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Thin airfoil load control during post-stall and large pitch angles using leading-edge trips

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ABSTRACT

Dynamic stall significantly impacts the performance of wind turbines. This article describes the effects of a leading-edge trip wire passive flow-control device, applied to a NACA 0012 airfoil undergoing dynamic stall to high angles of attack. The Reynolds number is 20,000. Surface pressure measurements were conducted to determine unsteady lift. Ceasing high rotation-rate airfoil motion, an increase in flow at the leading edge occurs, due to the momentum imparted on the fluid by the airfoil during rotation. The increased flow at the leading edge leads to a severe adverse pressure gradient, resulting in immediate leading-edge flow separation. For high rotation rate conditions, the leading-edge trip wire displayed limited abilities in controlling boundary layer separation, where decreases in the maximum lift and post-stall lift fluctuation were observed. Trip wire benefits are limited by the formation of vortex shedding at the leading edge, reminiscent to bluff body separation, which significantly dwarf vortex structures generated by the trip wire. Under post-stall flow conditions, the trip wire has little impact on the large-scale von-Karman vortex development, where load fluctuations occurred. The application of a trip wire resulted in reducing the maximum lift, but variations in its diameter did not alter the stall angle of attack.

1. Introduction

Ever-increasing requirements for clean energy production have led to a greater demand for renewable energy resources, including the application of horizontal-axis wind turbines (HAWT). Maximising the energy output of a HAWT requires detailed analysis of the environmental operating conditions in conjunction with the imposed aerodynamic loads created through its unsteady operation. Dynamic stall is one such unsteady phenomenon generated during the operation of a HAWT exposed to high yaw angles, unsteadiness in the atmospheric boundary layer and turbine-wake interaction. Such conditions lead to the formation of a characteristic leading-edge vortex, which has been widely investigated due to the excessive loads it imposes on the mechanical components and blades of HAWTs. Previous studies (Butterfield et al., 1991; Butterfield, 1989; Shipley et al., 1995) highlighted the necessity to study the dynamic-stall and post-stall aerodynamic characteristics of the turbine blades when exposed to high yaw angles, tower shadow and upwind turbine wakes.

Under dynamic-stall conditions, delayed separation occurs, which is subsequently followed by the formation of a leading-edge vortex structure as the angle of attack is further increased (Carr, 1988). The formation of dynamic-stall vortex structures is linked to adverse pressure gradients at the leading edge and typically results from geometric discontinuities or loss of momentum within the attached boundary layer at elevated angles of attack, well beyond steady-state angles of attack. The leading-edge vortex leads to increased force generation, which itself has been shown to vary with performance parameters such as Reynolds number, pitch rate, Mach number and airfoil geometry (Carr and Chandrasekhara, 1996; Jumper et al., 1987, 1989; McCroskey et al., 1976, 1981, 1982; McAlister et al., 1978; McCroskey, 1981; Robinson and Wissler, 1988). Control and manipulation of the leading-edge vortex can therefore be used to delay the onset of dynamic stall and force generation characteristics. However, practical methods of doing so are limited. Furthermore, improving operation of rotor blades in post-stall conditions requires accurate analysis of the aerodynamic behaviour such that blades can be developed to withstand the applied loads.

As the majority of research conducted on dynamic stall is focused on low angles of attack, where attempts to avoid airfoil stall are sought, research into stall and post-stall characteristics of the airfoils in dynamic stall conditions is still limited. This insight into the challenge of stalled and post-stalled flow conditions was also expressed in Butterfield (1989), who discussed the challenge in determining wind turbine blade loads at

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angles of attack between 12° and 30°. For post-stalled conditions, beyond 30°, flat-plate aerodynamic properties have generally been employed for the design of wind turbine blades (Butterfield, 1989; Jonkman, 2001). Although flat-plate approximations provide a starting point in the design process of a turbine blade, the method is somewhat flawed and should not completely be depended upon, due to blade thickness variations along the span, and the tendency of stalled, thick airfoil sections to behave in a manner similar to cylinders (Tangler, 2004). Under such conditions the application of flat-plate aerodynamic characteristics becomes invalid.

Similar to steady-state stall, under dynamic-stall conditions and immediately following dynamic stall, application of flat-plate analysis may not fully provide the correct aerodynamic loading on turbine blades. The resulting force fluctuation, outside of those predicted by flat plate analysis, are of concern to wind engineers and designers of HAWT components due to the over- or under-prediction of the aerodynamic loading during these conditions. In addition, these comments highlight the need for further experimental data relating to the stall characteristics of airfoils, with profiles specific to wind turbines, exposed to elevated angles of attack, and which have undergone dynamic stall and proceeded into a state of fully-separated flow.

Implementation of effective, inexpensive and simple flow-control devices can be a viable means to manipulate and control boundary-layer separation on turbine blades. However, greater understanding of such devices is still needed for stall and post-stall conditions at elevated angles of attack. Techniques applicable to the control of steady-state boundary layer separation have been investigated for their applicability for dynamic stall conditions. Katz, Nishri and Wygnanski (Katz et al., 1989) and Lachmann (2014) detail the process of laminar and turbulent separation and highlight numerous methods of both active and passive boundary layer control methods, whilst Choudhry et al. (2014) review current active and passive control methods utilised for the control of dynamic stall on wind turbines. These flow control techniques have a common objective to delay or reduce the extent of separation by either reducing the surface curvature at the leading edge, thus decreasing the adverse pressure gradient, or by introducing flow momentum within the boundary layer by utilising devices such as blowing or suction.

