

On the Active and Passive Flow Separation Control Techniques over Airfoils

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Abstract. In the present work, recent advances in the field of the active and passive flow separation control, particularly blowing and suction flow control techniques, applied on the common airfoils are briefly reviewed. This broad research area has remained the point of interest for many years as it is applicable to various applications. The suction and blowing flow control methods, among other methods, are more technically feasible and market ready techniques. It is well established that the uniform and/or oscillatory blowing and suction flow control mechanisms significantly improve the lift-to-drag ratio, and further, postpone the boundary layer separation as well as the stall. The oscillatory blowing and suction flow control, however, is more efficient compared to the uniform one. A wide range of parameters is involved in controlling the behavior of a blowing and/or suction flow control, including the location, length, and angle of the jet slots. The oscillation range of the jet slot is another substantial parameter.

1. Introduction

Potential flow theory describes various phenomena in the realm of fluid mechanics, but it is not adequate for most boundary layer cases, e.g. flow field around an airfoil. The boundary layer over a rigid surface keeps growing as long as the pressure gradient remains zero along the surface. For an adverse pressure, the thickness of boundary layer increases drastically. This adverse pressure and shear (viscous) forces reduce momentum in the boundary layer, and if any of these will be effective along a considerable length of the surface, the growth of boundary layer is halted. This is called separation. If separation over an airfoil can be avoided, the boundary layer remains thin and the pressure drop in the trailing edge would be prevented, and consequently, the drag force decreases to a minimum value [1].

A significant number of recent studies have been focused on the effects of the boundary layer on the lift and drag forces (e.g. [2-4]) since the existence of the boundary layer produces multiple designing and engineering challenges, particularly in the aerodynamic field [5-7]. Methods developed for the boundary layer manipulation are termed as the boundary layer separation control or flow separation control [8]. The ultimate goal of the boundary layer control over an airfoil is to increase the lift and decrease the drag, and therefore, to enhance the airfoil performance by increasing the lift-to-drag ratio along with stall-delay.

In the current paper, we provide a short review of recent studies associated with the blowing and suction flow separation control techniques over finite and infinite wings. The paper starts with an introduction to the passive and active flow control techniques and continues with the latest contributions in the field. It wraps up by discussing possible further research areas in the flow control field and ends with presenting some ongoing thoughts.



2. Boundary layer control methods

Controlling the behavior of mechanical systems is an integral concept that inevitably arises in entire engineering research fields from dynamics and robotics [9-11] to fluid mechanics [12-14] and turbulent boundary layers [4-7]. Boundary layer can be controlled through a passive method, which not needs a controller, and/or an active method, which requires a controller and controlling sensors [8]. In some literature, boundary layer management or flow management are used instead of the boundary layer control (e.g. [15]). As schematically shown in figure 1, the active flow control can be divided into two categories, predetermined and reactive. Predetermined active flow control includes uniform and non-uniform energy expenditure, regardless of the state of the flow. Reactive flow control is a particular active flow control in which the power expenditure of controllers is regularly tuned by measured parameters via in situ sensors [8, 16-17].

The classification of boundary layer control methods into active and passive categories is one of the most common schemes. Vortex generator, distributed roughness, streamlining, and uniform blowing and suction are among various devices that are employing for the passive flow control technique. On the other hand, some of the active flow control methods are heating wall, movement of surface elements, oscillatory blowing and suction, and synthetic jets.

2.1. Blowing and suction

Suction is the act of extracting fluid from the boundary layer before the fluid separates upstream. Blowing, on the other hand, can be defined as entering fluid into the boundary layer in order to increase its momentum. The blowing and suction flow control can be accomplished by using a uniform or an oscillatory (periodic) process. In the case of uniform blowing, the boundary layer momentum is increased by the injection of a high-energy fluid adjacent to the surface. If the fluid is injected tangentially, the boundary layer momentum will be increased directly. In the normal blowing, however, the fluid is injected perpendicular to the surface. In the case of oscillatory blowing and suction, periodical blowing (suction) to (from) the surface is applied which is more effective than the uniform blowing and suction. One way of achieving the oscillatory blowing and suction is by using a synthetic jet with zero mass flux as illustrated in figure 2 [18].

