



Contents lists available at <http://qu.edu.iq>

## Al-Qadisiyah Journal for Engineering Sciences

Journal homepage: <http://qu.edu.iq/journaleng/index.php/JQES>



# Enhancement of airfoil performance by rotating cylinder

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### ARTICLE INFO

#### Article history:

Received 18 January 2021

Received in revised form 12 March 2021

Accepted 15 May 2021

#### Keywords:

Airfoil  
Enhancement  
Rotating cylinder  
Performance  
NACA6409

### ABSTRACT

This study used a NACA 6409 smooth wing section. Its performance is compared to an enhanced design incorporating a revolving cylinder on the upper airfoil surface. The boundary conditions for the present work were Reynolds ( $10^5$ ), and the attack angles were (0,2,4,6,8,10,12,14,16). A turbulence model was developed (SST K- $\omega$ ), one of the aerodynamics models. This model is well-suited for sensing flow near a wall. The cylinder was evaluated at three positions (25,50,75) percent of the chord's length. The results indicated that position (25 percent C) was optimal, as it resulted in a 24.45 percent increase in lift coefficient at the angle of attack (12). And when the results were compared to those of other studies, they revealed a significant agreement.

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## 1. Introduction

There is a growing interest in flow control, especially aerodynamics, and there are plans to increase lift and reduce airfoil resistance. Because of the adhesive effects, the wings suffer flow separation at high angles of attack, leading to a significant lift force loss and increased drag. As a result, the efforts of academics have been intensified to research and investigation the latest methods and techniques in controlling flow separation. H. Park et al. [1] presented a passive technical analysis for separating flows. The tabs were put on the airfoil's back edge, both upper and lower. An investigation was conducted experimentally by varying (the height, and width) of the tabs and their spacing, the Reynolds numbers ( $2 \times 10^4$ ,  $4 \times 10^4$ , and  $8 \times 10^4$ ). The results indicated that the base pressure increased (drag was reduced) for all selected Reynolds numbers and that the base pressure increased by (30 %). [2, 3] Presented a study of the technique of vortex generators using different Reynolds numbers. , relied on a basic investigation, that when vortices are generated in a thicker boundary layer, the vortices transfer the high-

momentum fluid to the boundary layer. This makes it thinner and has a higher resistance to reverse pressure gradient. The results showed an improvement in the airfoil performance. W.W. Huebsch et. al. [4], view flow control as flow instability due to the viscous sublayer. The use of synthesis vortices to produce increased mixing, and absorption to obtain the correct synthesis (or a combination of the above). When the dynamic amplitude is comparable to the boundary layer height, the boundary layer state changes completely The results of this work demonstrate indicate that dynamic roughness can be employed effectively to control leading-edge separation flow in the Reynolds number range studied. the dynamic roughness is defined according to the scale of the approaching lamellar layer entered at the start of separation. The boundary layer changed earlier than the natural one. [5-10] conducted numerical and experimental investigations, or a combination of the two, on airfoils with various forms and dimples (external, internal, tennis ball shape, and teardrop shape). Experiments were conducted under various boundary

