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Study of Airfoil Flow Control with Microcylinders Using Optical Method

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This study aims to evaluate the effect of circular-shaped microcylinders on the flow field around an airfoil, using time-resolved particle image velocimetry. The results show that microcylinders can significantly modify the flow pattern around the NACA 0012 airfoil. The optimal configuration of microcylinder-airfoil depends on the angle of attack and the position of the microcylinder. The obtained results have practical implications for the development of more efficient and sustainable aircraft designs and wind turbine blades. The paper presents a physical analysis of flow fields using streamlines and vorticity structures to illustrate mechanisms of flow control for improving the aerodynamic properties of the airfoil. Overall, this work provides new insights into the fundamental physics of flow control using microcylinders, including general physics and optics, with potential application in various contexts, such as aerodynamics, flow control, airfoil design, optical diagnostics, and particle image velocimetry techniques.

topics: velocity measurements, optical method, experiments, time-resolved particle image velocimetry (TR-PIV)

1. Introduction

Airfoils are objects commonly studied by scientists due to their wide range of applications in aviation and wind turbine technologies [1]. The main focus of scientists is to improve the aerodynamic properties of airfoils in order to enhance their efficiency and performance. One of the parameters that intensively affect the airfoil performance is flow separation at high angles of attack (AOA) on the suction surface and the wake region behind it. Increased angles of attack lead to a sudden expansion of the wake region, causing stall occurrence, resulting in a notable increase in drag coefficient and decrease in lift coefficient. Reducing skin friction drag is also crucial for enhancing aerodynamic performance. Therefore, it is crucial to understand the physics of the flow as it governs the emerging interactions within modern engineering structures [2]. Various methods, both passive and active, have been proposed to enhance aerodynamic performance. These methods include the application of a sinusoidal surface [3], the use of air jets [4], the vortex generators [5], the implementation of split blades [6], and the combination of airfoils with vortex generators [7] on their surface and microcylinders [8].

Among the limited research conducted, the circular microcylinder stands out as the most commonly studied shape for supplementary objects. It was shown that the size, angle of attack, as well as the position of the microcylinder and the Reynolds number have an impact on the improvement of aerodynamic parameters. Existing studies in the literature have indicated that the optimal diameter of the cylinder should be $d/c = 0.01$, as microcylinders with smaller diameters do not significantly affect the flow [9]. The impact of microcylinders is most often tested at large rake angles of 16–23°, as these angles generate boundary layers that are influenced by strong pressure gradients [9]. The addition of microcylinders delays flow detachment [8]. An important factor influencing the effectiveness of microcylinder additions is their location relative to the airfoil. Placing the microcylinder too close to the leading edge of the airfoil blocks the flow and negatively affects the lift of the airfoil. As the gap increases, flow blockage decreases, resulting in increased lift. However, this also reduces the influence of the microcylinder on the airfoil flow. Hence, the gap cannot be excessively large [9]. This suggests that the effectiveness of the microcylinder in modifying the flow characteristics is dependent on the diameter of microcylinder and its location, emphasizing the importance of considering these parameters when studying aerodynamic interactions between microcylinders and airfoils.

A numerical study conducted by Mostafa et al. [10] revealed that the impact of adding a microcylinder in front of an airfoil is more pronounced at higher Reynolds numbers (5×10^5, 7.5×10^5, 1×10^6) compared to a lower Reynolds number (3.5×10^5), where the effect of the microcylinder addition was relatively smaller.

The main objective of the conducted optical studies is to gain insight into the aerodynamic behavior of the NACA 0012 airfoil and to explore the potential applications of flow control to improve its performance at high angles of attack and low Reynolds number. In the further part of the work, the effect on the flow characteristics around the NACA 0012 airfoil after adding a circular microcylinder at high angles of attack was checked.