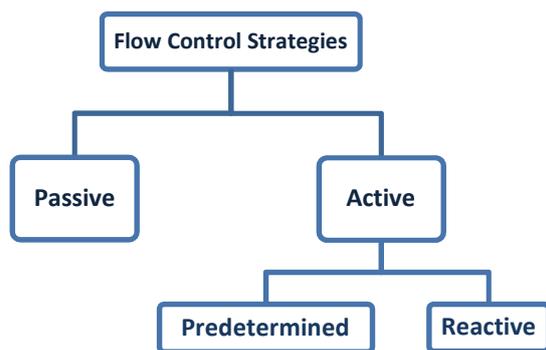


Figure 1. Classification of flow control strategies.

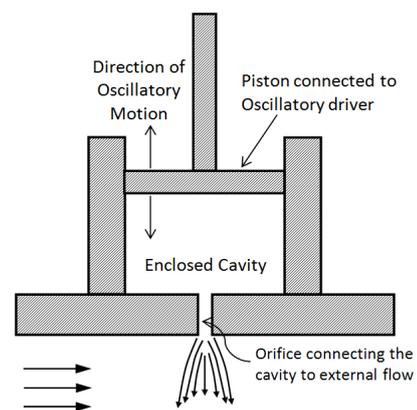


Figure 2. Synthetic jets with zero mass flux.

3. Recent contributions

Many investigations have been recently conducted on the active flow separation control, either experimentally or computationally. The fundamentals of the active flow control using synthetic jets over a NACA 0015 airfoil were studied by Parthasarathy and Das [19]. The chord Reynolds number was considered to be 896,000 at the angle of attack of 20 degrees wherein the flow was separated. The analysis of the phase-averaged pressure and streamlines clarified that the synthetic jet is strongly effective in increasing the lift coefficient, which is more pronounced for larger jet amplitudes and at smaller angles of jet injection. In a computational study, Montazer et al. [20] investigated the fundamental parameters of a synthetic jet actuator for controlling the flow separation around a NACA

0015 airfoil. By applying the response surface optimization method, it was presented that the synthetic jet is more effective for post-stall angles of attack, which can enhance the lift-to-drag ratio up to 66%. Feero et al. [21] experimentally examined the effectiveness of the active flow control through the synthetic jet technique to re-attach the stalled flow on a NACA 0025 airfoil at a relatively low Reynolds number. It was observed that the boundary layer was reattached in both low- and high-frequency actuation in a time-averaged sense.

In recent years, the study of the synthetic jets as an active flow control method over wind and water turbines have become more popular. Velasco et al. [22] simulated the flow field around a cross-flow vertical-axis water turbine favoring synthetic jets. It was revealed that the net torque and power output of the turbine can be considerably improved by employing synthetic jets over the extrados and intrados of the airfoil, which leads to an increase in the global efficiency of the turbine. The effects of the synthetic jet were also studied numerically by Moshfeghi and Hur [23] where they consider a finite span wing with the S809 airfoil at different angles of attack ranging from 0 to 25 degrees. The results for an attached flow showed that the synthetic jet causes early separation, and consequently, declines the lift coefficient, while for a separated flow the lift coefficient considerably enhances. They also observed that the lift does not follow a distinguished pattern for varying jet angles at a large angle of attack.