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conditions (Reynolds numbers, attack angles, and flow velocity). The reason behind using this technique is attributed to the dimples of various shapes generating eddies that retard or obstruct the flow's separation from the airfoil surface. These findings revealed an improvement in the airfoil's aerodynamic performance (lift and drag). Dilek F. [11] conducted a study to examine the unstable flow with increasing incidence angles and boundary conditions,  $Re = 103$ , and different angles of attack with the NACA 0012 wing, the vortex pattern was calculated using the formal figure. The flux shows to be very laminar, and the boundary layers were very thick at this Reynolds number. At lower angles of attack, there are flux, vortex detachment, and separation. For the NACA 0012 wing, the unstable  $8^\circ$  vortex can be observed. Angles of attack usually range from  $0^\circ$  to  $90^\circ$ . It is suggested that the aerodynamic forces induce an oscillation until a peak in the amplitude spectrum of the lift coefficient (Cl) is reached. At this low Reynolds number, the time-averaged streamlines, pressure, and skin friction coefficients are evaluated to see vortex development and separation from the airfoil's upper surface. Pavlenko A. M. et al. [12] conducted an experimental study to investigate the evolution of hydrodynamic turbulence that resulted from low-frequency vibrations. The results were obtained by using a low-velocity hot wire intensity meter. The results indicated that the vibrations in the wall generated disturbances in the separation region. The separation of the laminar boundary layer promoted the growth of the positive beams with the subsequent turbulence of the wall flow. Zhou Y. et al. [13] Conducted a numerical study by placing a small plate near the front edge of the airfoil. The purpose of this plate is to create an overlap between the eddies produced by the plate and the boundary layer on the airfoil surface to control the flow separation. The researchers focused on Mach number, plate length, and angle and their effect on controlling flow separation. The results indicated that Mach numbers less than (0.5) have the potential to preserve the airfoil (NACA 4405). However, Mach numbers greater than (0.5) can only obtain a slight improvement. Mahdi N. et al. [14] conducted a study to investigate delta airfoils' performance and flow characteristics with sweep angle ( $65^\circ$ ) and coarse axial ribs. It is compared to a smooth-surface delta wing. The study investigated the effect of the ribs on (the diameter, distance, and location) of vortices from the airfoil surface. The results indicated that the airtight type is positive in increasing the lift and reducing the drag. The ribs increase the flow near the upper surface except for the area near the summit. Sreejith B.K. & A. Sathyabhama [15], conducted a numerical and experimental study to verify the effect of the leading tuber with different ailerons at different angles of attack and Reynolds number  $10^5$ . The stall occurred at an angle ( $12^\circ$ ) in the normal wing, as observed from experimental results. The results indicated in this study that all airfoils with tuber have the same stall angle except (A2W15.5) where the stalling occurred at the angle ( $10^\circ$ ).

By evaluating past research, we discovered a dearth of interest in studying cylinder rotation on the upper surface of the wing. Therefore, this work will focus on studying the extent of its impact on aerodynamic performance and its potential to enhance performance.

## 2. Describe the problem and boundary conditions

In this work, the effect of cylinder rotation on the airfoil's upper surface is considered, to improve airfoil performance. The influence of cylinder diameter was significant to obtain excellent work and satisfy the desired goal (the cylinder diameter is the same for all situations). The number of rotations of the cylinder varied according to the location. The cylinder is placed at three places that can separate the boundary layer from the length of the chord's anterior edge of an airfoil. Table 1 shows. The boundaries of the conditions

were angles of attack ( $0^\circ, 2^\circ, 4^\circ, 6^\circ, 8^\circ, 10^\circ, 12^\circ, 14^\circ, 16^\circ$ ), flow velocity (10 m/s) and Reynolds number ( $10^5$ ).

**Table 1.** Data & position Cylinder.

Position cylinder	N (RPM)	Diameter cylinder (cm)
25% c	124	0.54
50% c	143	0.54
75% c	172	0.54

## 3. FE Setup

### 3.1. Grid and computational domain

Grid and computational domain are both crucial to obtain accurate results. A two-dimensional rectangle was created ( $3*1.35$ ) m, and the rectangle was 20 double the length of the chord. The height was 9 double the length of the chord. It was intended to obtain a fully developed flow. In front of the airfoil is 5 double the chord length, and behind it is 15 double the length of the chord, to avoid any impact on the walls Zhong W. [16] shown in Fig .1 a and b. The boundary conditions were Hare's Reynolds number ( $10^5$ ) and flow velocity (10 m/s); the flow is considered to be stable, non-viscous, and incompressible. The semi-implicit method was used for the pressure-related equation computational.

The wall Y-plus parameter is a dimensionless parameter that shows the accuracy and convergence of the results, with a value less than or equal to one indicating more accurate aerodynamic results. Using the following equations, calculate Y – Plus.

$$Y = \frac{y^+ \mu}{\rho u_*} \quad (1)$$

Where:

$$u_* = \sqrt{\frac{\tau_w}{\rho}} \quad (2)$$

$$\tau_w = 0.5 C_f \times \rho \times U_\infty^2 \quad (3)$$

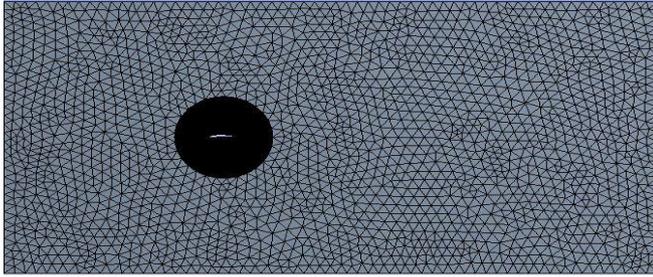
$$C_f = [2 \log Re - 0.65]^{-2.3}, \text{ For } (Re < 10^9) \quad (4)$$

