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Control of dynamic flowfield around a pitching NACA63$_3$ − 618 airfoil by a DBD plasma actuator

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ABSTRACT

High-fidelity computations of the flow control around a pitching NACA63$_3$ − 618 airfoil by a plasma actuator are conducted. The effectiveness of the plasma actuator and the effects of its installation position are investigated. The plasma actuator is installed at $x/c = 0\%$, 10%, and 60% from the leading edge of the airfoil. The installation position of 60% is chosen based on the investigation of the uncontrolled flowfield; the case with this position successfully enhanced the aerodynamic performances of the airfoil. The results show the importance of *a priori* investigation of the separation and the reattachment points for an uncontrolled flowfield. In addition, the results illustrate that a properly installed and actuated plasma actuator is capable of controlling the dynamic flowfields and improving the aerodynamic performances of an airfoil.

1. Introduction

Wind energy has attracted considerable attention as a source of renewable energy over the past decades. Usually, the blades of modern wind turbines are designed to produce power with maximum efficiency under the rated speeds of the wind and the rotor. The flow condition that each spanwise part of the blade experiences, however, is not static but dynamic due to the wind shear, yaw misalignment, gusts, or a combination of these phenomena. In wind farms, the wind conditions become more "dynamic" due to the wake of wind turbines located in the upstream side. With such dynamic conditions, the flow around the blade is no longer fully attached but is somewhat separated, or, often deeply stalled because the flow condition can be out of the range of the design condition. This results in the increase in structural fatigue loading and the deterioration of power efficiency of the wind turbine, even if the speeds of the wind and the rotor are under the rated condition. The aim of the current study is to mitigate this deterioration of power efficiency in the dynamic flowfield in order to gain the popularity of the wind energy.

To address these problems stated above, many researches have been focusing on applying the active flow control on the wind turbine blades. Recently, a dielectric barrier discharge (DBD) plasma actuator (Corke et al., 2010) (hereafter referred to as a "plasma actuator") is considered to be a prospective alternative device to the current complex mechanical or pneumatic systems. A typical plasma actuator consists of two thin electrodes and a dielectric. Because of its simple structure and characteristics, it can be easily installed on the existing machines and can adjust to several flow conditions by changing its operational parameters. Many experimental and computational studies have been conducted to prove the availability of a plasma actuator and to understand its control mechanism under various flow conditions around the following various stationary objects; simple airfoils (Bénard et al., 2009; Mabe et al., 2009; Post and Corke, 2004; 2006; Rizzetta and Visbal, 2011; Vorobiev et al., 2013; 2008), low-pressure turbine blades (Huang et al., 2006a; 2006b; Rizzetta and Visbal, 2007), bluff-bodies (Li et al., 2010; Rizzetta and Visbal, 2009), and wind turbine blades (Gross and Fasel, 2012; Jukes et al., 2013).

Thus far, the effective control mechanisms on the flowfield around stationary objects are being clarified (Asada et al., 2015; Bénard and Moreau, 2013; Greenblatt et al., 2012; Jukes and Choi, 2009; Sato et al., 2015b); with regard to the actuation method, it has been clarified that unsteady actuation provides

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better separation control capability than the steady actuation (Collis et al., 2004; Greenblatt and Wygnanski, 2000; Patel et al., 2008; Sidorenko et al., 2007). It has been reported that the most effective unsteady actuation parameter nondimensionalized by the freestream velocity and the chord length (F^+) is the order of unity (Asada et al., 2015; Post and Corke, 2004, 2006), or is near the subharmonic of the most unstable mode of the leading edge shear layer (Nonomura et al., 2013; Visbal, 2015). With regard to the installation position of the plasma actuator, Sato et al. investigated the effect of the installation position of the plasma actuator and concluded that an effective installation position is just the upstream of the natural separation point (Sato et al., 2015c).

By using the knowledge of effective mechanisms or plasma actuator parameters on the flowfield around a stationary airfoil, many studies have investigated the availability of a plasma actuator on dynamic flowfields (Frankhouser et al., 2015; Greenblatt et al., 2014; Mitsuo et al., 2013; Post and Corke, 2006; Rizzetta and Visbal, 2012). More recently, studies that apply plasma actuator on a wind turbine began to be reported (Aono et al., 2014; Cooney et al., 2016; Matsuda et al., 2012; Tanaka et al., 2013). These studies also successfully proved the applicability of a plasma actuator on dynamic flowfields. The general control mechanisms on dynamic flowfields is considered to be essentially similar to these on the corresponding stationary flowfields, and most of these studies employ F^+ of the order of unity. Here, these studies on dynamic flowfields with a plasma actuator generally focus on a flowfield around simple airfoils such as NACA0012 and NACA0015 airfoils. These airfoils have relatively sharp leading edges and thus the flow separates near the leading edge. Therefore, it is reasonable that most of these studies install a plasma actuator at the leading edge, although the optimal installation position of the plasma actuator in the dynamic flowfields in which the separation points move dynamically is not clear.

