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Dynamic stall control via adaptive blowing

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ABSTRACT

An aerodynamic load control concept termed “adaptive blowing” was successfully tested on a NACA 0018 airfoil model at Reynolds numbers ranging from $1.5\cdot10^5$ to $5\cdot10^5$. The global objective was to eliminate lift oscillations typically encountered on wind turbine blade sections. Depending on the jet momentum flux, steady blowing from a control slot in the leading-edge region can be utilized to either enhance or reduce lift by suppressing or inducing boundary layer separation respectively. Furthermore, high momentum blowing effectively eliminated the dynamic stall vortex during deep dynamic stall conditions. Based on these previous findings, the present work explores the feasibility of controlling unsteady aerodynamic loads by dynamically varying the jet momentum flux to compensate for transient changes of the inflow. Various scenarios including high amplitude pitching, rapid freestream oscillations and combinations of both were investigated in a custom-built unsteady wind tunnel facility. An iterative control algorithm was implemented which successfully identified the momentum coefficient time profiles required to minimize the lift excursions. The combination of fully suppressing dynamic stall and dynamically adjusting the lift coefficient provided an unprecedented control authority, producing virtually constant phase averaged lift in all cases.

1. Introduction

Unsteady aerodynamic loads acting upon wind turbine rotor blades are a major problem for turbine designers. Both the relative flow speed and the geometric incidence at a given blade segment exhibit significant temporal variations as a result of various factors including, but not limited to, atmospheric turbulence, the earth's boundary layer, the wakes of wind turbines located further upstream and tower shadow effects. These inflow variations which can be divided into periodic and random contributions lead to severe excursions in the aerodynamic loads. The resulting fatigue stresses are detrimental not only to the rotor blades but also various other turbine components such as the generator and the drive train [1]. It is clear that there is significant potential to reduce unsteady aerodynamic loads by means of active flow control. If the challenges related to actuator reliability and overall cost efficiency can be overcome, implementing control solutions on wind turbine rotor blades may have the potential to eventually reduce the cost of energy.

The aerodynamic loads exhibit particularly rapid and sharp variations when the boundary layer dynamically separates from the suction surface. This phenomenon termed “dynamic stall” occurs when the local geometric incidence (used synonymously with “angle of attack” throughout this work) abruptly exceeds a critical value. Rotor blades of horizontal axis wind turbines (HAWTs) typically operate at relatively high angles of attack in order to maximize torque. Rotor yaw-misalignment leads to significant cyclic angle of attack variations [2], which can cause dynamic stall especially at high wind speeds and low tip-speed ratios [3]. On vertical axis wind turbines (VAWTs), synchronous periodic variations in both angle of attack and relative flow speed are an innate feature of the working principle. At low tip-speed ratios, dynamic stall occurs periodically throughout the rotation of the blades [4]. Most dynamic stall research to date has been conducted under two-dimensional conditions at a steady, uniform inflow [5]. In this simplified scenario, the boundary layer initially remains attached as the static stall angle is dynamically exceeded. The transient separation process is dominated by the shedding of the dynamic stall

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vortex (DSV), which originates from the vortical fluid in the boundary layer close to the leading-edge. The DSV temporarily remains in place and grows in strength before being convected into the wake. The motion of the associated low pressure region across the suction surface leads to a temporary lift overshoot and a sharp drop in pitching moment [6]. After the shedding of the DSV, the boundary layer above the suction surface is fully separated, causing a dramatic loss in lift and an increase in drag. Even though surface pressure signatures confirm that this sequence of events also occurs on HAWT blades [5], the situations is more complex because of the three-dimensional nature of the problem [7,8].

As dynamic stall entails severe, potentially damaging load excursions, much previous research has been aimed at achieving its control, particularly for rotorcraft applications [9]. The control strategies relevant within the scope of this work can be grouped into two main categories: Methods that aim to control loads acting upon wind turbine rotor blades under pre-stall conditions and dynamic stall control. There are fundamental qualitative differences that distinguish dynamic stall control methods from the majority of the other concepts proposed for fatigue load reduction. Apart from some exceptions, these differences manifest both in the location of actuation (trailing-edge versus leading-edge region) and the mechanism by which control is achieved (i.e. changing the effective camber versus separation control). Significant changes in lift can be obtained with relatively small modifications of the airfoil geometry in the trailing-edge region, particularly when the boundary layer is attached, and hence many actuators used for active load control are positioned here. Dynamic stall, however, originates from flow reversal near the leading-edge and there are strong arguments supporting the assumption that the most effective approach for its control is to manipulate the vortex formation stage [10]. Accordingly, virtually all methods that have been shown to mitigate or suppress dynamic stall rely on control in the leading-edge region [11,12]. The classification adopted here is by no means universally valid or exclusive. For instance, some actuators located at the leading-edge can also potentially be utilized to counteract lift fluctuations when the boundary layer is fully attached. This is the case for the technique proposed in this work which combines dynamic stall control with the capability to dynamically adjust the lift coefficient.

