as [39]:

$$\frac{\partial \rho U_j}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_i U_j) = - \frac{\partial p'}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu_{eff} \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + S_M$$  \hspace{1cm} (2)

For which \( S_M \) is the total body forces, \( \mu_{eff} \) is the effective viscosity and \( p' \) is the pressure that has been modified. It is defined as follows [39]:

$$p' = p + \frac{2}{3} \rho k + \frac{2}{3} \mu_{eff} \frac{\partial U_k}{\partial x_k}$$  \hspace{1cm} (3)

$$\mu_{eff} = \mu + \mu_t$$  \hspace{1cm} (4)

where \( \mu_t \) is the viscosity for turbulence and \( \mu \) is the viscosity in molecular level.

For the k-ε model, the following relation holds [39]

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$  \hspace{1cm} (5)

where the constant \( C_\mu = 0.09 \).
The turbulence kinetic energy equation is as follows [39]:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j k) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_k}) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon + P_{kb}
\] (6)

The turbulence dissipation rate equation is as follows [39]:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_j \varepsilon) = \frac{\partial}{\partial x_j} \left[ (\mu + \frac{\mu_t}{\sigma_\varepsilon}) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon + C_{\varepsilon 1} P_{eb} \right)
\] (7)

where the values of the constants are [39]:

\[
C_{\varepsilon 1} = 1.44 \\
C_{\varepsilon 2} = 1.92 \\
\sigma_k = 1.0 \\
\sigma_\varepsilon = 1.3
\]

Also, \(P_{kb}\) and \(P_{eb}\) represent the forces of buoyancy and \(P_k\) is defined as follows [39]:

\[
P_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} (3 \mu_t \frac{\partial u_k}{\partial x_k} + \rho k)
\] (8)

The Standard k-\(\omega\) model does not use wall functions in the viscous sub layer region and therefore is able to detect the flow separation with the use of appropriate grid size. However, the k-\(\omega\) model does not respond well with flows away from the wall surfaces. Therefore it is not able to predict the flow accurately when separation occurs at the stall angle and when the flow is at a larger distance from the wall surfaces. The k-\(\omega\) model for turbulence [39] was initially developed by Wilcox and the relationship between the turbulence viscosity, turbulence kinetic energy and turbulent frequency is as follows [39]:

\[
\mu_t = \rho \frac{k}{\omega}
\] (9)
The equation for $k$ is [39]:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial }{\partial x_j} (\rho U_j k) = \frac{\partial }{\partial x_j} \left[ \left( \mu + \frac{\mu_k}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \beta' \rho k \omega + P_{kb} \tag{10}$$

The equation for $\omega$ is [39]:

$$\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial }{\partial x_j} (\rho U_j \omega) = \frac{\partial }{\partial x_j} \left[ \left( \mu + \frac{\mu_\omega}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + P_{\omega b} \tag{11}$$

where the values of the constants are [39]:

\[
\begin{align*}
\beta &= 0.075 \\
\beta &= 0.09 \\
\sigma_k &= 2 \\
\sigma_\omega &= 2 \\
\alpha &= 5/9
\end{align*}
\]

Also, the Reynolds stress tensor and $P_{\omega b}$ are defined as [39]:

$$-\rho \overline{u_i u_j} = \mu_t \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} (\rho k + \mu_t \frac{\partial U_k}{\partial x_k}) \tag{12}$$

$$P_{\omega b} = \frac{\omega}{k} ((\alpha + 1) C_3 \max(P_k, 0), \sin \phi - P_{kb}) \tag{13}$$

The Shear stress transport (SST) model [39] uses a combination of the $k$-$\varepsilon$ and the $k$-$\omega$ model to solve for the flow. The model uses series of blending functions to switch the equations to the $k$-$\varepsilon$ or the $k$-$\omega$ model. These blending functions use the distance from the nearest wall to switch between either of the two models. For flows near the walls the functions switch to the $k$-$\omega$ model while for the flows away from the walls the functions switch the equations to the $k$-$\varepsilon$ model. The blending functions for the SST model are as follows [39]:

$$F_1 = \tanh(\text{arg}_1^4) \tag{14}$$

$$\text{arg}_1 = \min \left\{ \max \left( \frac{\sqrt{k}}{\omega \beta^*}, \frac{500 \nu}{\omega y^*} \right), \frac{4 \rho}{C D_{\omega k} \sigma_{\omega 2} y^2} \right\} \tag{15}$$

$$C D_{k\omega} = \max \left( 2 \rho \frac{1}{\sigma_{\omega 2}} \frac{\partial k}{\omega \partial x_j} \frac{\partial k}{\partial x_j}, 1 \times 10^{-10} \right) \tag{16}$$
\[ F_2 = \tanh (arg^2) \]  
\[ arg^2 = \max \left( \frac{2 \sqrt{\kappa}}{\omega y \beta^+}, \frac{500 v}{\omega y^2} \right) \]

For which \( y \) and \( v \) are defined to be:

\( y = \text{distance to the nearest wall} \)

\( v = \text{kinematic viscosity} \)

where the values of the constants are [39]:

\( \beta^+ = 0.09 \)

\( \sigma_{w2} = 1/0.856 \)

Detached eddy simulation (DES) is a hybrid model [39] that uses the unsteady SST model near the wall regions and the LES model for regions away from the walls. The switch from the SST model to the LES takes place when the turbulent length becomes greater than the spacing of the grid at that local region. In this way the model can accurately detect the eddy formations away from the walls and at the same time use much less computational cost than is usually associated with the standard LES model. The kinetic energy equation involves the dissipation rate, for which the length scale used is defined as follows [39]:

\[ L_t = \frac{\sqrt{\kappa}}{\beta^+ \omega} \]  
\[ \varepsilon = \beta^+ k \omega \]  
\[ \epsilon = \frac{k^{1.5}}{L_t} \]

