Experimental Analysis of Aerodynamic Performance on asymmetric NACA 23018 Aerofoil incorporating a Leading-Edge Rotating Cylinder

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Abstract. The effects of Momentum Injection can play a vital role in increasing the efficiency of an aerofoil by increasing its lift and delaying the stall angle. Most of the studies regarding this concept analyzed the effects of momentum injection for higher velocity ratios (cylinder tangential velocity to free stream velocity) only. Almost no or less studies analyzed this effect for lower velocity ratios which created a research gap in this field. In this paper, a rotating cylinder is placed at the leading edge of an asymmetric aerofoil NACA 23018 and the aerodynamic performance with and without a rotating cylinder was studied for lower velocity ratios (<0.2). The experimental analysis was carried out for two Reynolds numbers (Re): 2 \times 10^5 and 2.5 \times 10^5 corresponding to two free stream velocities: 20 m/s and 25 m/s, respectively, for six different angles of attack (−5°, 0°, 5°, 10°, 15° and 20°). The experimental analysis showed that incorporating a leading-edge rotating cylinder increased the maximum lift coefficient by around 24% and delayed the stall angle by around 20%.

1. Introduction
Since the first powered flight, aircrafts are being used for fastest, quickest and easiest transportation of cargo and personnel both for civil and military purposes. Advancement in aerospace structure is a key to increase the aerodynamic efficiency and decrease the travel time which ultimately reduces the operating costs. Incorporating a rotating cylinder at the leading edge of a wing can play a vital role in increasing aerodynamic performance in terms of increasing lift, stall angle, range and endurance of an aircraft. The incorporation of a rotating cylinder injects additional energy to the airflow which in turn restricts the flow separation to some extent over the upper surface of the aerofoil. The lift coefficient increases significantly with a rise in the rotational speed of the cylinder, albeit at a cost of an increase in drag coefficient. A remarkable feature of using this concept is the delaying in stall angle to a certain extent also. Previous studies have been limited to velocity ratios greater than 1.0 whereas the effect of leading-edge rotating cylinder at velocity ratios lower than 1.0 has been a neglected area of research. The aim of this study is to further extend the current knowledge by examining the effect of a leading-edge rotating cylinder on a thick asymmetric NACA 23018 aerofoil at lower velocity ratios (0 to 0.16) at a high Reynolds number (2 \times 10^5 and 2.5 \times 10^5).
There is a considerable amount of literature including both computational and experimental approaches exploring the potential scopes for improvement in the performance of aerofoil as well as aircraft. The various approaches that have been put forward to augment the efficiency of aerofoil include boundary layer suction, boundary layer blowing, suction jet length optimization, blowing and suction slot geometry optimization, using synthetic and plasma jet actuators, moving surface boundary layer control (MSBC) etc. The basic concept of MSBC using a rotating cylinder to increase the aerodynamic efficiency dates back to the mid-19th century. In 1852, the German scientist, Gustav Magnus, noticed that lift force is also generated by spinning balls. This effect is called Magnus Effect, and a lift force caused by a spin is called a Magnus force. Owing to its potential gain, scientists have tried to employ this effect, albeit in different fields. This concept has an enormous advantage in lift production due to incorporation of a moving wall to inject additional energy to the boundary layer around the spinning body. Several techniques can be applied to the aerofoil based on this concept, including blowing and suction in leading and trailing edge of an aerofoil [1-5]. Modi and his team were prominent researchers in this field, who carried out several experimental and numerical studies to appreciate the effect of moving surfaces on the aerofoils boundary layer control and the increment of aerofoils performance [6-9]. They also conducted various experiments with several alternative configurations of the position of the rotating cylinder, including leading edge, trailing edge, upper forward surface, and etc. They have documented the potential results in the increment of the lift to exceed 100% and the stall angle to reach more than 30° in high velocity ratios. They also investigated numerically the MSBC with a symmetric Joukowsky aerofoil with leading-edge rotating cylinder and a D-section, that consists of two rotating cylinders. They concluded that the injection of an additional momentum using rotating cylinder can be very effective in controlling the boundary layer.