2. Methodology

The experiment was carried out in a wind tunnel with a square cross-section of 0.3×0.3 m^2 and a length of 2 m. The object of the research, the NACA 0012 airfoil-microcylinder configurations, was located in the centre of the measurement section of the wind tunnel. The NACA 0012 airfoil had a chord dimension of $c = 0.2$ m and a span of 0.26 m. The circular-shaped microcylinder with dimension $d/c = 0.015$ was added to the airfoil and the distance s between the microcylinder and the surfaces of the airfoil was $s = 0.025c$, see Fig. 1. The inlet velocity was $U_\infty = 5$ m/s, and the Reynolds number equaled 66400.

The research utilized the particle image velocimetry (PIV) method with hardware and software provided by Dantec Dynamics. The flow images were recorded using the SpeedSense VEO340 CCD camera. For illumination, a two-pulse laser emitting two pulses with a power of 25 mJ and a wavelength of 527 nm, with a repetition frequency of up to 20 kHz, was employed to illuminate DEHS oil particles with an approximate size of 1 μm.

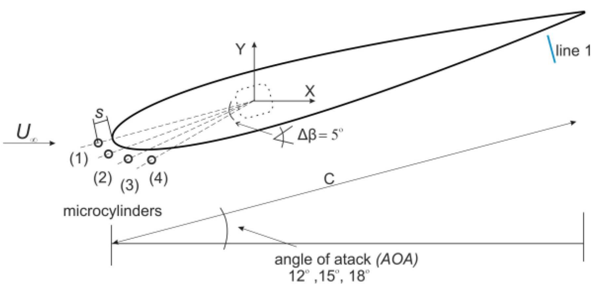

Fig. 1. Scheme of measuring the profile of a NACA 0012 airfoil with added microcylinders.

3. Results

The PIV measurements were conducted at high angles of attack (AoAs) ranging from 12 to 18° on both the controlled and uncontrolled airfoil. The velocity field attended as the observable parameter, allowing for qualitative and quantitative comparisons through the PIV tests. The normalized streamwise velocity U/U_∞ (a) and turbulent kinetic energy $TKE/(U_\infty)^2$ (b) are shown in Fig. 2.

After analyzing the results, the qualitative change in the airflow around the airfoil at different angles were observed. As the angle of attack (AoA) increases from 15 to 18° compared to the 12° angle, we observe earlier detachment of the boundary layer at the lower edge of the airfoil. In addition, under the separation point, there is an area of velocity acceleration for all angles. In terms of normalized turbulent kinetic energy, an intensified turbulence field appears at the lower edge of the airfoil for angles 15° and 18°, which is not observed at the 12°

