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Advanced Optical Methods in Analysis of Flow Around an Airfoil with a Circular Microcylinder

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Advanced optical methods, specifically time-resolved particle image velocimetry, were used to analyse the aerodynamics of the NACA0012 airfoil at a 17-degree angle of attack. A circular microcylinder ($d/c = 0.015$) was positioned at three locations ahead of the airfoil's leading edge to examine its effect on the flow dynamics. The results demonstrate that an optimally positioned microcylinder can significantly modify the flow field, enhancing the aerodynamic performance of airfoils and wind turbines. Detailed physical analysis of the flow fields, including streamlines and vortex structures, elucidates the flow control mechanisms. The findings highlight the potential for enhancing the aerodynamic properties of airfoils and wind turbines. The integration of microcylinders represents a novel approach to passive flow control, underscoring the technique's potential to enhance lift and reduce drag. These findings not only deepen our understanding of flow dynamics but also showcase the practical utility of innovative particle image velocimetry techniques in experimental aerodynamics. Consequently, this research contributes to both fundamental physics and the practical applications in aerospace engineering and wind energy optimization.

topics: optical method, particle image velocimetry (PIV), microcylinder, NACA0012

1. Introduction

Flow separation is a detrimental phenomenon that occurs on wind turbine blades at high angles of attack, where the flow detaches from the suction surface due to adverse pressure gradients. Flow separation negatively impacts the aerodynamic coefficients, leading to a decrease in lift and an increase in drag, thereby reducing the efficiency and operational stability of the blades [1]. Controlling flow separation has been a critical area of research due to its significant implications for the performance and durability of wind turbines [2].

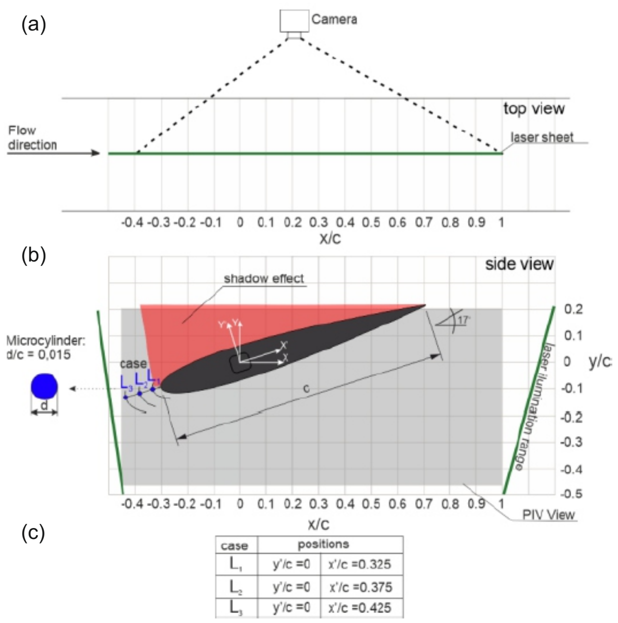
Flow control methods can be divided into active and passive techniques. Active flow control, such as uniform blowing and suction, requires additional external energy, which can increase the complexity and operational costs of wind turbines [3]. On the other hand, passive flow control methods, which involve modifications to the airfoil geometry or the addition of elements like vortex generators and microcylinders, are more frequently used in practical applications due to their simplicity and cost-effectiveness [4]. One such passive flow control method is the addition of a cylinder in front of the leading edge of an airfoil. The placement and size of the cylinder are crucial factors; improper placement can result in decreased lift and increased drag before reaching the critical angle of attack [5].

Recent studies have shown that strategic positioning of microcylinders can significantly affect the flow characteristics around the airfoil, delaying flow separation and enhancing aerodynamic performance. Chen et al. [6] and Kumar et al. [7] investigated parameters affecting the efficiency of microcylinders, such as their diameter and distance from the leading edge, demonstrating their impact on the lift-to-drag ratio and overall aerodynamic efficiency.

The current study aims to build on this body of knowledge by employing advanced optical methods, specifically time-resolved particle image velocimetry (PIV), to analyze the flow around a NACA 0012 airfoil at a 17-degree angle of attack. The aim of this study is to determine the optimal configuration (microcylinder–airfoil) for delaying boundary layer detachment at high angles of attack and low Reynolds numbers. The findings will provide insights into the potential applications of microcylinders in enhancing the aerodynamic performance of wind turbines and other airfoil-based systems.