$$Re = \frac{\rho c U_\infty}{\mu} \quad (5)$$

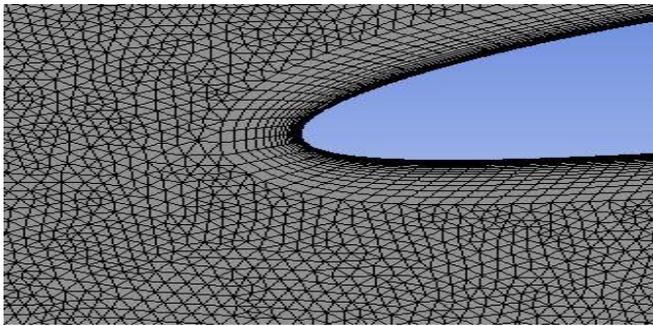
### 3.2. Grid-independence

It is crucial to study the relationship between the mesh size and the accuracy of the solution increase in the number of cells must be investigated against variation in the convergent solution. The appropriate test methodology for mesh independency has been adapted, Fish et al.[17]

The current work was carried out by selecting five meshes to check the number of cells ranging from (125536) to (633421), and this selection was implemented at the angle of attack ( $12^\circ$ ). The convergence of lift and pull values occurred at a network consisting of cells of (517613), and the difference was almost negligible.



(a)



(b)

**Figure 1.** Grid for domain

**Table 2.** Grid-independence

Iteration	Grid	Y+	C <sub>L</sub>	C <sub>D</sub>
923	125536	3.5	0.93419	0.03659
1846	281562	2.5	1.20001	0.04993
3218	374648	1.5	1.23986	0.05927
4509	517613	0.9	1.40609	0.06562
6340	633421	0.8	1.41352	0.06684

### 3.3. Turbulence model and governing equation

It is essential to find or use a disturbance model that can capture the phenomenon of transition. The current work assumes incompressible, turbulent, viscous, steady, and 2-dimensional flow with an adopted (SST k- $\omega$  turbulence model), [15, 17, 18]. For the kinetic Energy of perturbation  $k$  and the specific dissipation rate  $\omega$ , see the equations below.

Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (6)$$

Momentum Equation

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial y} \left[ \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] \quad (7)$$

$$\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] \quad (8)$$

SST K- $\omega$  Turbulence model

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho U_i k) = \tilde{P}_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_i} \right] \quad (9)$$

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho U_i \omega) = \alpha \rho S^2 - \beta \rho \omega^2 + \frac{\partial}{\partial x_i} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (10)$$

Where:  $\beta^*$  is 0.09, and  $\sigma_{\omega 2}$  is 0.856.  $F_1$  is the blending function, and  $S$  is an invariant measure of the strain rate. In (the k- $\epsilon$  model), the blending function equals zero when it is away from the surface, but in (the k- $\omega$  model), it is one inside the boundary layer Menter et al. [19].  $\tilde{P}_k$ , definition production limiter, the purpose of its use in the SST Model is to eliminate or prevent the accumulation of disturbances that occur in stagnation areas. Calculate all other constants through a combination of (k- $\omega$ ) and (k- $\epsilon$ ) models via  $\alpha, \sigma_\omega, \sigma_k, etc.$  Menter et al. [19, 20].

## 4. Results and discussions

The study conducted a numerical analysis to investigate the problem in the flow control due to a cylinder placed on the upper surface of the airfoil with a fixed diameter of (0.54 cm), at different positions (25%, 50%, 75%) the length of the line from the front edge of the airfoil where the velocity of free flow was (10 m/s).

### 4.1. Validation

To determine the validity and convergence of current search results. Lift coefficients were calculated at various angles of attack ( $0^\circ$  to  $10^\circ$ ), then compared with those obtained in previous research E.N. Garcia et al. [21] Shown in Fig. 2 The study conditions under which the current research was conducted were similar to those used in previous studies. One of the most critical conditions is NACA6409, which is the same used in current research. There was a difference between the study previous and the current study, (the different circumstances of the two studies). found an acceptable error rate at an angle of attack ( $10^\circ$ ) of (1.46%).