The pitch control mechanisms integrated in contemporary wind turbines are an effective means to regulate overall turbine performance and limit the blade loads during high wind conditions. However, the ever increasing size of wind turbines makes it impossible to maintain an optimum angle of attack along the entire blade by adjusting the pitch angle alone [13,14]. Furthermore, the speed of deflection is limited by the large moment of inertia of the blades [15]. Hence, while pitch control is likely to be retained in future wind turbine designs, additional distributed control devices capable of locally adapting the aerodynamic characteristics of the blades offer more flexibility and a faster response. Excellent reviews of the various approaches and the multidisciplinary aspects of their implementation have been provided by Barlas and van Kuik [16,17], Johnson et al. [18] and Pechlivanoglou et al. [19]. The most common approach to control lift is to adapt the effective camber via control devices located in the trailing-edge region, such as rigid flaps [20,21], deformable trailing-edge geometries [22,23] and deployable Gurney flaps (microtabs) [24,25]. Even though significant progress has been made in this field, each technique still has some deficits that need to be overcome to reach a technology readiness level sufficient for the implementation into a full-scale turbine [26].

Dynamic stall control is commonly aimed at reducing the detrimental load excursions by either mitigating the strength of the DSV or eliminating it entirely. A survey covering various control approaches ranging from geometric modifications in the leading-edge region to periodic excitation of the boundary layer is presented in Ref. [27]. Recent approaches to control dynamic stall by means of localized ejection of momentum have included vortex generator jets [28], synthetic jets [29,30] and combustion-based pulsed jets [31].

Some efforts have been made to optimize the effect of control by adjusting or deactivating it during a portion of the cycle. McCloud et al. used cyclic blowing in order to reduce the energy consumption while maintaining a delay of separation similar to that achieved with steady blowing [32]. Greenblatt et al. showed that intermittent zero mass-flux excitation was as effective at suppressing lift stall as continuous excitation [33]. Furthermore, the detrimental drag increase in the prestall regime was avoided when control was temporarily deactivated. A reduction in drag penalty was also achieved with deployable vortex generators that were retracted when not required for control [9].

The load control method proposed in this work is in part based on steady blowing which was originally conceived as a tool for lift enhancement [34,35] shortly after Prandtl presented the boundary layer concept [36]. In this classical application, flow reversal that would otherwise be caused by an adverse pressure gradient is suppressed by directly injecting high momentum fluid tangentially to the airfoil surface [37]. Steady blowing can also be utilized to produce the opposite effect: the boundary layer is destabilized when the jet velocity U_j is below the local boundary layer edge velocity [38], causing a shift of turbulent separation to a location further upstream. When the control slot is located at or near the leading-edge, a low momentum wall-jet can induce full separation above the suction surface, causing a dramatic loss in lift [11,39]. Since lift reduction is not desired in most practical applications, this mechanism has received little attention to date. It appears likely that the lowering of near-wall momentum precipitates flow reversal in the presence of an adverse pressure gradient. The control input of steady blowing is commonly quantified based on the momentum coefficient, which provides a good indicator of the effect of control for relatively high jet speeds [40]. For a two-dimensional airfoil, it is defined as

$$C_\mu = \frac{\rho_j h U_j^2}{\frac{1}{2}\rho_\infty c U_\infty^2}, \qquad (1)$$

where h is the control slot height, c refers to the airfoil chord length, ρ_j is the density of the fluid ejected from the slot and ρ_∞ is the density of the free-stream [41]. Even though C_μ is a less suitable scaling parameter for low-momentum blowing where separation is induced [38], it is retained in this work for consistency.

In addition to lift enhancement, steady blowing has also been demonstrated to be an effective tool for dynamic stall control. Retreating-blade stall was delayed on a full-scale helicopter rotor with blowing from a control slot located at 8.5% chord [32]. More recently, wind tunnel tests on a VR-7 airfoil model showed that steady blowing from a control slot located at 25% chord inhibited the bursting of the separation bubble, leading to a reduction of unsteady load fluctuations [42,43]. Sun and Sheikh [44] investigated dynamic stall control via tangential blowing on a NACA 0012 airfoil by numerically solving the Reynolds averaged Navier-Stokes equations. Their results indicate that control near the leading-edge is more effective than control further downstream. Steady blowing with $C_\mu = 9\%$ at a chordwise location of $x/c = 0.006$ was predicted to almost completely eliminate the dynamic stall vortex.

This work builds upon a previous study in which dynamic stall control via steady blowing was studied with detailed flow field measurements [27]. Experiments carried out on a NACA 0018 airfoil model showed that high-momentum blowing from the leading-