2. Methodology

The experimental tests were conducted using the optical method, i.e., time-resolved particle image velocimetry (PIV), in the wind tunnel in which the measuring section had a square cross-section with



case	positions	
L_1	y'/c =0	x'/c =0.325
L_2	y'/c =0	x'/c =0.375
L_3	y'/c =0	x'/c =0.425

Fig. 1. Measurement setup for the NACA 0012 airfoil; (a) top view, (b) side view, (c) position characteristic of microcylinder.

dimensions of 0.3×0.3 m^2, and a length of 2 m. A diagram illustrating the measurement setup is shown in Fig. 1. The NACA 0012 airfoil was placed in the central part of the measurement section. The tested microcylinder had a diameter of $d/c = 0.015$. The first position (L_1) of the microcylinder was at a distance $x'/c = -0.325$ from the adopted coordinate system, while the second (L_2) at $x'/c = -0.375$ and the third (L_3) at $x'/c = -0.425$. For the specific positions and dimensions of the microcylinders used in the experiments, refer to the table in Fig. 1. The NACA 0012 profile was illuminated from below using a laser beam. The illuminated area was captured by a SpeedSense VEO340 camera, positioned in front of the airfoil. The camera, equipped with a 50 mm Nikkor lens, provided a resolution of 1280×800 pixels and had 18 GB of internal memory. The flow was examined at a velocity of 5 m/s, resulting in a Reynolds number Re = 66400, based on the chord length. The turbulence intensity at the wind tunnel inlet was maintained below 0.5% during the measurements. The PIV system used DANTEC DYNAMICS software for data processing. The measurement area, illustrated in dark grey in Fig. 1, was spanned over $-0.45 < x/c < 1$ and $-0.45 < y/c < 0.2$. To capture the flow dynamics, measurements were performed at a frequency of 600 Hz, yielding 3000 pairs of images, with a time interval of 100 μs between each pair. Di-ethyl-hexyl-sebacic-acid-ester (DEHS) oil droplets, approximately 1 μm in diameter, were used as seed particles to visualize the flow. These particles were introduced into the flow, and their movement was tracked to obtain velocity fields around the airfoil.

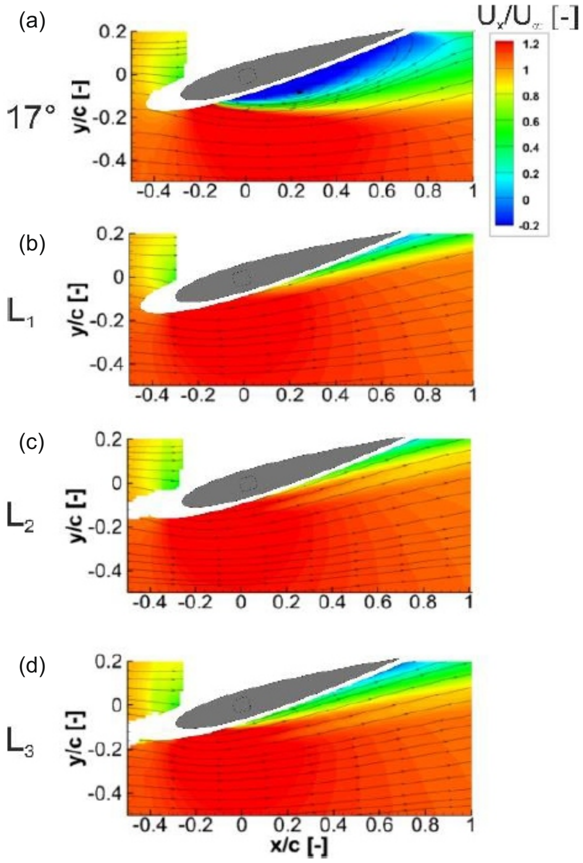


Fig. 2. Normalized streamwise velocity U_x/U_∞ [-] for the NACA 0012 airfoil at a 17° angle of attack with different microcylinder position.

The detailed setup ensured accurate and high-resolution data capture, facilitating a comprehensive analysis of the flow characteristics and the impact of the microcylinder positions on delaying flow separation and improving aerodynamic performance.

