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Passive flow control of a stalled airfoil using a microcylinder

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ABSTRACT

The effect of passive flow control using a microcylinder near the leading edge of a stalled airfoil (NACA 0012) at a Reynolds number of 6×10^6 is investigated through a computational study. Detailed parametric analyses for the microcylinder are carried out based on Reynolds averaged Navier-Stokes (RANS) calculations in order to determine the optimal control parameters. Computations using delayed detached eddy simulation (DDES) for the controlled and uncontrolled cases are supplemented to capture the transient vortical structures in the massive separation region and further verify the numerical results from RANS. It is found that the total aerodynamic forces of the entire system are highly sensitive to the spacing between the surfaces of the airfoil and the microcylinder. When a superior set of control parameters is adopted, significant enhancement of lift coefficient and lift-to-drag ratio can be achieved after stall, accompanying a pronounced decrease of drag coefficient. Both RANS and DDES results indicate that the heavy stall can be effectively delayed and the extent of large separation region on the airfoil suction surface can also be diminished by such a little control device. A physical analysis of the flow fields is performed to illustrate the mechanisms of flow control for the improvement of airfoil aerodynamic performance.

1. Introduction

Flow separation on wind turbine blades often occurs at high wind speeds (Prasad and Dimitriadis, 2017). Airflow separating from the suction surface of an airfoil at a high angle of attack (AoA) is unavoidable, due to a large adverse pressure gradient. Airfoil stall occurs usually when the separation region becomes larger and finally covers almost the whole suction surface as the AoA is further increased. When the stall happens, the loss of lift and increase of drag as well as generation of aerodynamic noise resulting from separation are usually unfavorable. Dynamic airfoil stall is a principal impediment for vertical axis wind turbines to achieving improved aerodynamic efficiency (Buchner et al., 2015; Li et al., 2017). Naturally, flow control of stalled airfoils to improve their aerodynamic performance has attracted widespread research interest for many decades.

Flow control techniques can be mainly divided into active or passive methods based on energy expenditure (Gad-el-Hak, 2000). As for stalled airfoils, many investigations have been conducted to suppress the boundary layer separation. Actuators are popularly used for active flow control and they have received sustained attention (Corke and Matlis, 2000; Sosa et al., 2007; Jukes, 2015). Although obvious benefits can be obtained by actuators, their inherent weaknesses such as structure complexity and high cost are also apparent in flow control. The strengths and drawbacks of various actuators were highlighted in the review by Cattafesta and Sheplak (2011). Passive techniques are relatively simple and cheap. Thus they have gathered considerable attention in practical applications. A leading edge slat (Weick and Shortal, 1933; Houghton and Carpenter, 2013) and vortex generators (Bragg and Gregorek, 1987; Johnston and Nishi, 1990) are classical passive control devices to control the airfoil lift. The slat is usually adopted in the configuration of a multi-element airfoil. The pressure gradient on the main airfoil is reduced with the slat introduced, which causes a stall delay and higher lift values at high AoA. The mechanisms of vortex generators on separation control lie in the enhancement of near-wall momentum through vortices transferring the momentum from the outer flow to the wall region (Lin, 2002). The control effect of vortex generators on various airfoils have been widely investigated over decades (Velte and Hansen, 2013; Manolesos and Voutsinas, 2015; Gao et al., 2015; Wang et al., 2017). Various other passive control methods were proposed recently for airfoil stall control such as leading edge protuberances (Johari et al., 2007), a thin control plate (Rinoie et al., 2009) and hairy flaps (Brücker and Weidner, 2014). Off-surface control element is another passive flow control method, in which the control element is located outside the boundary layer. It is found by Veldhuis and van der Steen (2010) that the

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off-surface vortex generators or cylinders could perform better than the on-surface devices, if the optimum configuration was adopted. The vortex shedding from the off-surface elements will interact with the boundary layer, add momentum to the near-wall region, and so delay the flow separation.

In this paper, the off-surface flow control method is adopted for airfoil stall control. A microcylinder is chosen as the control element and proposed to be installed near an airfoil leading edge. The idea was first inspired by the small control cylinder suppressing the vortex shedding of a main cylinder (Strykowski and Sreenivasan, 1990), and then encouraged by the recent work about an off-surface cylinder controlling the leading edge separation of an elongated bluff body (Michelis and Kotsonis, 2015). Sakamoto et al. (1991) conducted an experiment on a square prism with the introduction of a small circular cylinder. They found a considerable reduction in the fluctuating forces and a maximum reduction of 30% in the time-averaged drag. Igarashi (1997) also carried out experimental studies on the drag reduction of a small control cylinder for a square prism. It was found by Igarashi that the drag of the prism was decreased about 50% when the optimal control parameters were adopted. Sakamoto and Haniu (1994) investigated the control effect of a small circular cylinder on the flow over a large circular cylinder at a Reynolds number of 6.5×10^4. A maximum drag reduction of 50% was confirmed in their experiment and the fluctuating lift and drag were also reduced. The control effect of a small rod upstream of a main circular cylinder at a Reynolds number of 2×10^4 was also investigated experimentally by Lee et al. (2004). The total system drag was observed to be reduced by a maximum of 25% in their experiment. Michelis and Kotsonis (2015) did not concentrate on the total drag reduction. In their experiment, an off-surface cylinder was placed in the vicinity of the leading edge of an elongated bluff body and it was found that the separation bubble on the surface of the bluff body was eliminated, when the optimal location of the control cylinder was adopted.