### 4.2. Lift and drag

Lift on an airfoil is often caused by the angle of attack and the form of the airfoil. To ensure the airfoil deflects the incoming air, the airfoil at an angle that produces a force the airfoil in the opposite direction of deflection was oriented. Moreover, aerodynamic force, is classified as lift and drag. A lift can be produced on many foil shapes, but the cambered airfoils can do so even at zero attack angles Sharma et al. [22].

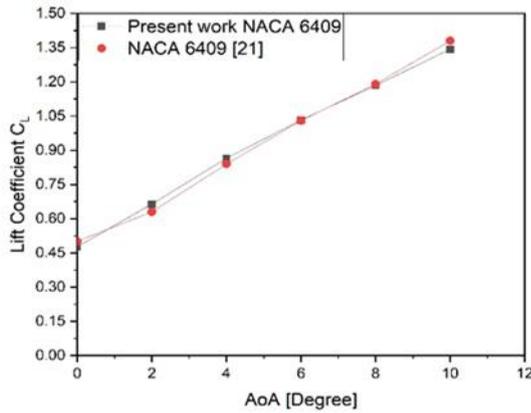
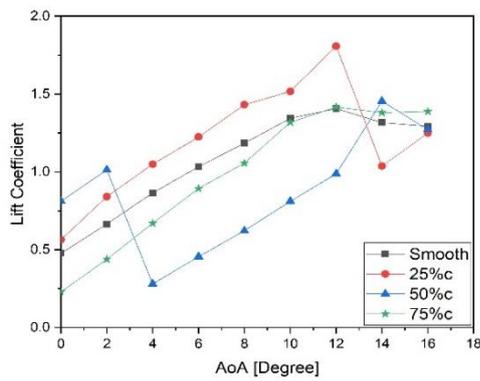
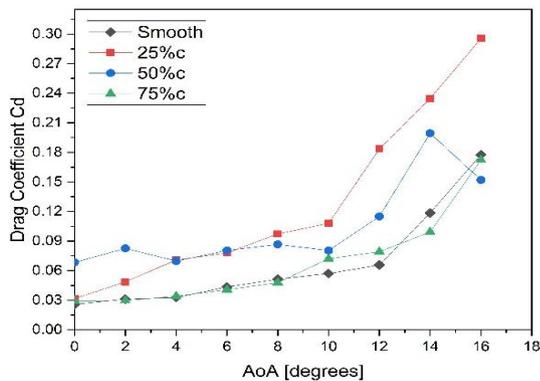


Figure 2. Lift Coefficients of the present research and researcher [8] with the Angle of Attack



(a)



(b)

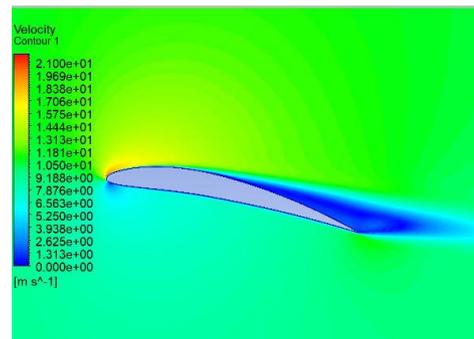
Figure 3. Lift and Drag coefficients with angles of attack

From Fig. 3-a, is observed that the lift coefficient of the smooth airfoil starts from a value higher than zero, and this proves the hypothesis above about the zero-attack angle and its output for the lift coefficient. As shown in Fig. 3-a,

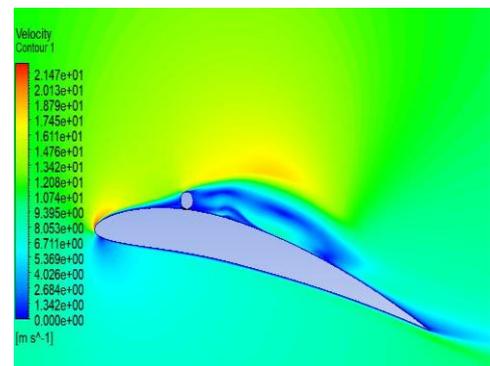
it can be seen that the best lifting coefficient is at the position (25%*c*) where the percentage of improvement was in the lift coefficient (24.45%), and this is owing to the cylinder's position and its critical function in delaying the boundary layer's separation process. Fig. 3-b, is shown the airfoil behavior illustrated concerning the drag coefficient, demonstrating that an increase in the angle of attack results in an increase in the drag coefficient. However, the proportions ranged in increasing the drag coefficient according to the effect of the cylinder position at the other positions.

