ROLE OF FREE STREAM TURBULENCE AND BLADE SURFACE CONDITIONS ON THE AERODYNAMIC PERFORMANCE OF WIND TURBINE BLADES

By

Victor Hugo Maldonado

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Examining Committee:

Luciano Castillo, Thesis Adviser
Charles Meneveau, Member
Zvi Rusak, Member
Deborah Kaminski, Member
Sheppard Salon, Member

Rensselaer Polytechnic Institute
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ABSTRACT

Wind turbines operate within the atmospheric boundary layer (ABL) which gives rise to turbulence among other flow phenomena. There are several factors that contribute to turbulent flow: The operation of wind turbines in two layers of the atmosphere, the surface layer and the mixed layer. These layers often have unstable wind conditions due to the daily heating and cooling of the atmosphere which creates turbulent thermals. In addition, wind turbines often operate in the wake of upstream turbines such as in wind farms; where turbulence generated by the rotor can be compounded if the turbines are not sited properly. Although turbulent flow conditions are known to affect performance, i.e. power output and lifespan of the turbine, the flow mechanisms by which atmospheric turbulence and other external conditions (such as blade debris contamination) adversely impact wind turbines are not known in enough detail to address these issues. The main objectives of the current investigation are thus two-fold: (i) to understand the interaction of the turbulent integral length scales and surface roughness on the blade and its effect on aerodynamic performance, and (ii) to develop and apply flow control (both passive and active) techniques to alleviate some of the adverse fluid dynamics phenomena caused by the atmosphere (i.e. blade contamination) and restore some of the aerodynamic performance loss.

In order to satisfy the objectives of the investigation, a 2-D blade model based on the S809 airfoil for horizontal axis wind turbine (HAWT) applications was manufactured and tested at the Johns Hopkins University Corrsin Stanley Wind Tunnel facility. Additional levels of free stream turbulence with an intensity of 6.14% and integral length scale of about 0.321 m was introduced into the flow via an active grid. The free stream velocity was 10 m/s resulting in a Reynolds number based on blade chord of $Re_c \simeq 2.08x10^5$. Debris contamination on the blade was modeled as surface roughness with a 24-grit abrasive sheet. The role of turbulence and surface roughness on the aerodynamic performance of the wind turbine blade was investigated utilizing the following experimental techniques: (i) static pressure measurements

around the blade, (ii) constant temperature anemometry (CTA) hot-wire and pitot-tube measurements of the velocity deficit at the wake, and (iii) two-dimensional particle image velocimetry (2-D PIV) measurements of the mean global flow. Results indicate that turbulence significantly increases the blade's lift coefficient for moderate to post-stall angles of attack (where the range tested was from zero to 18 degrees). This was accompanied without an increase in the drag coefficient for angles of attack below 14 degrees (prior to stall) and a significant reduction in drag for post-stall angles of attack at 16 and 18 degrees. This resulted in considerable increases to the aerodynamic efficiency of the blade, as quantified by the lift to drag ratio, L/D for all angles of attack except zero degrees. Conversely, surface roughness had a detrimental effect on the aerodynamic performance, as verified by 2-D PIV measurements of the mean flow which indicates that surface roughness promotes flow separation. Vortex generators (which are a form of passive flow control and sometimes utilized in wind turbine blades to mitigate the adverse effects of surface roughness) were demonstrated to be very effective in restoring aerodynamic performance. There was a significant increase in the lift coefficient of the blade (while marginally reducing the drag coefficient) thereby increasing the L/D ratio drastically from 1.076 to 2.791 at 18 degrees angle of attack. Finally, earlier work focused on the feasibility of synthetic jets (active flow control) to improve the aerodynamic and aeroelastic performance of wind turbine blades without free stream turbulence or surface roughness. Wind turbine models (including S809 airfoil-based) demonstrated a re-attachment of the flow for a small range of post-stall angles of attack. This effect resulted in a manipulation of the aerodynamic forces (i.e. increases in the maximum lift coefficient and stall angle of attack) and also a reduction in the amplitude of blade structural vibration at the natural frequency.