The \( L_t \) is replaced with \( C_{DES} \Delta \), which is the DES local grid spacing, and the equations become as follows [39]:

\[ \epsilon = \frac{k^{1.5}}{C_{DES} \Delta} \]

This switches the DES model from RANS to LES when the following holds [39].

\[ C_{DES} \Delta < L_t \]

where

\[ \Delta = \max (\Delta_i) \]
The grid spacing used is selected to be the maximum length [39] to allow the DES model to switch back to the RANS model when the length scale is smaller than the local spacing for flows that are attached in the boundary region.

1.6. Thesis Structure

In this research, a configuration of the NACA 0024 airfoil with a leading edge rotating cylinder is analyzed using the SST turbulence model. Published experimental data [7] are compared with the numerical results for this airfoil configuration. Moreover, the DES turbulence model is used to analyze the flow field past the airfoil section. The SST analysis for the same airfoil configuration with a flap is also carried out. Finally, the SST simulation of the NACA 0024 airfoil with two rotating cylinders is performed.

Chapter 2 discusses the analysis on a NACA 0024 airfoil with a leading edge rotating cylinder that has 30% of its surface area exposed to the free stream velocity. The SST turbulence model is used for the simulations and the results are compared with published experimental data for the same airfoil cylinder configuration.

Chapter 3 analyzes the same airfoil with the DES model to detect the far field vortices and wake regions. This model uses LES in the regions away from the wall surfaces and therefore it is able to detect eddies and vortices more accurately.

Chapter 4 discusses the effect of the leading edge rotating cylinder on the same airfoil with a flap. While in chapter 5 the effect of two rotating cylinders on the airfoil with the flap are presented. Chapter 6 summarizes the conclusions drawn from the research and talks about the future work in the field of airfoil moving surfaces.
Chapter 2: Leading Edge Rotating Cylinder: SST Turbulence Model

2.1. Experimental data

In this section the Al Garni et al. [7] experimental data are used to validate the following numerical results. The experiment was carried out in a wind tunnel powered by 5.8 kW fan where the free stream velocity was at 5 m/s. The speed of the rotating cylinder was varied from a circumferential speed of 0 to 20 m/s which correspond to a ξ value of 0 to 4. For the pressure measurements they used a micro manometer with a precision of 0.2 mm of water. The airfoil surface had 12 holes on the top and bottom surfaces of the airfoil with 1 mm diameter for the pressure measurements. The lift and pressure coefficients were plotted for different rotational speeds. They used a hot wire for the velocity measurements with an IFA 200 Analogue to Digital converter. For the flow visualization they used a Nichrome wire with a diameter of 0.1 mm. A 65 V power was connected to the end points of the wire to generate the smoke for the flow visualization.

2.2. Geometry

The SST analysis of the NACA 0024 airfoil with a leading edge rotating cylinder with its surface area exposed to the free stream velocity has been published by Ahmed and Nazari [40]. The geometry of the airfoil with the rotating cylinder and the domain region are presented in Figures 1 and 2.

![Figure 1: Airfoil geometry dimensions for airfoil with cylinder; airfoil, cylinder and flap configuration [7]](image)
2.3. Meshing

Tetrahedral meshing elements have been used to generate the grid for the region of the domain. An inflation layer with $y^+$ of $< 1$ is used near the airfoil surface. The mesh elements near the airfoil surface and for the far field regions of the domain are presented in Figures 3 and 4. A grid independence analysis has also been performed for the case with $\alpha = 5^\circ$ and $U_c/U_\infty = 0$. This is to achieve grid-independent results and is presented in Figure 5. In the analysis $1.21 \times 10^6$ elements have been used.
2.4. Boundary conditions

The boundary conditions are as follows:

1. The inlet boundary condition was set to 5 m/s which corresponds to a $\text{Re}=6.6 \times 10^4$ for the airfoil with a chord length of 0.2 m.

2. The outlet boundary condition was set to have a gauge pressure of 0.0 Pa.

3. All the remaining four sides of the domain were set to have a symmetry boundary condition.

4. The cylinder boundary condition was set to a wall with no-slip conditions. For the case of rotation, a wall angular velocity of -1600 radians/second was added to the boundary settings. The negative sign is for the clockwise rotation of the cylinder so that the cylinder pushes the flow parallel to the free stream velocity down the top surface of the airfoil. This corresponds to a cylinder circumferential speed of 20 m/s.

5. The airfoil boundary condition was set to a wall with no-slip conditions.
2.5. Results and discussion

The SST results for this airfoil and cylinder configuration is presented and discussed. The results are compared with the published experimental data [7].

**Figure 6:** $C_L$ vs. $\alpha^\circ$ for SST model and Exp. results [7], $\xi = 0$

**Figure 7:** $C_L$ vs. $\alpha^\circ$ for SST model and Exp. results [7], $\xi = 2$
Figure 8: $C_L$ vs. $\alpha$ for SST model and Exp. results [7], $\xi = 4$

The lift coefficient values for cases of $U_c/U_\infty = 0$, 2 and 4 are plotted for different angles of attack in Figures 6-8. The SST results [40] are compared with the experimental data [7]. For $U_c/U_\infty = 0$ the SST gives the maximum $C_L = 0.97$ at $\alpha = 10^\circ$ while the experimental $C_L = 0.86$ at the same angle of $\alpha = 10^\circ$. It is to note that the numerical lift coefficient values overlap with the experimental data for $\alpha \leq 8^\circ$.