### 4.3. Velocity Contours

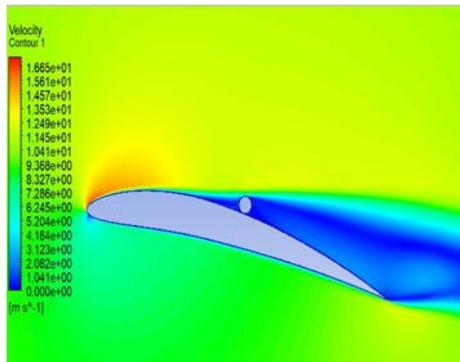
the area of separation of the flow from the airfoil surface can be possibly determined, it is also possible to observe the effect of the position of the cylinder on the performance of the aileron (delaying the separation process). In Fig. 4-a, the separation in the airfoil is observed to be smooth at an angle of 12°; from the gradient, see the separation area, as shown in Fig. 4-a. Fig. 4-b explains the velocity distributions in the airfoil with the cylinder at the position (25%*c*). Note that the process of re-bordering the boundary layer adhesion to the upper surface of the airfoil, explains the increase in the lift coefficient at the angle of attack (12°). Fig. 4-c shows the cylinder at the position of (50%*c*), from the gradation of colors, see the process of separation of the flow occurred early and before the cylinder. The position of the cylinder becomes ineffective inflow. Fig. 4-d represents the velocity trends of the cylinder at (75%*c*). Through the results and contour, it is found that the cylinder is in the area of separation. Thus, the flow cannot be re-adhered at the airfoil surface which becomes utterly ineffective.



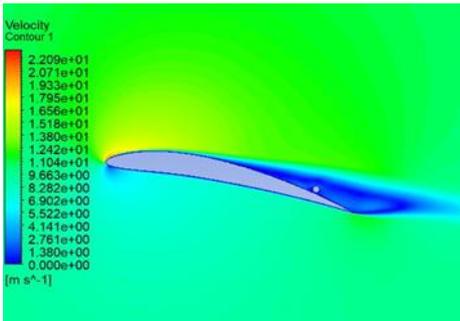
(a)



(b)

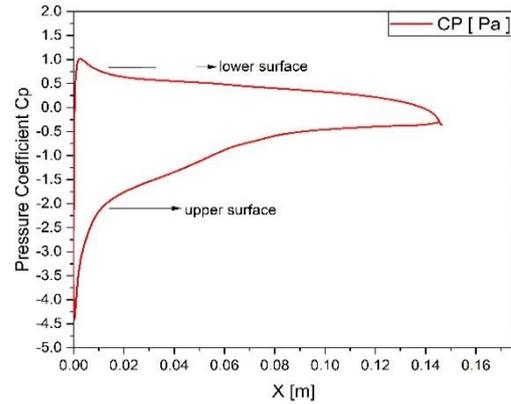


(c)

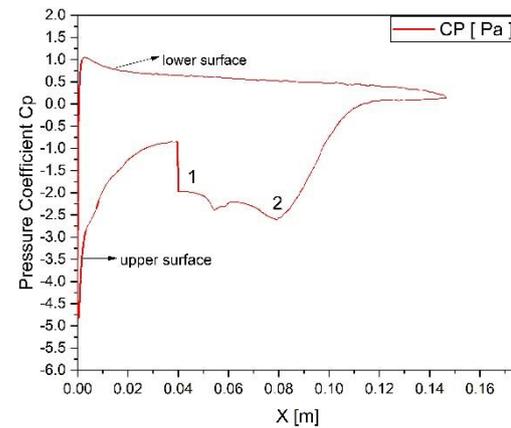


(d)