3. Results

The results of optical PIV measurement of the flow around the NACA 0012 profile with an added microcylinder in three positions are presented in Figs. 2–4. In particular, the normalized streamwise velocity (U_x/U_∞ [-]) is presented in Fig. 2, and the normalized turbulent kinetic energy ($TKE/(U_\infty)^2$ [-]) in Fig. 3, and the instantaneous vorticity (ω [1/s]) in Fig. 4 around the NACA 0012 airfoil set at a 17° angle of attack.

Each of the above-mentioned figures includes four separate contour plots, each representing a different configurations of experiment. Figure 2a shows the case without any microcylinder placed in front of the airfoil. The flow separates from the suction surface, which is indicated by the large blue region of low velocity above the airfoil, signifying the

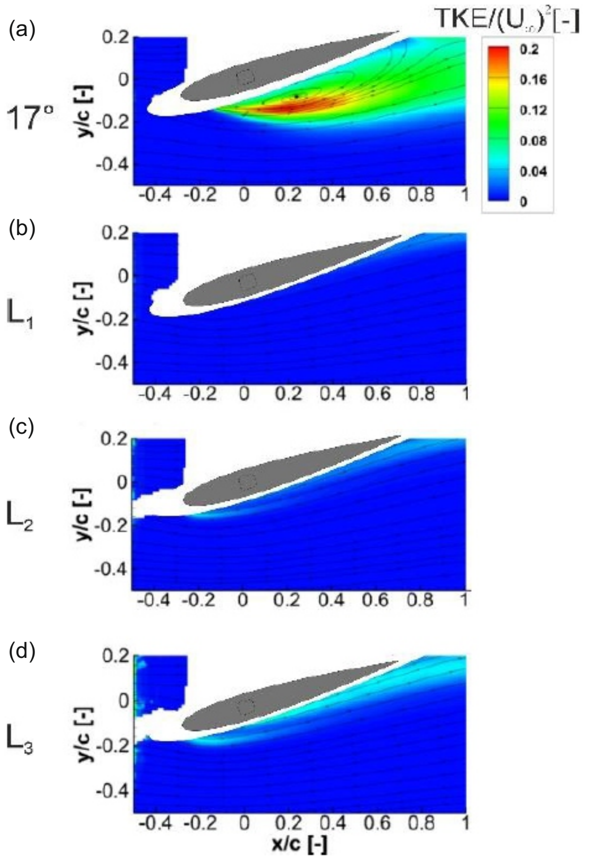


Fig. 3. Normalized turbulent kinetic energy $TKE/(U_\infty)^2$[-] for the NACA 0012 airfoil at a 17° angle of attack with different microcylinder position.

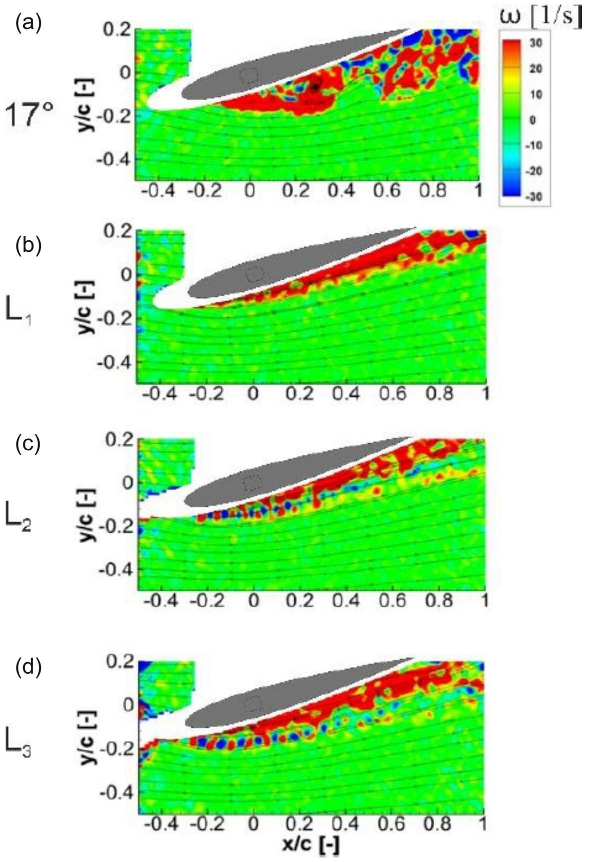


Fig. 4. Vorticity ω [1/s] for the NACA 0012 airfoil at a 17° angle of attack with different microcylinder position.

separated flow region. Additionally, the microcylinder modifies the flow, resulting in a smaller region of low velocity compared to the basecase, indicating a delay in flow separation and smoothed streamlines over the airfoil surface. The last plot, which depicts the microcylinder positioned at L_3, shows that the region of low velocity is slightly larger than in the L_2 case, but still a notable improvement in delaying flow separation. The L_2 position appears to be the most effective among the tested configurations, as it shows the smallest regions of low velocity, indicating the most stable flow and a delay in flow separation.