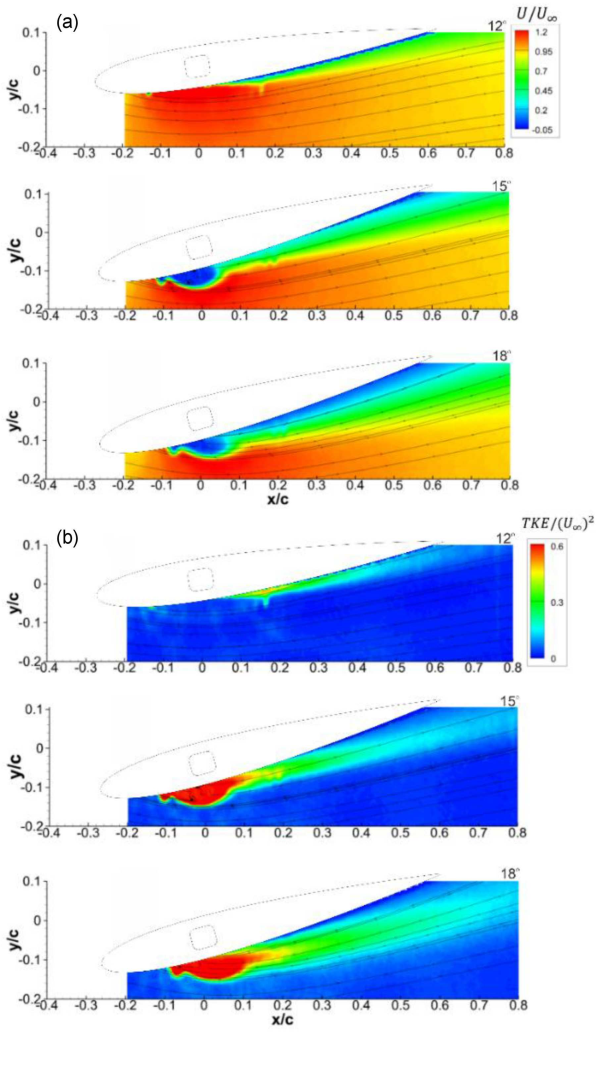

Fig. 2. The streamwise velocity U/U_∞ and the turbulent kinetic energy $TKE/(U_\infty)^2$ for different angle of attack (AoA).

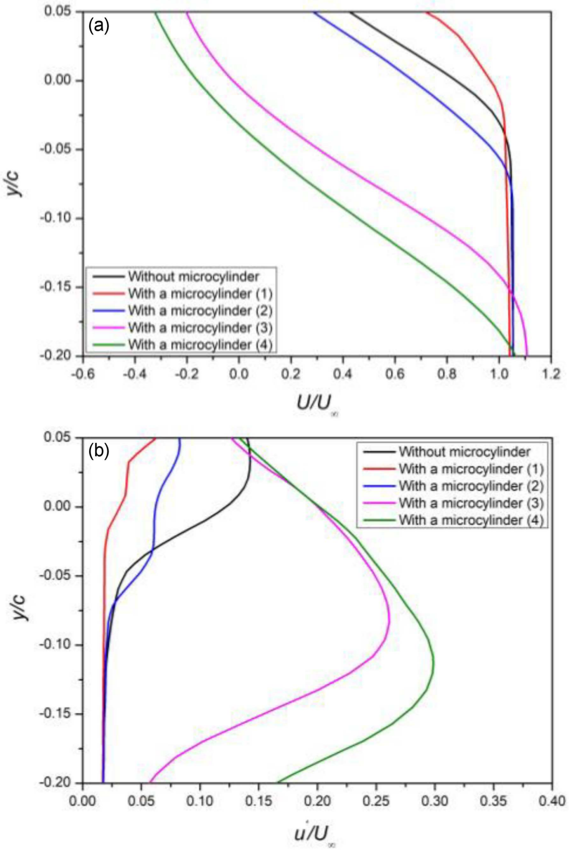

Fig. 3. The streamwise velocity component (a) and the fluctuation velocity component (b) along line 1 at AoA = 15°, both without and with microcylinder added at positions 1–4.