The passive flow control has also been the point of interest in many researches. Yousefi and Saleh [24] conducted a three-dimensional suction flow control study to investigate the aerodynamic characteristics of a wing with a NACA 0012 airfoil section. Two different suction slot distributions were considered at the leading edge of the wing, center suction and tip suction. The results indicated that the lift-to-drag ratio increases by the suction jet length for both center suction and tip suction distributions. The center suction distribution, however, was more effective in the enhancement of the overall aerodynamic performance. It was concluded that the tip suction is more efficient when the jet length is less than half the wingspan, and consistently, the center suction provides better aerodynamic performance when the jet length is greater than half the wingspan. The effects of center suction and tip suction on the streamlines behind the wing are shown in figures 3 and 4 [24], respectively. In another study, Yousefi et al. [25] and Yousefi and Saleh [17] investigated the effects of suction and blowing jet width on the aerodynamic characteristics of a NACA 0012 airfoil. It was found that the jet width of about 3.5% ~ 4% of the chord length is optimum for tangential blowing, while for perpendicular blowing smaller jet widths are more efficient. Consistent with the literature, the suction jet width of 2.5% of the chord length is the value that maximizes the lift-to-drag ratio.

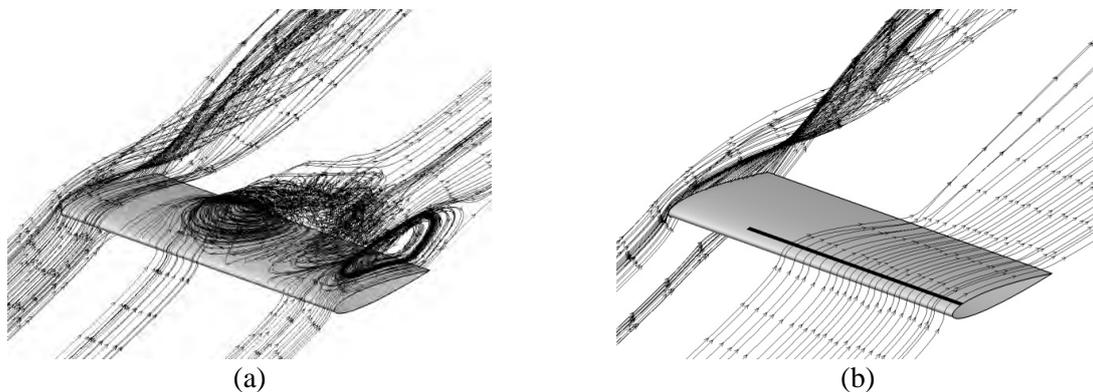


Figure 3. The effects of suction jet length on streamlines over the finite wing at angle of attack of 18° for center suction, (a) no control, (b) suction jet length of $1.5C$ [24].

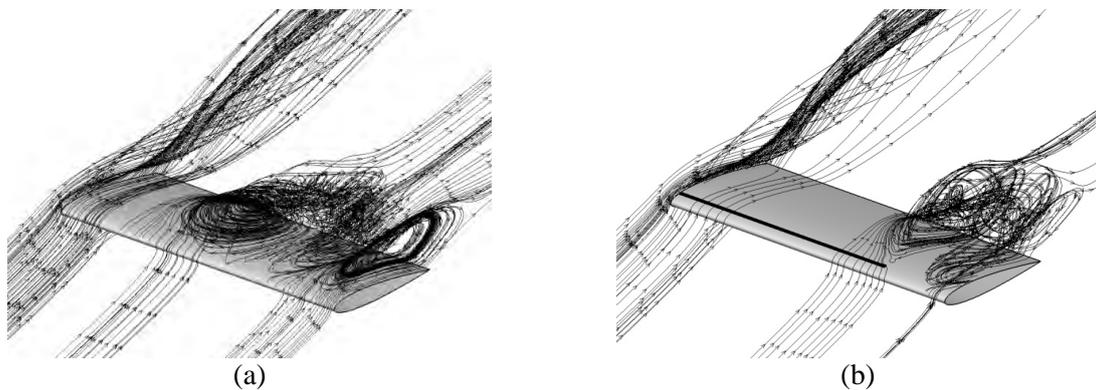


Figure 4. The effect of suction jet length on streamlines over the finite wing at angle of attack 18° for tip suction, (a) no control, (b) suction jet length of $1.5C$ [24].