For $U_c/U_\infty = 4$, the SST gives the maximum $C_L = 1.56$ while the maximum experimental $C_L = 1.62$. The numerical results are in good agreement with experimental data in terms of lift coefficients. However, the stall angle for the numerical results is at $\alpha = 18^\circ$ while the experimental data shows the stall angle to be at approximately $\alpha = 30^\circ$. It is to note that the lift coefficient values for the SST drop significantly beyond the stall angle. This is in comparison with the experimental results where the lift coefficient values decrease at a very slow rate after the stall angle. Similarly, for $U_c/U_\infty = 2$, the lift coefficient values agree well with the experimental data for $\alpha < 13^\circ$.

The $C_p$ plots for $\alpha = 0^\circ$ for cases of $U_c/U_\infty = 0$, 2 and 4 are plotted for the top and bottom surfaces of the airfoil. The SST results [40] are compared with the experimental data [7] in Figures 9-11.
At this angle of attack, the $C_p$ values of the top and bottom surfaces of the airfoil are overlapping for $U_c/U_\infty = 0$. This is the case for both the SST and the experimental results. It is to note that $x/c = 0$ is the center line of the rotating cylinder. At $x/c = 0.4$, the SST gives a $C_p$ value of -0.47 while the experimental results give a value of $C_p = -0.63$. 

Figure 9: $C_p$ plot for $\alpha = 0^\circ$ with SST model and Exp. results [7], $\xi = 0$

Figure 10: $C_p$ plot for $\alpha = 0^\circ$ with SST model and Exp. results [7], $\xi = 2$
For $U_c/U_{∞} = 4$, the experimental data shows some differences between the $C_p$ values of the top and bottom surfaces of the airfoil. The SST results, however, show a very small difference for the top and bottom surfaces of the airfoil at a close vicinity of $x/c = 0$. 

Figure 11: $C_p$ plot for $α = 0^{}$ with SST model and Exp. results [7], $ξ = 4$

Figure 12: $C_p$ plot for $α = 10^{}$ with SST model and Exp. results [7], $ξ = 0$
Figure 13: \(C_p\) plot for \(\alpha=10^\circ\) with SST model and Exp. results [7], \(\xi = 2\)

Figure 14: \(C_p\) plot for \(\alpha=10^\circ\) with SST model and Exp. results [7], \(\xi = 4\)

The SST results [40] and the experimental results [7] of \(C_p\) for \(\alpha = 10^\circ\) for cases of \(U_c/U_\infty = 0, 2\) and 4 are also presented for the top and bottom surfaces of the airfoil in Figures 12-14. The SST results agree well with the experimental data. For \(U_c/U_\infty = 0\), the results are very close to the experimental data at \(x/c = 0.13\) and \(x/c = 0.6\)
for the top surface. As the $U_c/U_\infty$ increases from 0 to 4, the SST value of $C_p$ changes from -2.6 to -3.1 at the leading edge of the airfoil on the top surface. Therefore, the lift force increases on the airfoil. This is also illustrated from the increase in the area under the $C_p$ graph. As the ratio of $U_c/U_\infty$ increases, the corresponding area under the pressure coefficient graph increases. This again indicates an increase in the lift force on the airfoil. For $U_c/U_\infty=4$, the experimental and SST results overlap at $x/c = 0.2$ on the bottom surface of the airfoil. Moreover, the overall trends of the plots for all the cases of $U_c/U_\infty=0, 2$ and 4 agree well with those of the experimental data.

Figure 15: $C_p$ plot for $\alpha=20^\circ$ with SST model and Exp. results [7], (a) $\xi = 0$, (b) $\xi = 4$
Similarly, the $C_p$ plots for $\alpha = 20^\circ$ for cases of $U_c/U_\infty = 0$ and 4 are presented in Figure 15. For the case of $U_c/U_\infty = 0$ the results agree well with the experimental data. This is because both the SST and experimental data predicted stall conditions for this case. However for $U_c/U_\infty = 4$, the SST results indicate stall conditions for this case as well, whereas the experimental data does not show stall conditions for the airfoil for this case. Hence the area under the $C_p$ graph and the corresponding lift force on the airfoil does not decrease for the experimental results.

![Graph](image)

**Figure 16:** Mean velocity profiles $U/U_\infty$ for $\alpha = 0^\circ$ with SST model and Exp. results [7]
(a) $\xi=0$, (b) $\xi = 4$

The mean velocity profiles at different sections of the airfoil for $\alpha = 0^\circ$ are plotted in Figure 16 for both cases of $U_c/U_\infty = 0$ and 4. The SST and the experimental data agree well for both cases. The effect of the added momentum injected by the rotting cylinder can be seen from the velocity profiles at locations from $x/c = 0.2$ to 1.0. This is because there is a drastic increase in the velocity values near the airfoil surface.
Similarly, the mean velocity profiles for $\alpha = 10^\circ$ are presented in Figure 17 for both cases of $U_c/U_\infty = 0$ and 4. The effect of the rotating cylinder can be seen for this case as well. At $x/c = 0.6, 0.8$ and $1.0$ the SST results agree very well with the experimental data. The streamlines for $\alpha = 20^\circ$ for cases of $U_c/U_\infty = 0$ and 2 are presented in Figures 18 and 19. They are compared with the corresponding results of the experimental [7] smoke flow visualizations. Both the SST and the experimental results show a clear indication for the delay of the boundary layer separation from the top surface of the airfoil as the speed ratio increases from 0 to 2. In addition, it can also be seen from the SST results that the size of the vortices created from the flow separation decreased when the cylinder rotation was present.
Figure 18: Plot of stream lines for \( \alpha = 20^\circ \) for \( \xi = 0 \), (a) SST, (b) Exp. [7]