Previous experimental studies have clearly shown the effectiveness of a small circular cylinder for controlling the flow around a bluff body. However, the geometrical shape of a stalled airfoil at a high AoA is distinctively different from a square prism, a circular cylinder or an elongated bluff body. The previously investigated diameter (or characteristic scale) ratio of the two components was mainly varied in the range of 0.05–0.3. Although the control circular cylinder is small compared to the main body, significant increase would be introduced in the total drag of the entire system, if such a control cylinder were installed near the leading edge of an airfoil before stall. Consequently a microcylinder with a much smaller diameter was adopted in the present investigation for the airfoil flow control.

As for the flow over a stalled airfoil, many numerical investigations using computational fluid dynamic (CFD) tools were carried out. The traditional CFD method based on Reynolds averaged Navier-Stokes (RANS) equations can provide generally accurate predictions for the lift and drag coefficients of an airfoil before stall. However, the accuracy of RANS predictions for airfoil flow starts to decline after stall. The transient and massively separated flow structures on the suction surface of a stalled airfoil cannot be resolved by RANS approaches, due to the turbulent scales of flow are completely modeled in the Reynolds averaging process. Even RANS model operates in an unsteady mode, which is termed as unsteady RANS (URANS), the three-dimensional separated eddies with various scales still cannot be captured. In general, RANS models are numerically stable and accurate for simulation of attached and mildly separated flows. However, they are not able to accurately predict the massively separated flows. Large eddy simulation (LES) is able to capture the unsteady flow features and provide relatively accurate solutions. In LES, a large range of turbulent scales are directly resolved and the small turbulent scales are modeled by a subgrid model. However, the computational cost of LES for flows at high Reynolds numbers is tremendous, mainly due to the huge grid requirements for resolution of the small but dynamically important eddies in the near-wall region. Mary and Sagaut (2002) performed a LES investigation of flow past an airfoil near stall at a Reynolds number of 2.1×10^6. The largest grid with 7.2 million cells was adopted in their simulations. Recently, Alferez et al. (2013) conducted LES studies on the stall development around a NACA 0012 airfoil at a Reynolds number of 10^5. A large number of grid points were used in the near-wall region and the total number of grid cells in their simulations was 160 million. Detached eddy simulation (DES) was proposed by Spalart et al. (1997) to diminish the near-wall grid requirement for LES. In DES, RANS model is adopted near the solid surface within the boundary layer. Different from LES, the near-wall small but dynamically important eddies are not resolved. Away from the wall, the switch from RANS to LES is automatically realized. Delayed detached eddy simulation (DDES) is an improved version of DES (Spalart et al., 2006). It was suggested to be adopted to resolve the problem of model stress depletion and grid induced separation (Spalart, 2009). Schmidt and Thiele (2003) performed a DES simulation of flow around an A-airfoil at a Reynolds number of 2×10^6 at AoA = 13.3°. The unsteady trailing-edge vortices were successfully captured in their simulation. Im and Zha (2014) employed URANS, DES and DDES methods to investigate the dynamic stall flows over a NACA 0012 airfoil at high AoAs at a Reynolds number of 1.3×10^6. The predicted lift and drag from DES and DDES were in good agreement with the experiment, whereas URANS gave significantly overpredicted forces. DDES method was also adopted by Manni et al. (2016) in their numerical investigations of stall cells over a NACA 0012 at a Reynolds number of 10^6. Xu et al. (2017) conducted DDES simulations of flow over a S809 airfoil at a Reynolds number of 6.5×10^5 at various AoAs ranging from 0° to 90°. The realistic three-dimensional flow structures were revealed in their simulations.

In this work, both RANS and DDES methods are adopted to investigate the control effect of a microcylinder for a stalled airfoil at high AoAs. Detailed parametric studies based on RANS calculations are performed to extract the optimal control parameters related to a microcylinder for stall control. Simulations using DDES are supplemented to verify the obtained RANS results and provide transient flow information from the realistic flow fields. The physical mechanisms of this passive flow control technique are illustrated by visualization of streamlines and three-dimensional vortical structures.

2. Problem definition

Turbulent flow over a NACA 0012 airfoil with and without control is simulated to investigate the aerodynamic interaction between the airfoil and the microcylinder. Attention is fixed on the controlled airfoil at high AoAs ranging from 16° to 23°. The microcylinder is located near the airfoil leading edge. The geometric arrangement of the two components is shown in Fig. 1, which is similar to the rod-airfoil configuration as a benchmark test case for numerical noise prediction (Jacob et al., 2005). However, the diameter of rod used for control and the gap between the rod and the airfoil are much smaller in this study. The freestream Mach

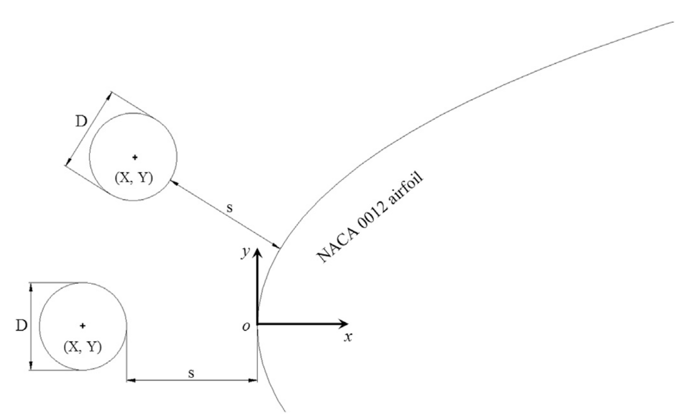

Fig. 1. Schematic of a microcylinder near the NACA 0012 airfoil leading edge (two locations for the microcylinder are displayed).