The effects of steady blowing flow separation control technique were analyzed by Svorcan et al. [26]. Three different flow fields were considered including subsonic flow past an Aerospatiale A airfoil, transonic flow past a NACA 0012 airfoil, and transonic flow in linear compressor/turbine cascade. It was found that lift coefficients and lift-to-drag ratios are improved for all controlled cases. The steady blowing was also found to be of significant importance in controlling the boundary layer separation in the study of the flow field around NACA 0012 and LA203A airfoils performed by James et al. [27]. A secondary blowing jet was positioned on the suction side of the airfoils at 60% of the chord length. The results of this study demonstrated that the secondary blowing causes the separation point to move downstream, the lift coefficient to increase, and the stall of airfoils to delay. Zhang et al. [28] computationally studied the suction flow control over a NACA 0012 airfoil at different angles of attack. The results indicated that the flow separation point travels toward the trailing edge by increasing the suction coefficient as defined in [29], and the vortex shedding can be fully suppressed when the suction coefficient is greater than 0.01 for a steady flow. Furthermore, the increase in suction coefficient resulted in the increase of lift-to-drag ratio. Hafien et al. [30] considered self-adapting flexible flaps on the upper side of the NACA 0012 airfoil. The results indicated that the size and intensity of the vortex-shedding can be considerably reduced, which explains the increase of the lift-to-drag ratio.

Consistent with the active flow control, the research field of the aerodynamic performance of wind and water turbines undergoes many studies investigating the effects of passive flow control techniques. Shehata et al. [31] investigated the effects of the suction flow control on the stall angle of Wells turbine. It was found that with the use of suction flow separation control, the torque coefficient can be increased by more than 17% before stall and by almost 40% within the stall regime. They further extended their work by employing multi-suction slots over the turbine blade [32] to enhance the performance of the turbine in the stall regime. It was observed that the airfoil with three suction slots located at 40%, 55% and 90% of the chord from the leading edge can improve the torque coefficient by 26.7% and 51% before and after the stall, respectively. In another study, Moshfeghi et al. [33] further investigated the influences of a passive flow control method on the aerodynamic performance of S809 airfoil by splitting the airfoil along the span. The split location was considered as the integral parameter and the effects of split location on power coefficient, low-speed shaft torque, and flow patterns were numerically studied. It was deduced that the torque is quite sensitive to the split location and injected flow angle for an attached flow. This sensitivity significantly declines for a highly separated flow in the stall region. Moreover, for a partially separated flow, splitting may impose either positive or negative effect on the torque generation.

4. Closing remarks

In the current paper, we briefly reviewed the latest advances in the field of active and passive flow control where we focused on the blowing, suction, and synthetic jets flow control methods. From a flow control point of view, blowing is fundamentally different from the suction. The primary

advantage of suction is that it maintains the boundary layer attached to the surface, and consequently, drag decreases. The blowing, on the other hand, is much more sensitive, and in most cases, it reduces the aerodynamic performance. The blowing at the leading edge increases the lift by producing additional vortices but causes pressure to significantly improve such that the boundary layer detaches from the surface, and therefore, drag increases. The blowing at the trailing edge, however, can enhance the lift, particularly by using smaller oscillation range. Hence, perpendicular suction at the leading edge and tangential blowing at the trailing edge are the best locations for suction and blowing jet slots [17, 24-25].

The use of synthetic jets not only stabilizes the boundary layer but also increases the mixing level between the inner and outer portions of the boundary layer by adding (extracting) momentum to (from) the boundary layer. The optimum jet width is determined to be 2.5 percent of the chord length [25] in order to maximize the aerodynamic performance. However, the effects of the jet dissipate before it reaches the trailing edge of the airfoil if the jet width is not adequate. This is due to the strong momentum of the free-stream flow.

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