Unsteady Separation Control on Wind Turbine Blades

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Dedicated to my parents

Dr. Sanaullah Choudhry and Mrs. Tahira K. Choudhry

For their unbounded support and love

Summary

Dynamic stall is one of the primary causes of unsteady loads on wind turbine blades. The process can be instigated by a multitude of factors, common in wind turbine operating environments, such as inflow turbulence, wind gusts and sustained yaw misalignment. The unsteady separation due to dynamic stall can lead to excessive loads, much larger than the design loads for the turbine, and vibrations in the blade, leading to fatigue damage. Furthermore, massive flow separations can lead to performance losses for the turbines. Therefore, it is of utmost importance to devise methods to control the unsteady separation on wind turbines and to reduce its impact on the performance and structural integrity of the system.

Dynamic stall on wind turbine blades is initiated by a rapid variation in wind speed and direction. However, no viable methods are available that could reliably predict the occurrence of unsteady separation for wind turbines. Therefore, in the present research, an analytical method has been developed and validated against well-known test cases to quickly and reliably deduce the variations in the sectional angles of attack, based on the variability of wind speed and direction of the oncoming flow. The concept of limiting reduced frequency as a precursor for unsteady separation is proposed in this initial study. Furthermore, it is illustrated, using high-quality wind data, that unsteady separation principally exists near the root regions of turbine blades where thick airfoil sections are generally used.

Further research was conducted to determine the effects of wakes on the occurrence of dynamic stall. For this study, the mean and turbulent wind conditions in the wake were acquired through Large Eddy Simulation of a wind turbine wake performed at the University of Adelaide. The data was used to determine the influence of wakes on the occurrence of dynamic stall on wind turbines operating in the wake of an upstream turbine. It was shown that the primary cause of large unsteady loads on downstream wind turbines is the rapid variation in the wind direction. It is emphasized that the model can be used during wind turbine design phase to determine the regions of the blade where the dynamic stall control is necessary.

After determining the occurrence of dynamic stall on the turbine blades under normal operating conditions, the second objective of the present research was to gain a deeper insight into the dynamic stall process, particularly the lift characteristics of thick airfoils under unsteady separation. Experiments were conducted to understand the non-linear lift behavior of the airfoil during dynamic stall at constant pitch rates. It was shown that the thickening of the boundary layer during pitch-up resulted in an apparent increase in the thickness and camber of the airfoil. It is, furthermore, proposed that the primary dynamic stall vortex also increases the effective camber of the airfoil. This results in the sudden increase in the lift-slope when the vortex is formed. This effect was further demonstrated using numerical simulations of the thick NACA 0021 airfoil at low turbulence levels. During steady-state operation, a long separation bubble on the airfoil surface was found to be responsible for the increased lift-slope, greater than the theoretical maximum, and the abrupt stalling behavior of the foil. It was proposed that this long separation bubble was responsible for an apparent increase in the airfoil's camber. Furthermore, removing the bubble, through an artificial increase in turbulence, degraded the lift-to-drag ratio of the airfoil. However, due to the absence of the bubble, the steady-state stall angle of attack was significantly increased. This study, therefore, illustrated that apparent changes in thickness and camber of the airfoil during dynamic stall process are principally responsible for the non-linear lift behavior.

It was observed, in the experiments, that an increase in the reduced frequency or the Reynolds number resulted in the increase in the strength of the primary dynamic stall vortex. It was also observed that the stall intensity of the airfoil undergoing unsteady separation is also dictated by the primary vortex. Therefore, an increase in the reduced frequency or the Reynolds number resulted in increased stall intensity. Hence, in order to improve the post-stall lift behavior of the airfoil, it is necessary to modify the primary dynamic stall vortex. This can be accomplished by reducing the strength of the vortex and delaying its formation on the airfoil by minimizing the reversed flow accumulation that leads to the formation of the vortex. In order to propose appropriate control methodologies for dynamic stall on wind turbine blades, literature survey illustrated that the required control would need to be implemented passively, near the leading edge of the airfoil. It was, furthermore, observed that the control methodologies need to be deployed before the formation of the dynamic stall vortex in order to affect the post-stall behavior of the foil. Finally, the required control needs to influence the flow field to a large extent to diminish the effects of the vortex. Therefore, three different methods were proposed to control the dynamic stall process. These included streamwise vortices generated using leading edge vortex generators, spanwise-vortices generated using a novel concept of a thin elevated wire affixed at the leading edge, and a cavity on the upper surface of the airfoil. It is demonstrated through experiment that all three methods influence the formation of the dynamic stall vortex during unsteady separation. However, the methods that promoted enhanced mixing, namely the vortex generators and the elevated wire, were observed to favorably reduce the excessive lift associated with the primary vortex structure. It was also observed that the stall intensity was significantly reduced for these methods since the strength of the primary dynamic stall vortex was significantly reduced. It was, furthermore, illustrated that these methods aid in the lift recovery after separation, leading to reduced stall intensity and post-stall load fluctuations. On the other hand, the cavity was observed to consistently delay the unsteady separation. However, the primary vortex structure was not affected to large degree and, therefore, the stall intensity was similar to the baseline airfoil. Out of these three methods, it is proposed that the vortex generators and the novel elevated wire concept can be used to control the process of dynamic stall on wind turbine blades. These methods are not only easier to implement on existing blades, but also improve the steady-state performance of the airfoil through sustained lift and reduced drag, even at high angles of attack.

The research presented in this thesis aims to improve the unsteady stalling conditions of wind turbine blades. This is accomplished by minimizing the primary dynamic stall vortex lift generated during pitch-up and reducing the abrupt lift-decay after separation. The thesis presents a comprehensive review of dynamic stall on wind turbine blades as well as investigates previous attempts in controlling the unsteady separation. The new research conducted in the thesis has been presented in the form of journal manuscripts, arranged in an order that will assist the development of ideas. The research as a whole provides renewed insight into dynamic stall control on wind turbine blades.

DECLARATION

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Contents