Many of the studies on the flow control that use rotating cylinder at the leading edge were conducted on the symmetric aerofoils. In 2014, Ahmed et al. conducted a computational analysis on the effects of MSBC on NACA 0024 aerofoil [10]. They documented an increment in lift coefficient of 36% relative to the base aerofoil and increment in stall angle of 122% relative to the base aerofoil. In 2015, Huda et al. conducted a computational analysis of the effect of MSBC on NACA 0010 aerofoil [11]. They documented an increment of lift by 145% relative to the base aerofoil at velocity ratio 2.0. But their research was restricted to only two velocity ratios: 0 and 2 respectively. In 2017, Faisal et al. conducted an investigation on controlling the flow using a rotating cylinder at the leading edge of NACA 0018 aerofoil [12]. Their study was limited to only symmetric aerofoil. Effect on the asymmetric aerofoil was absent from their investigation. The effect of the gap between the rotating leading-edge cylinder and the aerofoil is also an important parameter and needed to be studied. In 2018, Abdulla et al. conducted a computational analysis on the effect of the gap between leading edge cylinder and symmetric NACA 0012 aerofoil [13].

There are some studies on the flow control using leading edge rotating cylinder on asymmetric aerofoils as well. Yahiaoui conducted the numerical study of NACA 63218 aerofoil with leading edge rotating cylinder in 2015 [14]. Yet, that study was also limited to the effects at higher velocity ratios. Mokhtarian et al. conducted experiment with asymmetric NACA 63218 aerofoil with leading edge rotating cylinder [15]. Hassan et al. conducted a numerical study on the effect of MSBC using NACA 63218 aerofoil [16].

This paper is divided into four sections. The first section gives a brief overview of the literatures about the concept of using a leading-edge rotating cylinder. A methodology for the experimental analysis is provided in the second section. The third section provides the experimental results of this study. An analysis of the result is presented in the fourth section.

2. Methodology
The subsonic wind tunnel (AF -100) of the Aerodynamics laboratory of the Department of Aeronautical Engineering of Military Institute of Science and Technology was utilized to conduct the experiment. For the present investigation, an open circuit subsonic wind tunnel with a working section 300 mm x 300 mm x 600 mm was used as shown in Figure 1. It is a compact, open-circuit, suction
wind tunnel that is useful for studying aerodynamics. The wind tunnel can be operated at a maximum free stream velocity of 35 m/s and there is a capability of setting the angle of attack up to 90°. The chord length of the aerofoil section was 150 mm and the span was 300 mm with a grooved leading edge to accommodate the rotating cylinder as shown in Figure 2(a) and 2(b).

**Figure 1.** Schematic diagram of the wind tunnel with the components: (a) inlet cone, (b) pitot static tube, (c) angle measurement section, (d) test section, (e) traversing pitot tube, (f) safety nets, (g) diffuser, (h) axial fan unit, (i) silencer.

**Figure 2(a).** Test section of the wind tunnel with the experimental setup.

**Figure 2(b).** The wing section with the rotating cylinder at the leading edge (gray colored) and the aerofoil body (wooden colored).

The diameter of the rotating cylinder was 15 mm. The cylinder was rotated in 0, 3000, 3500, 4000, 4500, and 5000 rpm. A steel rod of 10 mm was inserted into the three-component balance, which was in contact with the support plate. In 37.5 mm position from the leading edge of the aerofoil, the rod was attached to the aerofoil. The balance plate has the provision to place the aerofoil at a different angle of attack. A three-component balance was installed in the test section of the wind tunnel in order to measure a pitching moment, a lift, and a drag. The load acting on the aerofoil was transmitted by the attached cables to the three load cells (AFT, FORE and DRAG) via the steel rod. The output of the strain gauged load cells was obtained using an amplifier and a display section controlled by a microprocessor. A digital display connected to a display section provided the data of lift and drag force.

From figure 2(a) it can be observed that, cylinder and the shaft of the aerofoil body was attached to a coupler. For this experiment, it was required to change the angle of attack of the aerofoils and the
position of the cylinder as well. The coupler was used for two purposes mainly. One was to hold the motor in a preferred place during the experimental procedure and another was to provide the same orientation between cylinder and aerofoil in case of changing the angles of attack. As the cylinder was being propelled by a motor, which was located outside of the test section, a groove has to be cut on the test section on both walls. The drawings of the test section side walls were transferred to solid works software and then processed by the computer numerical control (CNC) machine. Thereby, the exact replica of the existing wind tunnel test section that fits in the wind tunnel was created. One end of the cylinder is attached with cylinder cap to connect with the bearing which was connected with the rear sidewall disc. The purpose of the rear sidewall disc was to provide a support for the cylinder cap by guiding it to the three-component balance of the wind tunnel. The other end of the cylinder was connected with coupler to ensure a provision to attach the shaft of the motor to easily rotate the cylinder. The connecting arm was used for two purposes mainly. One was to hold the motor in a preferred place during the experimental procedure and another was to provide the same orientation between cylinder and aerofoil in case of changing the angles of attack. The front sidewall disc was connected between the aerofoil and connecting arm to provide a rigid support.