Generally, actual sectional airfoils of wind turbine blades are asymmetric and relatively thick as seen in DU airfoils (Timmer and Rooij, 2003), NACA $63-6XX$, or NACA $64-6XX$ airfoils (Grasso, 2011; Timmer, 2009). Here, NACA63_3-618 airfoil, which is the objective airfoil of the current study and is a family of NACA 6 series airfoils, is used as a sectional airfoil of a certain large-scale wind turbine. NACA 6 series airfoils are developed for maximizing the region over which the flow remains laminar. Originally these airfoils are designed to operate at high Reynolds numbers, but these still have applications at low Reynolds numbers (Brehm et al., 2008). The current study assumes a small-scale wind turbine model and focuses on a sectional airfoil of blades in the low-speed operation, and Reynolds number based on the chord length and the velocity experienced by the sectional airfoil at a certain spanwise location can be the order of 10^4. Around a NACA $63-6XX$ or NACA $64-6XX$ airfoil, the flow separates around the mid-chord of the airfoil under the wide range of Reynolds numbers and angles of attack (Brehm et al., 2008).

Flowfields around a stationary airfoil and a pitching (dynamic) airfoil at low Reynolds numbers have been investigated in details (Galbraith and Visbal, 2008; Gross and Fasel, 2010; Jones et al., 2008; Kojima et al., 2013; Visbal and Gordnier, 2009); the flowfield around a general airfoil at low Reynolds numbers is characterized by a laminar separation bubble (LSB) irrespective of whether the airfoil is a stationary or pitching airfoil. With respect to the dynamic flowfields, the behavior of the LSB becomes more important because its breakdown can trigger the consequent dynamic stall process (Visbal and Gordnier, 2009). Here, the behavior of the LSB and thereby the characteristics of the flowfield is sensitive and depends on the configurations such as airfoil shape, frequency of the pitching motion, and so on. Considering the importance of the behavior of the LSB in dynamic flowfields and/or at low Reynolds numbers, the optimal installation position of the plasma actuator in dynamic flowfields around a pitching airfoil should be investigated. Especially, the leading edge of an actual wind turbine blade is subject to erosion and thus the installation of the plasma actuator to the leading edge should be avoided. Therefore, investigations on the installation position of the plasma actuator is critical to the practical application of a plasma actuator on wind turbines.

In the current study, high-fidelity large-eddy simulations (LESs) of the dynamic flowfield around a pitching NACA63_3-618 airfoil at a Reynolds number of 8.4×10^4 are conducted in order to understand the effectiveness of the plasma actuator on a dynamic flowfield and to understand the effective installation position of the plasma actuator. First, the details of dynamic flowfields are investigated, and then the effects of a plasma actuator installed at various locations based on the investigation of an uncontrolled flowfield is discussed.

2. Computational methods

2.1. Flow conditions and airfoil shape

The airfoil used in the current study is a NACA63_3-618 airfoil that dynamically rotates around its quarter-chord location from the leading edge according to the following sinusoidal equation for the angle of attack (also denoted as *AoA*): $\alpha=\alpha_{mean}+\beta\sin(\omega t)$. Here, α_{mean}, β, and the reduced frequency ($k=\omega c/2U_\infty$) are set as 0°, 15°, and 0.117, respectively. This reduced frequency and the pitching amplitude is based on of the fluctuation of the *AoA* which is experienced by a section airfoil with a chord length of 0.2m of a small wind turbine model under an operation condition near cut-in speed of wind with yaw misalignment. In the current study, the pitching amplitude and the center *AoA* is intentionally modified so that the lower surface of the airfoil experience a dynamic stall in order to expand the understandings of a dynamic flowfield, although the control effects during negative *AoA* is out of focus of this paper and not discussed much here. The chord-based Reynolds number is set as 8.4×10^4 and the freestream Mach number is set as 0.1 where the compressibility of the fluid is almost negligible. The specific heat ratio and Prandtl number are set as 1.4 and 0.72, respectively.

2.2. Governing equations

The governing equations in the current calculations are the three-dimensional Navier–Stokes equations. These equations are nondimensionalized based on freestream density, freestream velocity, and chord length of the airfoil. The nondimensionalized governing equations are as follows:

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho u_k}{\partial x_k}=0, \tag{1}$$

$$\frac{\partial\rho u_i}{\partial t}+\frac{\partial(\rho u_i u_k+p\delta_{ik})}{\partial x_k}=\frac{1}{Re}\frac{\partial\tau_{ik}}{\partial x_k}+D_cS_i, \tag{2}$$

$$\frac{\partial e}{\partial t}+\frac{\partial((e+p)u_k)}{\partial x_k}=\frac{1}{Re}\frac{\partial u_l\tau_{kl}}{\partial x_k}+\frac{1}{(\gamma-1)PrReM_\infty^2}\frac{\partial q_k}{\partial x_k}+D_cS_ku_k, \tag{3}$$

$$S_i=Q_cE_i, \tag{4}$$

where x_i, u_i, q_i, ρ, p, e, τ_{ij}, δ_{ij}, and t correspond to nondimensional forms of the position vector, velocity vector, heat flux vector, density, pressure, energy per unit volume, stress tensor, Kronecker delta, and time, respectively. Additionally, Re, M_∞, and Pr denote Reynolds, Mach, and Prandtl numbers, respectively. The subscript