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Methods to control dynamic stall for wind turbine applications

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ABSTRACT

Dynamic stall (DS) on a wind turbine is encountered when the sectional angles of attack of the blade rapidly exceeds the steady-state stall angle of attack due to in-flow turbulence, gusts and yaw-misalignment. The process is considered as a primary source of unsteady loads on wind turbine blades and negatively influences the performance and fatigue life of a turbine. In the present article, the control requirements for DS have been outlined for wind turbines based on an in-depth analysis of the process. Three passive control methodologies have been investigated for dynamic stall control: (1) streamwise vortices generated using vortex generators (VGs), (2) spanwise vortices generated using a novel concept of an elevated wire (EW), and (3) a cavity to act as a reservoir for the reverse flow accumulation. The methods were observed to delay the onset of DS by several degrees as well as reduce the increased lift and drag forces that are associated with the DSV. However, only the VG and the EW were observed to improve the post-stall characteristics of the airfoil.

1. Introduction and background

Dynamic stall is the process of delayed flow separation on airfoils caused by rapid excursions in the angle of attack beyond the steady-state stall angle [1]. The delay in flow separation results in increased lift, well beyond the steady-state maximum value, as well as in the formation of a coherent vortex near the leading edge (LE) of the airfoil [2,3]. This dynamic stall vortex (DSV) results in further increase in the lift and drag forces generated by the airfoil. Once the vortex sheds, the airfoil goes into a state of deep stall. The overall loss of lift due to dynamic stall has been observed to be far more severe than that observed during steady-state operation [4]. After the initial study by Kramer [5], due to its limited perceived applicability at the time, little attention was given to the problem of dynamic stall, until it was found to occur on the retreating blades of helicopters during forward flight [6,7]. The periodic increases in lift and pitching moments, due to the DSV formation, not only severely limits the flight envelopes and attainable performance of the vehicle but also imposes high demands on the material selection for the blade. Furthermore, a large hysteresis in the lift force is observed when the angles of the blade section reduces, indicating a delay in flow reattachment and lift recovery during the process. On the other hand, dynamic stall has also been observed on wind turbine blades [8–11], where it leads to increased fatigue damage accumulation at the rotor-hub joint due to large excursion in lift [12] as well as increased noise generation due to blade-vortex interaction [13]. In wind turbines, dynamic stall is caused by rapid variations of wind speed and direction [8,14,15] and is, therefore, more unpredictable compared to the rotor blades of helicopters. Furthermore, due to operation in the wake of other turbines, which consists of large-scale vortical structures of high turbulence intensity and velocity deficits [9,16–18], the problem of dynamic stall is considerably aggravated for downstream wind turbines [9].

Therefore, the primary motivation towards the research into the unsteady separation is to principally avoid or suppress the process to some extent. However, the control requirements are basically application-driven. For example, as shown in Fig. 1a, the primary requirement of dynamic stall control on helicopter blades is to reduce the overall hysteresis in the lift force, while maintaining the average lift during the process. Furthermore, it is desirable to delay the process to higher angles of attack and to reduce the aerodynamic damping due to the DSV formation. Dynamic stall due to sinusoidal oscillations is generally classified as either light- or deep-stall [19]. The light-stall regime is defined when the downstroke motion of the airfoil begins prior to the formation of the dynamic stall vortex, whereas deep-stall occurs when the dynamic stall vortex, and the consequent lift overshoot, are observed prior to the downstroke [20]. Therefore, in Fig. 1a, the uncontrolled case (solid line) is representative of a deep-stall condition on the airfoil.

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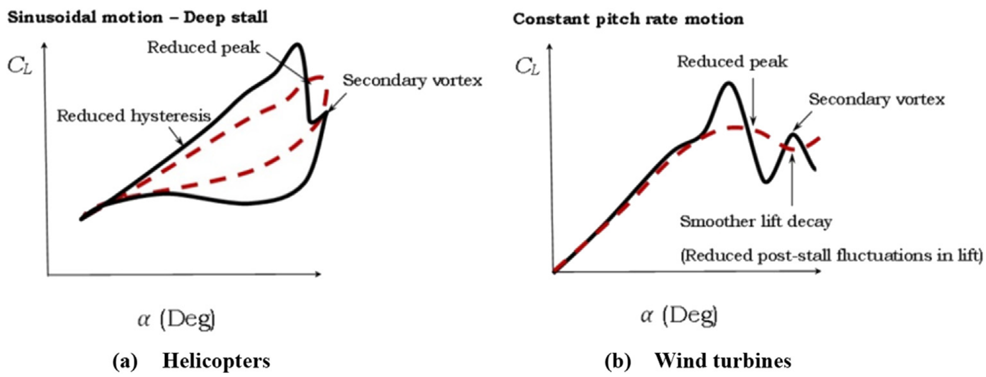

Fig. 1. Control objectives for dynamic stall for different applications. The dashed curves are the desired controlled cases.