Figure 19: Plot of stream lines for \( \alpha = 20^\circ \) for \( \xi = 2 \), (a) SST, (b) Exp. [7]
Chapter 3: Leading Edge Rotating Cylinder: DES Turbulence Model

3.1. Results and discussion

In this section, the results for the DES turbulence model are presented for the airfoil with the cylinder. The same geometry, grid and the boundary conditions have been used as in Section 2.3 and 2.4. The graphs of lift and drag coefficient vs. angle of attack are presented in Figures 20-23. The graphs of lift-to-drag coefficient are also plotted for a range of α and are presented in Figures 24 and 25.

Figure 20: $C_L$ vs. $\alpha^\circ$ for $\xi = 0$ using DES, SST models and Exp. [7] data

Figure 21: $C_L$ vs. $\alpha^\circ$ for $\xi = 4$ using DES, SST models and Exp. [7] data
The results for DES model are compared with the SST results [40] and Experimental data [7]. For DES model the maximum $C_L = 1.25$ for the case with $\xi = 4$ and the stall angle is at $\alpha = 15^\circ$, whereas the maximum $C_L = 0.6$ for the case with $\xi = 0$ and the stall angle is at $\alpha = 8^\circ$. For the case of $\xi = 4$, there is an increase for all the $C_L$ values for $\alpha \leq 8^\circ$ from the corresponding values of the airfoil with no rotation. This means that the graphs of $\xi = 4$ and $\xi = 0$ are not overlapping for the region of $\alpha \leq 8^\circ$. For both cases of speed ratios, the DES model produced $C_L$ values which, compared to the SST model, were an under estimate. This is also true for the stall angles for each case. However, as presented later, the DES model was able to accurately predict a reduction in the drag coefficient for the case of $\xi = 4$.

The graph of $C_D$ vs. $\alpha$ is plotted for both the cases of $\xi = 4$ and $\xi = 0$. The rotating cylinder reduces the drag coefficient for the airfoil for the range of $\alpha \leq 5^\circ$. Hassan and Sankar [8] also reported a drop in the drag coefficient for low angle of attacks with the use of rotating cylinders. This is clear from the plot of drag coefficient vs. $\alpha$. The $C_D = 0.01$ for $\alpha = 0^\circ$ for the case of $U_c/U_\infty=4$ while for the case of $U_c/U_\infty=0$ the $C_D = 0.03$ for $\alpha = 0^\circ$.

![Graph](image)

**Figure 22:** $C_D$ vs. $\alpha^\circ$ for $\xi = 0$ using DES, SST models

The drag coefficient values for the case of $U_c/U_\infty=0$ start to significantly increase from $\alpha = 8^\circ$. This is because beyond this angle of attack the airfoil is stalling and the flow separation causes an increase in the drag coefficient. Similar trend is
shown for the case of $U_c/U_c=4$ where the drag coefficient increases significantly beyond $\alpha = 15^\circ$. It is important to note that the rotating cylinder not only reduced the drag for $\alpha \leq 5^\circ$, but also caused the drag coefficient to remain approximately close to the before-stall value of the no-rotation case for up to $\alpha = 15^\circ$.

![Figure 23: $C_D$ vs. $\alpha^\circ$ for $\xi = 4$ using DES, SST models](image1.png)

**Figure 23:** $C_D$ vs. $\alpha^\circ$ for $\xi = 4$ using DES, SST models

![Figure 24: $C_L/C_D$ vs. $\alpha^\circ$ for $\xi = 0$ using DES, SST models](image2.png)

**Figure 24:** $C_L/C_D$ vs. $\alpha^\circ$ for $\xi = 0$ using DES, SST models
The plot of the lift-to-drag coefficient ratio against the angle of attack $\alpha$ is presented next. The maximum $C_L / C_D = 20$ at $\alpha = 10^\circ$ for the case with $\xi = 4$ while for the case with $\xi = 0$, the maximum $C_L / C_D = 11.5$ at $\alpha = 8^\circ$. This increase in the lift-to-drag ratio is favorable in terms of the aerodynamic characteristics and is mainly due to the rotating cylinder adding extra momentum to the flow.

![Figure 25: $C_L / C_D$ vs. $\alpha$ for $\xi = 4$ using DES, SST models](image)

It is to note that at $\alpha = 0^\circ$, the $C_L / C_D = 1.0$ for $\xi = 4$, which is an increase from 0.0 for $\xi = 0$ at the same angle of attack. The highest values of the lift-to-drag coefficient ratio for $\xi = 0$ and 4 occur at $\alpha = 7^\circ$ and $11^\circ$, respectively. After these points, the $C_L / C_D$ values start to decrease. There is a drastic drop in the values of the $C_L / C_D$ beyond the stall angles of $\alpha = 8^\circ$ and $15^\circ$ for $\xi = 0$ and 4, respectively. This is due to the separation of the boundary layer from the top surface of the airfoil. With the flow separated on the top surface of the airfoil the lift drops significantly and the airfoil is said to be at a stall, and at the same time the drag increases due to the vortices generated from the separation of the flow. Therefore, beyond the stall angle the lift decreases and the drag on the airfoil increases. The use of the rotating cylinders in this case delayed the stall angle from $\alpha = 8^\circ$ to $\alpha = 15^\circ$. 