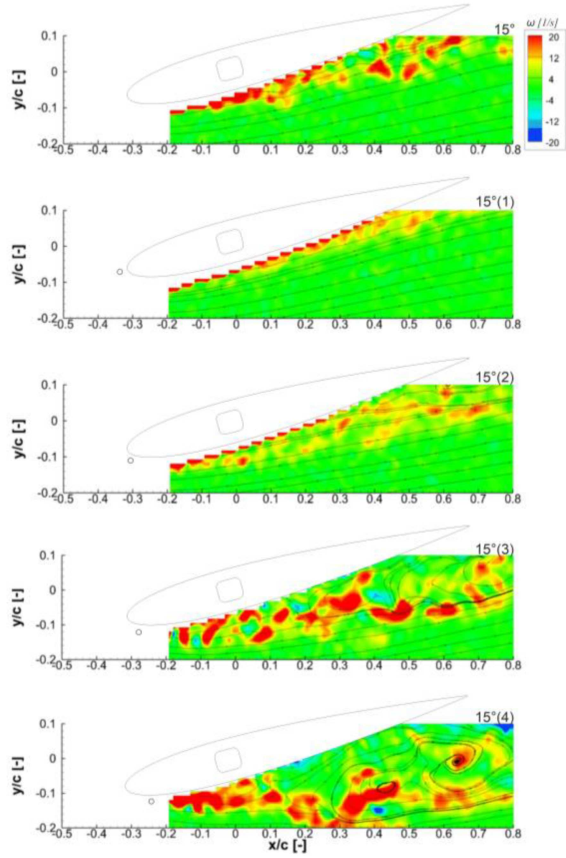

Fig. 4. The instantaneous vorticity (ω [1/s]) at AoA = 15°, both without microcylinder and with microcylinder added at positions 1–4.

angle. The streamlines have been added to highlight flow variations in both the normalized streamwise velocity U/U_∞ fields and the normalized turbulent kinetic energy $TKE/(U_\infty)^2$ near the lower edge of the airfoil.

In the second part of the experiment, microcylinders were introduced at four specific positions in relation to the airfoil: two positions in front of the leading edge (position 1 and 2), and at two positions below the lower edge of the airfoil (position 3 and 4). These additions were implemented at the selected angle of 15°, which was chosen for further investigation due to its significant quantitative differences compared to the 12° angle. Furthermore, at the 15° angle, an increase in the turbulence field along the suction surfaces of the airfoil was observed, which is considered a undesirable phenomenon.

Figure 3a illustrates the normalized streamwise velocity profiles for an angle of 15°, for both situations, without microcylinders and with microcylinders at four distinct positions. The location from which the profiles were downloaded is marked on the diagram in Fig. 1. Upon analyzing the graph (Fig. 3a), it is evident that the normalized velocity profile without added microcylinders exhibits an enlarged region with lower velocity values near the lower edge, especially from $y/c = 0.025$ to 0.05. Conversely, the introduction of microcylinders at position 1 results in an increase in velocity (U/U_∞) in this region to approximately 0.5, concurrently reducing the area of this velocity from y/c = 0 to 0.05. This is the most favorable outcome because it minimizes the drop in inlet velocity near the lower edge of the airfoil. For position 2, a slight decrease in velocity is observed in comparison to the configuration without the microcylinder. However, positions 3 and 4, as depicted in Fig 3a, exhibit a significant reduction of velocity, indicating an earlier detachment of the boundary layer compared to the case without the microcylinder.

In the same cases, the distribution of fluctuations u'/U_∞ is depicted in the graph in Fig. 3b. It is worth noting that a slight increase in fluctuations is observed in the region from $y/c = -0.05$ to 0.05 for cases with microcylinders 1 and 2, compared to the case without microcylinders. For cases 3 and 4, the fluctuations are substantially larger in the range $y/c = -0.2$ to -0.05.

Figure 4 shows the instantaneous vorticity at AoA = 15°, both without microcylinders and with the inclusion of microcylinders at four different positions. Analyzing the presented results, it is evident that an intensified vortex field forms beneath the lower edge of the airfoil. Following the addition of circular-shaped microcylinders, the most significant reduction is observed for position 1. However, for positions 2–4, the reduction is smaller in comparison to the case without microcylinders, but still greater than that observed for position 1. For positions 2, 3, and 4, there is no reduction compared to the case without microcylinders, and the results have even deteriorated. An intensified vortex field is observed under the lower edge of the airfoil.

4. Conclusions

Summarizing the presented results, a significant qualitative changes are observed when comparing angles 12° and 15°. At angle of 15°, there is an increase in negative velocity fields and a larger region of higher turbulence along the on the suction surface of the airfoil. The introduction of the microcylinder had a positive effect at positions forward the leading edge of the airfoil. Particularly, the placement of a microcylinder at position 1 yielded the most substantial improvements, as indicated by the graphs and the observed instantaneous vortex fields.

Acknowledgments

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