Here, the lift overshoot is principally due to the formation of the DSV and the subsequent stall occurs when the DSV departs from the airfoil surface. Secondary peaks in the lift force can also be observed in the uncontrolled case just prior to the downstroke motion. Note that the large hysteresis in this case is caused by the flow separation that follows the DSV departure. On the other hand, the controlled case (dashed line) in Fig. 1a is representative of the light-stall conditions. In this case, the formation of the DSV is delayed to higher angles due to the control. Furthermore, the DSV formed should be of a reduced strength and therefore would result in a smaller lift rise. This is advantageous since once the vortex convects the resultant hysteresis in the lift will be significantly smaller. Furthermore, the peak negative pitching moment excursions associated with the DSV will also be reduced considerably compared to the uncontrolled case.

For wind turbines, the primary control objectives are similar to the helicopter case. However, in this case, due to gusts of significant length scales or consistent yaw-misalignment, the angles of attack might not reduce to small enough values to allow flow reattachment. Therefore, the blade would operate under unsteady separated flow condition for extended periods of time. Hence, the primary control objective here, as shown in Fig. 1b, is not only to reduce the increased vortex lift but also to decrease the lift decay after the vortex departs and to reduce the fluctuations in the lift post-separation. This control objective would lead to improved post-stall behaviour of the turbine resulting in reduced vibrations of the blade, improved aerodynamic performance and fatigue life.

It is interesting to note that the lift behaviour of the airfoil for the constant pitch rate case and the sinusoidal case are largely similar. The only difference is that for the sinusoidal case the airfoil is allowed to return to the initial angles of the cycle. However, for the constant pitch rate case, the airfoil pitches at a constant pitch rate to a maximum angle of attack and holds the angle for extended periods of time. Therefore, for the sinusoidal case, a control technique is required to assist in the flow and lift recovery process during the downstroke motion. This is synonymous, to some extent, for the control requirement of smoother lift decay during the constant pitch rate case. The purpose of mentioning the similarity for both cases is to illustrate that the effects of control are transferrable from one case to the other.

Several attempts have been made to control dynamic stall, particularly for applications in helicopter rotors. An extensive literature review was performed to understand the feasibility and effectiveness of different methods that have been used to control dynamic stall, particularly the lift associated with the DSV. Gardner et al. [21] studied the influence of fluid injection into the flow through different jet configurations and noted a considerable reduction in the vortex lift. Karim and Acharya [22] used flow removal as a means to reduce the vortex strength. Similarly, periodic excitation has been shown to reduce the hysteresis in the lift considerably [23,24]. However, this method was confined to light dynamic stall conditions. It should be noted that the methods involving flow addition or removal require complex plumbing and reservoirs of compressed air or vacuum tanks to influence the flow field and therefore are not feasible for practical applications. On the other hand, passive flow-control methods, such as vortex generator (VG), have recently been investigated as a means to control dynamic stall. These methods have a zero net-mass flux and, therefore, are easier to implement. It has generally been observed that an increase in the VG height can results in a decrease of the lift hysteresis [25]. Furthermore, VG configurations producing counter-rotating streamwise vortices have been observed to be more beneficial for reducing the lift hysteresis compared to the configurations that produce co-rotating streamwise vortices [26]. However, these studies have also been limited to the light dynamic stall cases and, therefore, no indications can be made regarding the method's potency to reduce the DSV strength. A unique arrangement of VGs on the underside of the airfoil was proposed by Mai et al. [27]. This arrangement was found to be beneficial in reducing the influence of the VGs during steady-state operation at lower angles. At higher angles, the VGs were observed to delay the steady-state flow separation from the airfoils. However, testing at dynamic conditions indicated that the VGs were unable to influence the formation of the primary DSV and, therefore, did not decrease the vortex lift or improve the ensuing severe flow separation. Although, similar to other studies, the lift hysteresis was significantly reduced due to the streamwise-vortices created by the VGs during the downstroke. In addition to streamwise vortices, spanwise-oriented vortices, produced through unsteady actuation of plasma actuators, result in a reduced DSV lift and the subsequent hysteresis [28]. However, the vortices generated in this case are co-rotating and significantly weaker compared to the vortices generated by VGs. More conventional methods such as LE slats have also been shown to reduce the hysteresis in the lift and slightly delay the onset of vortex formation [29,30]. However, the increase in drag, due to a slat deployment, reduces the applicability of this method. Other LE modifications such as the Variable Droop Leading-Edge (VDLE) concept [31] and the Dynamically Deforming Leading-Edge (DDLE) concept [32] have been used to reduce the strength of the DSV. During VDLE, the airfoil LE is drooped such that the overall camber of the foil changes. On the other hand, the DDLE concept changes the LE radius as the airfoil undergoes the pitching motion. Both methods, though difficult to implement on actual blades, illustrate the significant impact of airfoil geometry on the