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The mean velocity profiles at different sections of the airfoil are presented in Figure 26 for $\alpha = 0^\circ$ for $\xi = 0$. The results of the DES model are compared with the SST model [40] and experimental data [7]. It is to note that $x/c=0.0$ for this case is located at the leading edge of the airfoil.

![Figure 26: Mean velocity profiles $U/U_\infty$ for $\alpha = 0^\circ$ for $U_c/U_\infty = 0$ with Exp. results [7]. (a) DES, (b) SST](image)

For $\xi = 0$, the DES model shows better results at $x/c=1.0$, where the flow is starting to detach from the airfoil. At this position the results are closer to the experimental data. Also at $x/c=0.4$, slight improvements are present with the DES model.
model. In Figure 27 the mean velocity profiles at different sections of the airfoil are plotted using the DES and SST models for $\alpha = 13^\circ$ for both cases of $\xi = 0$ and $\xi = 4$.

The results of the DES model are compared with the SST model. It is to note that $x/c=0.0$ for this case is located at the centre line of the rotating cylinder. For $\xi = 0$ the DES model shows reverse flows at $x/c=0.2$ and for $\xi = 4$ the reverse flow starts at $x/c= 0.6$. This is due to the added momentum of the rotating cylinder. However, for $\xi = 4$, the SST model did not show any reverse flows or separated regions at this angle of attack. This is because the SST stall angle was at $\alpha = 18^\circ$ while for the DES model the stall angle was predicted to be at $\alpha = 15^\circ$.
Figure 28: Vorticity contours using DES model for $\alpha = 20^\circ$, (a) $U_c/U_\infty = 0$ (b) $U_c/U_\infty = 4$

The vorticity contours for $\alpha = 20^\circ$ for both cases of $\xi = 0$ and $\xi = 4$ using the DES model are presented in Figure 28. For $\xi = 0$, large vortices and wake regions are produced in the flow region past the airfoil section. But for $\xi = 4$, the added extra momentum from the rotating cylinder reduces the size of the vortices in the flow on the top surface of the airfoil and in the region past the airfoil section. In Figure 29 the pressure contours for $\alpha = 20^\circ$ for both cases of $\xi = 0$ and $\xi = 4$ are plotted to show the corresponding pressure values of the wake regions and vortices in the flow. The reduction in the size of the vortices for the case of $\xi = 4$ can be seen from the pressure contours as well. The pressure contours for $\xi = 0$ show multiple circular regions of positive and negative pressures in the region of the flow past the airfoil section. These correspond to the vortices created in the flow which can be seen from the vorticity
contours. For the case with $\xi = 4$, the pressure contours appear to have fewer circular regions with positive and negative pressures. Also, the pressure differences between these regions are significantly lower as compared to the case of $\xi = 0$. Therefore the vortices are reduced both in size and number of occurrence. Sahu and Patnaik [25] also produced similar results for their NACA 0012 airfoil. The size and number of occurrence of the far field vortices reduced with the use of a leading edge rotating cylinder. It is important to note that for their case the cylinder surface area exposure to the free stream velocity was larger than compared to the case in this research. This is because the NACA 0024 airfoil has a larger thickness than the NACA 0012.

Figure 29: Pressure contours using DES model for $\alpha = 20^\circ$, (a) $U_c/U_\infty = 0$ (b) $U_c/U_\infty = 4$
Similarly, the vorticity and pressure contours are also plotted in Figures 30 and 31 for $\alpha = 13^\circ$ for both cases of $\xi = 0$ and $\xi = 4$. There is a clear reduction in the size of the vortices with the use of the rotating cylinders. The pressure contours for $\alpha = 13^\circ$ show that there is an increase in the pressure values on the bottom surface of the airfoil for $\xi = 4$. This in turn increases the lift coefficient of the airfoil.

![Vorticity contours using the DES model for $\alpha = 13^\circ$, (a) $U_c/U_\infty = 0$ (b) $U_c/U_\infty = 4$](image)

**Figure 30:** Vorticity contours using the DES model for $\alpha = 13^\circ$, (a) $U_c/U_\infty = 0$ (b) $U_c/U_\infty = 4$

The change in the lift coefficient values of the airfoil with time for $\alpha = 20^\circ$ and $\xi = 0$ is presented in Figure 32. It is to note that at this angle of attack, the airfoil is beyond its stall angle and therefore the lift coefficient values oscillate with the change in time around an average value. However, for $\alpha = 10^\circ$ and $\xi = 4$, the lift values reach to a constant value with the change in time as presented in Figure 33. This is because the airfoil is well before its stall angle.
Figure 31: Pressure contours using DES model for $\alpha = 13^\circ$, (a) $U_c/U_\infty = 0$ (b) $U_c/U_\infty = 4$

Figure 32: $C_L$ vs. Time [s] for $\alpha = 20^\circ$ and $U_c/U_\infty = 0$
The $C_p$ plots for $\alpha = 10^\circ$, $13^\circ$ and $20^\circ$ are plotted for both cases of $\xi = 0$ and $\xi = 4$ in Figures 34-36. For each angle of attack, there is a clear increase in the lift coefficient when $\xi$ is increased from 0 to 4. This is because the area under the curve of the $C_p$ plot which represents the lift coefficient is increased with the use of the rotating cylinder.