Figure 3a shows the normalized TKE without the microcylinder placed in front of the airfoil. The results show high TKE values along the suction side of the NACA 0012 airfoil, indicating significant turbulent activity and flow separation in this region. The presence of the microcylinder (cases L_1 and L_2, Fig. 3b–c) drastically reduces the TKE values near the leading edge, as shown by the dominant blue regions, indicating a significant reduction in turbulent activity and flow separation. In the L_3 case (Fig. 3d), the TKE values are slightly higher compared to the L_2 case, but still significantly lower than the basecase. This indicates a less effective, but still noticeable reduction in turbulent activity and delay in flow separation compared to the case without microcylinders. The L_2 case appears to be the most effective among the tested configurations, as it shows the lowest TKE values, indicating the most stable flow with reduced turbulence.

Figure 4 presents the instantaneous vorticity (ω) distributions for the NACA 0012 airfoil at a 17° angle of attack. There are four different configurations: (a) without a microcylinder and (b–d) with microcylinders positioned at three different locations (L_1, L_2, and L_3). According to Fig. 2a (here no microcylinder is placed in front of the airfoil), the large blue low-velocity region above the airfoil indicates significant flow separation. This separated flow region is characterized by high levels of vorticity, represented by the red and blue contours near the trailing edge in Fig. 4a. Figure 4b shows a noticeable reduction in the size of the high vorticity region compared to the configuration without a microcylinder. This configuration shows a significant improvement in aerodynamic performance. For the microcylinder positioned at L_2 (Fig. 4c), the vorticity plot reveals an even smaller region of low velocity (see Fig. 2) than in the L_1 case. In this configuration two vortex paths can be observed, namely one behind the microcylinder and the other behind the airfoil, which eventually merge further downstream. Flow separation is further delayed and the streamlines over the airfoil are smoother. In the final configuration, the microcylinder is placed at position L_3 (Fig. 4d). Similar to the L_2 case, two distinct vortex paths can be seen. The plot indicates that although the L_3 position is less effective than L_2, it still provides a considerable improvement in delaying flow separation and reducing vorticity levels.

Among the tested configurations, the L_2 position is the most effective in delaying flow separation and reducing vorticity, leading to improved aerodynamic performance.

4. Conclusions

The results of this study provide significant insights into the impact of microcylinder's position on the flow characteristics around an airfoil at high angle of attack. An advanced optical method, specifically time-resolved particle image velocimetry (PIV), demonstrates how microcylinders can be used as an effective passive flow control technique to delay in flow separation and reduce turbulent kinetic energy (TKE).

The baseline measurements without any microcylinders showed flow separation and high TKE near the leading edge of the airfoil. The microcylinders being in different positions (L_1, L_2, and L_3) effectively modified the flow field, delay flow separation, reducing the region of low velocity, and the areas of high TKE. Among the positions tested, the L_2 case emerged as the most effective configuration. It showed the smallest regions of flow separation and the lowest TKE values, indicating the most stable and attached flow, and thus delaying flow separation. The L_1 and L_3 configurations also demonstrated improvement over the base case, but were less effective compared to the L_2 case.

In the cases with microcylinders at positions L_2 and L_3, two distinct vortex paths were observed, namely one behind the microcylinder and another behind the airfoil, which eventually merged further downstream. This indicates that the placement of the microcylinder significantly affects the flow dynamics and the interaction between the vortices generated by the microcylinder and the airfoil.

This finding is consistent with the concept that passive flow control methods, which do not require external energy, can be highly effective in improving aerodynamic performance through optimal placement and sizing of control devices. The study highlights the utility of optical PIV methods in providing high-resolution, detailed visualizations of flow fields, which are important for understanding the complex interactions between flow control devices and the airflow.

Acknowledgments

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