Figure 4. Velocity contours

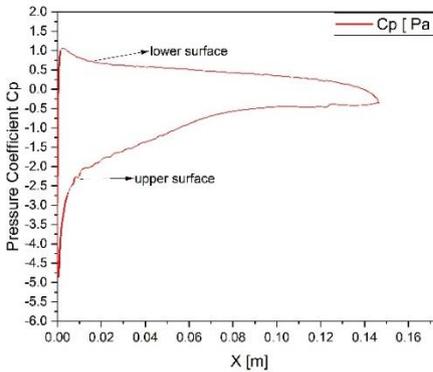


(c)

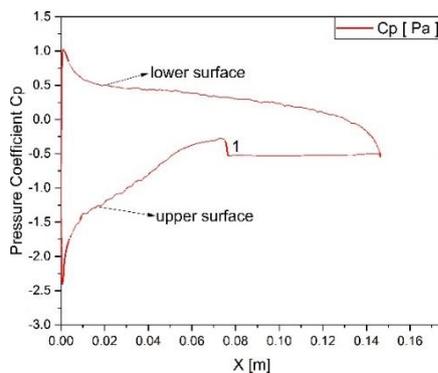


(d)

Figure 5. Pressure coefficient with position



(a)



(b)

4.4. Pressure Coefficient

Fig. 5 represents the air pressure coefficient on the NACA 6409 airfoil (Fig. 5-a) the smooth airfoil, (Figs-b, c, d) for the modified airfoil, at the angle of attack ( $12^\circ$ ) where the negative value indicates the pressure factor on the upper surface of the wing. The positive value represents the pressure coefficient on the lower surface of the wing. The results obtained indicate that the more negative the pressure coefficient on the upper surface, the higher the lift coefficient. All of the above is based on Bernoulli's principle. In Fig. 5-b, two locations (1 and 2) change the shape of the curve as a result of the cylinder's action on the wing surface at 25% c.

Fig. 5-c, shows the extent of the effect of the cylinder rotation at a position (25%). A change occurred in the shape of the lower curve at region (1), which represents the upper surface of the airfoil. The reason for the change is the effect of the cylinder rotation. Fig. 5-d, where the cylinder position is 75% c. The curve is similar to that of the smooth airfoil, when compared to Fig. 5-a, the result indicates, that there is no effect of cylinder rotation on the flow in position 75% c.

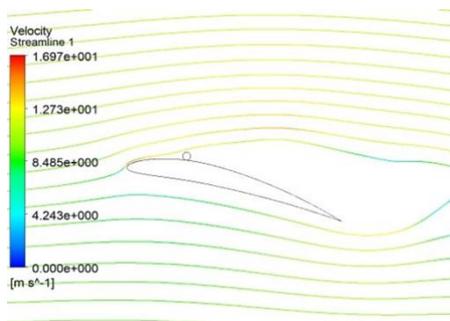


Figure 6. Velocity streamlines contour at an angle of attack ( $14^\circ$ )

## 5. Conclusions

A numerical study was performed on the airfoil (NACA 6409) to investigate aerodynamic performance with and without cylinder rotation on the airfoil's upper surface. Three positions of the cylinder (25%, 50%, 75%) were chosen from the front edge of the airfoil.

The results showed the following:

1. There is a difference in the coefficient of lift and drag values using roller rotation technology and without roller rotation on the wing's upper surface (NACA6409). This means that the lift coefficient increases with the increase in the angle of attack due to the rotation of the cylinder and the resulting pressure difference around the airfoil. The lift coefficient reaches its maximum value at an angle ( $12^\circ$ ), and the stall angle occurs at an angle ( $14^\circ$ ), the angle at which the boundary layer separated. as shown in Fig .6. Velocity streamlines
2. The rate of increase in lift coefficient was (24.45%) position (25%). At the location of the cylinder (50%), there was no significant improvement in aerodynamic characteristics despite the increase in the lift coefficient for the angles ( $0^\circ$ ,  $2^\circ$ ). After these angles, an early separation occurred at an angle of attack ( $4^\circ$ ), and this is entirely undesirable. The site (75%) has a slight increase in the lift coefficient of (3.7 %).
3. The lift coefficient increases with increasing angle of attack in case the rotation of the cylinder is present or not. From the results discussed, the site (25%) is the best in terms of optimization used in this work.

## Authors' contribution

All authors contributed equally to the preparation of this article.

## Declaration of competing interest

The authors declare no conflicts of interest.

## Funding source

This study didn't receive any specific funds.

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