It is to note that the negative $C_p$ represents the pressure coefficients on the top surface of the airfoil. At $\alpha = 10^\circ$, the maximum negative $C_p$ = -2.5 for $\xi = 4$ and the maximum negative $C_p$ = -1.2 for $\xi = 0$. Similarly at $\alpha = 13^\circ$, the highest negative $C_p$ values are -2.7 and -0.95 for the cases of $\xi = 4$ and 0, respectively. Moreover, for $\alpha = 20^\circ$, the maximum negative $C_p$ value on the top surface of the airfoil is changed from -1.4 to -2.9 as $\xi$ is increased from 0 to 4.

The location of the $x/c=0.0$ is at the center line of the rotating cylinder. And it is important to mention that these maximum negative values of $C_p$ occur at a location of approximately $x/c = -0.06$. This is where the outer edge of the rotating cylinder is located. For $\alpha = 20^\circ$ and $\xi = 4$, the $C_p$ curve on the top surface of the airfoil drops significantly after $x/c = 0.06$. This is because the airfoil is stalling at this angle of attack and therefore the $C_p$ curve drops drastically once it has passed the rotating cylinder region. It is to note that this is not the case for $\alpha = 10^\circ$ and $13^\circ$ with $\xi=4$.
Figure 34: $C_p$ plot for $\alpha = 10^{\circ}$ using DES model

Figure 35: $C_p$ plot for $\alpha = 13^{\circ}$ using DES model, dashed line for $\xi = 4$ and solid line for $\xi = 0$
Figure 36: $C_p$ plot for $\alpha = 20^\circ$ using DES model, dashed line for $\xi = 4$ and solid line for $\xi = 0$
Chapter 4: Leading Edge Rotating Cylinder with 30° Flap: SST Turbulence Model

4.1. Geometry

In this section, the SST analysis of the NACA 0024 airfoil with the leading edge rotating cylinder, with a 30° flap is presented and discussed. The geometry of the airfoil with the cylinder and the flap are presented in Figures 37 and 38.

![Figure 37](image)

**Figure 37:** Airfoil geometry dimensions for airfoil with cylinder with a flap; airfoil, cylinder and flap configuration and dimensions [7] where δ=30° and the flap length is 0.04 m from the trailing edge

![Figure 38](image)

**Figure 38:** Domain region and dimensions, for airfoil with cylinder with a flap

4.2. Meshing

Tetrahedral meshing elements and an inflation layer with $y^+$ of < 1 were used to generate the grid. The mesh elements near the airfoil surface and for the far field regions of the domain are presented in Figures 39 and 40. The same meshing process and boundary conditions have been used for this new geometry as in Section 2.3 and 2.4, and therefore the grid independence analysis of Section 2.3 holds for this mesh as well.
4.3. Results and discussions

In this section the results for the airfoil with a rotating cylinder and a flap are analyzed. The SST results for the simulations are presented. The lift and the drag coefficient graphs for the cases of $U_c/U_\infty = 0$ and $U_c/U_\infty = 4$ are plotted against the angle of attack and are presented in Figures 41-44. The results are compared to the SST results [40] of the airfoil without the flap. Similarly the graphs of $C_L/C_D$ are presented in Figures 45 and 46.

![Figure 41: $C_L$ vs. $\alpha$ for $\xi = 0$, using SST model for $\delta = 0'$](image)
For \( \frac{U_c}{U_\infty} = 0 \), for \( \delta = 30^\circ \) the maximum \( C_L = 1.67 \) while the maximum \( C_L = 0.97 \) for \( \delta = 0^\circ \). The stall angle for both \( \delta = 30^\circ \) and \( \delta = 0^\circ \) is at \( \alpha = 10^\circ \). For \( \frac{U_c}{U_\infty} = 4 \), for \( \delta = 30^\circ \) the maximum \( C_L = 2.1 \) while the maximum \( C_L = 1.56 \) for \( \delta = 0^\circ \). The stall angle for \( \delta = 30^\circ \) is at \( \alpha = 17^\circ \) and for \( \delta = 0^\circ \) it is at \( \alpha = 18^\circ \). The lift coefficient for the airfoil with the flap increased with the use of a leading edge rotating cylinder. The \( C_D \) graphs are presented for \( \delta = 0^\circ \) and \( \delta = 30^\circ \) for \( \frac{U_c}{U_\infty} = 0 \) and 4.
Figure 44: $C_D$ vs. $\alpha$ for $\xi = 4$, using SST model

For $U_c/U_\infty = 0$, for $\delta = 30^\circ$ the maximum $C_L/C_D = 14$ at $\alpha = 5$ while for $\delta = 0^\circ$, the maximum $C_L/C_D = 12.5$ at $\alpha = 9$. Similarly, for $U_c/U_\infty = 4$, for $\delta = 30^\circ$ the maximum $C_L/C_D = 16$ at $\alpha = 5$ while for $\delta = 0^\circ$, the maximum $C_L/C_D = 17$ at $\alpha = 10$. It is to note that at $\alpha = 0^\circ$, the value of $C_L/C_D$ increased significantly for the case of $\delta = 30^\circ$ for both cases of $U_c/U_\infty = 0$ and 4.