Closed loop active control systems require continuous feedback, and often are associated with increased cost and complexity. Active boundary-layer control techniques currently investigated for control of the dynamic stall process include adaptive airfoil geometries (Chandrasekhara et al., 1998, 2004; Feszty et al., 2004; Geissler et al., 2004; Greenblatt and Wygnanski, 2002; Kerho, 2007; Lee and Gerontakos, 2006; Yu et al., 1995), upper surface blowing (Müller-Vahl et al., 2014, 2016; Sun and Sheikh, 1999; Weaver et al., 1996, 2004; Yen and Ahmed, 2013), periodic boundary layer excitation (Gardner et al., 2011; Greenblatt et al., 2001; Greenblatt and Wygnanski, 2001; Magill and McMacMus, 1998; Yu et al., 1995), boundary layer suction (Alrefai, Acharya, 1996; Karim and Acharya, 1994) and more recently, the use of plasma actuators (Greenblatt et al., 2014; Lombardi et al., 2013; Post and Corke, 2006). Other active flow-control methods utilise changes in the airfoil geometry via application of flaps and slats at fixed locations (Carr et al., 2001; Joo et al., 2006; McAlister and Tung, 1993). Both methods have been proven to delay separation and mitigate the formation of the leading-edge vortex. However, the application of such mechanisms requires complex actuators, where aerodynamic loading and response time are large and thus limit the applicability of the system (Geissler et al., 2005). Of these methods, all have been demonstrated to influence dynamic stall to moderately-high angles of attack, although they all consist of highly complex systems that must be tuned to the conditions such that an efficient control of the boundary layer is achieved. In real conditions, less complex systems are preferred due to lower maintenance and installation costs.

With an increasing demand for clean, renewable energy, wind turbine size and numbers have increased significantly. Furthermore, placement of the turbines away from urban areas results in increased demand on the turbine due the harsh operating conditions and their remote operating locations (Pao and Johnson, 2009). As such, implementation of active boundary layer control systems become increasingly complex and costly to both implement and maintain. For this reason, the use of passive boundary-layer control devices presents a viable means to control dynamic stall, due to simpler installation, lower production cost and ease of use.

Control of separation and increased stall angle of attack on airfoils operating in steady-state conditions have been achieved through the utilisation of devices that generate stream-wise vorticity. Examples include classical vortex generators, airfoils modified with tubercles (Fish et al., 2011; Hansen et al., 2011; New et al., 2016), and changes to the wing layout, for example by using undulating-leading edges (Rostamzadeh et al., 2013). Using stream-wise vorticity, significant potential in suppressing separation at moderate angles of attack and increasing the aerodynamic performance at angles of attack close to stall were demonstrated. Although much interest in the application of tubercles for steady-state boundary layer control has been generated, their application has, to an extent, been limited with respect to dynamic stall conditions. One such study into the use of this flow control method under dynamic-stall conditions was undertaken by Hrynuk (2015), who concluded that the base flow structure (span-wise to stream-wise vorticity) was modified for a wing with tubercles, although a single span-wise vortex remained present and shed into the wake once the airfoil transitioned into a deep stalled phase. Their results showed that utilising tubercles on an airfoil led to an increase in the airfoil dynamic stall angle of attack, which resulted in sustained lift generation with no significant drag penalty. From the previous literature, tubercles have been shown to be beneficial at pre-stall angles of attack, however in deep-stall flow conditions they do not show any effect on the flow separation process.

Passive boundary-layer control devices using leading-edge vortex generators (Geissler et al., 2005) and cylindrical and triangular protrusions mounted on the underside of the leading edge (Heine et al., 2013), have been shown to reduce the maximum lift, drag, and pitching moment fluctuations at high angles of attacks during dynamic stall. In addition to vortex generators, leading-edge trip wires and span-wise cavities were also investigated by Choudhry (2014) for low, quasi-steady rotation rates, such that $\kappa < 0.025$ where $\kappa = \omega c / 2U_\infty$, in order to reduce the load fluctuation during the dynamic-stall process. Here ω is the angular velocity in rad/s, c is the airfoil chord length in m and U_∞ is the free-stream velocity in m/s.

In Choudhry et al. (2014), a trip wire with a diameter of 0.95% of the airfoil chord length was located at a range of displacements from the leading edge was shown to reduce the stall intensity and improve post-stall flow characteristics, where maximum aerodynamic force fluctuation was reduced with respect to a clean airfoil. The stall intensity is defined as the lift slope after separation and the overall reduction in lift after the initial peak lift and prior to the secondary peak lift generation (Choudhry et al., 2014). Surface pressure measurements showed that peak lift was reduced by 50% and stall intensity was also reduced under dynamic-stall conditions for airfoils equipped with the leading-edge trip wire, compared with the clean airfoil case. As the low rotation rates led to reductions in stall intensity (Choudhry et al., 2014; Choudhry, 2014), the feasibility of investigating the effects of leading-edge trip wires under conditions of high rotation rates is warranted.

This article aims to describe the effects of thin airfoil dynamic stall control where operating conditions are subject to high angles of attack and high rotation rates, typical of high wind shear and gust-like conditions. In this work, airfoil conditions were investigated whereby the airfoil angle of attack increases until stall is achieved, and then continues to operate at the elevated angle to simulate stalled operating conditions. Control of the dynamic-stall process and post-stall flow characteristics is investigated by utilising a fixed-displacement leading-edge trip wire whereby span-wise vorticity can be introduced to minimise the aerodynamic load variation prior to and after dynamic stall occurrence.