The validation of the experimental analysis of NACA 23018 base aerofoil analysis was carried out by comparing it to the experimental data provided by Abott et al. at Reynolds number $3.1 \times 10^6$ [17]. The comparison of their experimental data to that of our study is presented in the Figure-3. It is evident that the maximum deviation of a data in our study from that in their study was 8.3%, which was likely caused by experimental uncertainty.

![Figure 3. Experimental validation of NACA 23018.](image)

3. Results and Analysis
Figure represents the relationship between the coefficient of lift ($C_L$) and an angle of attack (AOA) for a base NACA 23018 & a modified NACA 23018 aerofoils from the experimental analysis at Re $2 \times 10^5$ and Re $2.5 \times 10^5$. Here, we observed that the incorporation of a cylinder at the leading edge causes an increment in maximum lift coefficient at all velocity ratios, except for the zero-velocity ratio case. At a zero-velocity ratio, the performance degrades compared to the base aerofoil. Without any rotation
of the cylinder, there is no momentum injection. Therefore, the channel between the between the
cylinder and the aerofoil body caused the flow separation early than the base aerofoil and hence forced
the lift to decrease.

In addition, lift coefficient degraded more than the base aerofoil for the negative angle of attacks.
The base or unmodified NACA 23018 aerofoil stalls at 12° angle. It was observed that the leading-
edge rotating cylinder caused a further gain in stalling angle by 3° AOA when the rotation started. The
leading-edge rotating cylinder causes an increment in drag coefficient compared to the base aerofoil at
all velocity ratios and remains between 0.35 to 0.4. A wide variation of the \( C_D \) was observed in the
experimental analysis because of the irregular oscillation of the vibrating cylinder due to its rotation.
When the cylinder vibrated, more irregular channel was created in between the cylinder and the
aerofoil body. Thus, this resulted in the higher increment of the drag coefficient in the experimental analysis.

The detailed analysis of increment of $C_{\text{Lmax}}$ and stall angle is presented in the following table. From the table it is noticeable that, for lower velocity ratio, there was no delay in the stall angle. But, for the higher velocity ratios there was a delay in stall angle about 20%. A table is presented below to analyse the effect of momentum injection for both cases of Reynolds Number. It can be observed that, gain in $C_{\text{Lmax}}$ is better in case of lower Reynolds number. But stall angle got delayed at lower velocity ratios in the case of higher Reynolds number.

**Table 1.** Result analysis by comparing the gain in $C_{\text{Lmax}}$ and stall angle than base aerofoil at $\text{Re } 2 \times 10^5$ and $\text{Re } 2.5 \times 10^5$.

| $U_c/U$ | Gain in $C_{\text{Lmax}}$ than base aerofoil | Gain in stall angle than base aerofoil | $U_c/U$ | Gain in $C_{\text{Lmax}}$ than base aerofoil | Gain in stall angle than base aerofoil |
|---------|---------------------------------------------|--------------------------------------|---------|---------------------------------------------|--------------------------------------|
| 0       | -6.48%                                      | 0%                                   | 0       | -7.02%                                      | 0%                                   |
| 0.12    | 6.48%                                       | 0%                                   | 0.09    | 2.63%                                       | 20%                                  |
| 0.14    | 14.81%                                      | 0%                                   | 0.11    | 13.16%                                      | 20%                                  |
| 0.16    | 16.67%                                      | 20%                                  | 0.13    | 14.91%                                      | 20%                                  |
| 0.18    | 20.37%                                      | 20%                                  | 0.14    | 18.42%                                      | 20%                                  |
| 0.2     | 24.07%                                      | 20%                                  | 0.16    | 21.93%                                      | 20%                                  |