Figure 45: $C_L/C_D$ vs. $\alpha$ for $\xi = 0$, using SST model
Figure 46: $C_L / C_D$ vs. $\alpha$ for $\xi = 4$, using SST model

The $C_P$ plots for $\alpha = 5^\circ$, $10^\circ$ and $15^\circ$ are presented in Figures 47-49 for $U_c/U_\infty = 0$ and 4 for the airfoil with $\delta = 30^\circ$. For $\alpha = 5^\circ$, the $C_P$ graphs for both cases $U_c/U_\infty = 0$ and 4 are very close to each other. This is because at this angle there is no significant difference in the lift coefficients of each case. For $\alpha = 10^\circ$, there is a change in the maximum negative $C_P$ values from $-3.6$ to $-4.1$ for $U_c/U_\infty = 0$ and 4, respectively.

For $\alpha = 15^\circ$, there is a drastic change in the $C_P$ values at the top surface of the airfoil. This is because for the case of $U_c/U_\infty = 0$, the airfoil is at stall conditions while for $U_c/U_\infty = 4$ it is before its corresponding stall angle of $\alpha = 17^\circ$. Also it is to note that the area under the $C_P$ graph for the case of rotation is much larger than the area for the case with no rotation.

This under-the-curve area represents the lift coefficient of the airfoil at that angle of attack. At $\alpha = 15^\circ$, at $x/c = -0.06$, the $C_P$ values changed from $-1.8$ for $U_c/U_\infty = 0$ to $C_P = -5.9$ for $U_c/U_\infty = 4$. The centre of the rotating cylinder is positioned at $x/c = 0.0$. The pressure contours for $\alpha = 10^\circ$ and $15^\circ$ are presented in Figures 50 and 51 for the airfoil with $\delta = 30^\circ$ for both cases of speed ratios. For $\alpha = 15^\circ$, the region of -20 Pa on the top surface of the airfoil increased drastically when the ratio of $U_c/U_\infty$ was increased to 4. This lower pressure on the top surface of the airfoil indicates an increase in the lift generated on the airfoil for the case of $U_c/U_\infty = 4$. 
Figure 47: $C_p$ plots for $\alpha = 5^\circ$ and $\delta = 30^\circ$ using SST model

Figure 48: $C_p$ plots for $\alpha = 10^\circ$ and $\delta = 30^\circ$ using SST model

Figure 49: $C_p$ plots for $\alpha = 15^\circ$ and $\delta = 30^\circ$ using SST model
The mean velocity profiles for $\alpha = 5^\circ$ and $\alpha = 10^\circ$ for both cases of $U_c/U_\infty = 0$ and 4 are presented in Figures 52 and 53 for the airfoil with $\delta = 30^\circ$. For the case of $U_c/U_\infty = 4$ at $\alpha = 5^\circ$, the effect of the added momentum to the flow by the rotating cylinder can be seen from the velocity profiles at $x/c = 0.2$ to 1.0. Similar trends can be seen for the velocity profiles at $\alpha = 10^\circ$. 

Figure 50: Pressure contours for $\alpha = 10^\circ$ and $\delta = 30^\circ$ using SST model (a) $\xi = 0$, (b) $\xi = 4$
Figure 51: Pressure contours for $\alpha = 15^\circ$ and $\delta = 30^\circ$ using SST model (a) $\xi = 0$, (b) $\xi = 4$

Figure 52: Mean velocity profiles $U/U_\infty$ for $\alpha = 5^\circ$ and $\delta = 30^\circ$ using SST model (a) $\xi = 0$, (b) $\xi = 4$
For $\alpha = 10^\circ$, for the case of $U_c/U_\infty = 0$, there is a reversed flow at $x/c = 1.0$. This represents flow separation and vortex formation. At $x/c = 1.0$, for the case of $U_c/U_\infty = 4$, there is no reversed flow due to the extra momentum that was supplied to the flow by the rotating cylinders.

**Figure 53:** Mean velocity profiles $U/U_\infty$ for $\alpha = 10^\circ$ and $\delta = 30^\circ$ using SST model
(a) $\xi = 0$, (b) $\xi = 4$
Chapter 5: Leading Edge Rotating Cylinder with 30° Flap with a Second Rotating Cylinder: SST Turbulence Model

5.1. Geometry

The SST analysis of the NACA 0024 airfoil with the leading edge rotating cylinder, with a 30° flap and with a second rotating cylinder positioned on the flap is presented and discussed here. The geometry of the airfoil with the cylinders and the flap are presented in Figures 54 and 55. The airfoil, the leading edge cylinder and the flap configuration and dimensions are from [7]. The flap length is 0.04 m from the trailing edge with δ=30°.

![Figure 54: Airfoil geometry dimensions for airfoil with cylinder with a flap and with a second rotating cylinder](image1)

![Figure 55: Domain region and dimensions for airfoil with cylinder with a flap and with a second rotating cylinder](image2)

5.2. Meshing

Similar tetrahedral meshing elements with an inflation layer of $y^+$ of < 1 have been used to generate this grid as well. The mesh elements near the airfoil surfaces and in the far regions of the domain are presented in Figures 56 and 57. The same meshing process and boundary conditions have been used for this geometry as were used in Section 2.3 and 2.4. Therefore, the grid independence analysis of section 2.3 holds for this mesh as well.
Figure 56: Meshing for the domain for airfoil with cylinder with a flap and with a second rotating cylinder

Figure 57: Meshing near the airfoil surface for airfoil with cylinder with a flap and with a second rotating cylinder

5.3. Results and discussion

In this section the results for the airfoil with a leading edge rotating cylinder and a 30° flap and a second rotating cylinder are presented and discussed. The SST model was used for the simulations. The lift and the drag coefficients for the cases of $U_c/U_\infty = 0$ 4, for the airfoil with one leading edge rotating cylinder are presented in Figures 58 and 59. They are compared with the results of the airfoil with two rotating cylinders. A speed ratio of $U_c/U_\infty = 4$ was used for both of the cylinders. Similarly, the graph of $C_L/C_D$ is also presented in Figure 60. For the case of the airfoil with two cylinders, the speed ratios for both of the cylinders are kept at $U_c/U_\infty = 4$ throughout the analysis.
Figure 58: $C_L$ vs. $\alpha$° for $\delta = 30^\circ$ using SST model

For $U_c/U_\infty = 0$, the maximum $C_L = 1.67$ and the stall angle is at $\alpha = 10^\circ$. For $U_c/U_\infty = 4$, the maximum $C_L = 2.1$ with the stall angle at $\alpha = 17^\circ$. For the two-cylinder case, the maximum $C_L = 2.4$ with the stall angle at $\alpha = 18^\circ$. The $C_D$ and $C_L/C_D$ graphs are also presented for $U_c/U_\infty = 0, 4$ and for the case of the airfoil with two cylinders.

Figure 59: $C_D$ vs. $\alpha$° for $\delta = 30^\circ$ using SST model

Figure 60: $C_L / C_D$ vs. $\alpha$° for $\delta = 30^\circ$ using SST model
The pressure contours for $\alpha = 20^\circ$ for $U_c/U_\infty = 0, 4$ and for the case of the airfoil with two cylinders are also presented in Figure 61. The case with two cylinders has a pressure of $-20$ Pa on a larger area on the top surface of the airfoil as compared to the other two cases. Therefore, it has the largest lift coefficient. This is because of the extra momentum added to the flow from the two rotating cylinders. For the other two cases with only one leading edge rotating cylinder, the airfoil is at stall conditions.

Figure 61: Pressure contours for $\alpha = 20^\circ$ and $\delta = 30^\circ$ using SST model (a) $\xi = 0$, (b) $\xi = 4$ and (c) 2 cylinders with $\xi = 4$ for each
The mean velocity profiles for $\alpha = 20^\circ$ for $U_c/U_\infty = 0, 4$ and for the case of the airfoil with two cylinders are presented in Figure 62 and discussed. For $U_c/U_\infty = 0$, there is a reversed flow starting from $x/c = 0.2$ while for $U_c/U_\infty = 4$ the reversed flow and hence the separation occurs at $x/c = 0.6$. However, for the case with two cylinders, there is no reversed flow up to $x/c = 0.8$. For this case, it is important to note the velocity profile at $x/c = 0.8$ where the velocity values have increased near the surface of the airfoil due to the rotation of the second cylinder.

**Figure 62:** Mean velocity profiles $U/U_\infty$ for $\alpha = 20^\circ$ and $\delta = 30^\circ$ using SST model
(a) $\xi = 0$, (b) $\xi = 4$ and (c) 2 cylinders with $\xi = 4$ for each
Chapter 6: Conclusions and Future Works

6.1. Summary

The results show that the aerodynamic characteristics of the airfoil are improved with the use of rotating cylinders as a moving surface on the airfoil. In chapter 2 the NACA 0024 airfoil with leading edge rotating cylinder generated a higher lift coefficient as compared to the case without the cylinder rotation. The lift coefficient for this airfoil was increased by 60% when the cylinder had a circumferential speed four times the free stream velocity. The Stall angle was increased by approximately 80% when the speed ratio was increased from 0 to 4. The drag coefficient for the airfoil increased drastically only after the delayed stall angle. In chapter 3 the DES model predicted the vortices and wake regions of the flow. For small angles of attack the DES model predicted the drag coefficient of the airfoil to have lower values for the case of rotation. Similar results were produced by Hassan and Sankar [8] where the drag coefficient values were decreased with the use of rotating cylinders. By using the leading edge rotating cylinder, the sizes of the vortices created in the flow field past the airfoil were significantly reduced. In Chapter 4 the effect of the rotating cylinder on the NACA 0024 airfoil with a flap was to increase the lift coefficient and the stall angle. The pressure contours showed that a larger area with a negative pressure was present on the top surface of the airfoil when the rotating cylinders were used. This negative pressure on the top surface leads to an increase in the lift generated on the airfoil. In chapter 5 the use of two rotating cylinders on the NACA 0024 airfoil with a flap also increased the lift coefficient drastically and delayed the stall angle. The lift coefficient of the airfoil was increase by 50% when two rotating cylinders were used with a circumferential speed of 20m/s. This corresponds to the speed ratio of 4. The stall angle of the airfoil was increased by 100% with the use of two rotating cylinders

6.2. Future Work

Some of the future work on this research could include a direct numerical analysis of a three dimensional wing incorporated with rotating cylinders. This could prove to be very interesting in terms of improving the aerodynamic characteristics of the whole wing. This is because during the takeoff the wings of an airplane do not produce the
same amount of lift as they normally do during the cruising time. The part of the wing towards the edge of the tip are slightly at a lower angle of attack during takeoff and hence do not contribute fully to the total lift generation on the wings. Using rotating cylinders on these regions of the wings could increase the lift generation on the wings. This would also reduce the fuel consumption of the aircraft during takeoff. Moreover, this would also make the use of these rotating cylinders practically possible. This is because it would be almost practically impossible to rotate a cylinder on the leading edge of the entire wing span. However having smaller sections of these cylinders on the wing at critical regions would not only improve the desired characteristics but it would also be practically plausible. Therefore, a three dimensional analysis of such configurations of the wing and the rotating cylinders would prove to be very beneficial in improving the aerodynamic characteristics of the entire wing.
References


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