There was some experimental uncertainty associated with this study. There was an extreme case of uncertainty of $\pm 0.02 \text{ kg m}^3$ in measuring the air density. Thus, the maximum uncertainty in air density was recorded $\pm 1.69\%$. There was an extreme case of uncertainty of $\pm 0.001 \text{ m}$ for measuring the chord length and the span of the wing using the digital height meter. So, the maximum uncertainty in measuring the chord length was $\pm 0.67\%$ and maximum uncertainty in measuring the span was $\pm 0.33\%$. The velocities required in this study were 20 and 25 m s$^{-1}$. In extreme case of the uncertainty in the measurement of 20 and 25 ms$^{-1}$ velocity was $\pm 0.1$ ms$^{-1}$, and for this the maximum uncertainty in measuring the velocity was $\pm 0.5\%$ for 20 ms$^{-1}$ and $\pm 0.4\%$ for 25 ms$^{-1}$ velocity. In the lift and drag equations for the wing, the term velocity is squared, so the final uncertainty in velocity measurement became $\pm 1.01\%$ for both cases of velocity. There was a typical uncertainty in measuring the rotational speed of the cylinder was $\pm 12.6$ rpm. So, the extreme uncertainty was $\pm 4.2\%$ for measuring the rotational speed of the cylinder. There was an extreme case of uncertainty of measuring the calibration reading of the transducer was $\pm 0.01$ kg. So, the maximum uncertainty was $\pm 0.2\%$ in this case. The overall uncertainty in experimental analysis was $(1.01^2 + 1.69^2 + 0.33^2 + 0.67^2 + 4.2^2 + 0.2^2)^{1/2} = \pm 4.71\%$ which may be considered as negligible. A sample case of comparative plot with error bar for velocity ratio 0.16 is presented in figure 5. From the figure, it can be observed that, for higher angles of attack the uncertainty also became higher.
Figure 5(a). Error bar analysis for $C_L$ at 0.16 velocity ratio for NACA 23018 aerofoil at Re $2 \times 10^5$.

Figure 5(b). Error bar analysis for $C_D$ at 0.16 velocity ratio for NACA 23018 aerofoil at Re $2 \times 10^5$.

Figure 5(c). Error bar analysis for $C_L$ at 0.16 velocity ratio for NACA 23018 aerofoil at Re $2.5 \times 10^5$.

Figure 5(d). Error bar analysis for $C_D$ at 0.16 velocity ratio for NACA 23018 aerofoil at Re $2.5 \times 10^5$.

The effect of lower velocity ratios (<0.2) in case of an asymmetric aerofoil can be observed from the plots. As expected, at higher velocity ratios the lift coefficient increased up to a certain extent prior to stall angle. It was due to the fact that higher velocity ratio ensured higher momentum injection and the flow became more energized as compared to the base aerofoil. The flow inside the channel between cylinder and aerofoil body was stagnant in case of cylinder without any rotation. But as the rotational speed increased there was some increment in active flow inside the channel. So, the high-pressure air was pushed at the bottom surface of the cylinder and increased the lift to some extent. The delay in the flow separation was the consequence of energized air particles with high velocities at the upper surface of the aerofoil. But drag also increased much in case of higher velocity ratios. There were some observable irregularities in the drag coefficient also. There was some induced drag due to the rotation of the cylinder. Also, the cylinder oscillated at higher velocity ratios and for this reason the combination of aerofoil with cylinder acted as a blunt body and drag increased to a certain extent. No previous studies addressed this phenomenon with lower velocity ratios and higher Reynolds
number on an asymmetric aerofoil. This study fills up this research gap in the ongoing studies on this topic.

4. Conclusion
The experimental investigation of the modified NACA 23018 aerofoils with leading edge rotating cylinder revealed that the performance of the modified aerofoil is superior to the base aerofoil for velocity ratios less than 1.0. As opposed to previous studies, study presented results only for higher velocity ratios. In the analysis, there were large adverse effects of vibrations on the performance of the aerofoil. The oscillations were generated on the cylinder, and thereby, there was some irregularities in the results $C_D$. This study is one step to fill the void in ongoing research on the effectiveness of MSBC using a leading-edge rotating cylinder for velocity ratios lower than or equal to 0.2 using a higher Reynolds number around $2 \times 10^6$ and more. One example of the use of the concept is its implemented in a short takeoff and landing (STOL) aircrafts, as they require high lift coefficient at low angle of attacks. In addition, the current study shows the practicability of incorporating leading edge rotating cylinder for a thick aerofoil in aviation. Besides, for some applications in wind turbine blades and control surfaces of aircraft this research indicates the superiority of lift at a low power requirement also. More configurations of this rotating cylinder may be tested for reducing the effect of vibration.

5. References
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