The 2013 World Congress on
Advances in Nano, Biomechanics, Robotics, and Energy Research (ANBRE13)
Seoul, Korea, August 25-28, 2013

On the Use of Rotating Leading Edge Devices in Wind Turbine Blades for Increased Power Production and Vibration Reduction

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ABSTRACT

An efficient computational tool based on combined blade element-momentum (BEM) methodology is used for studying the aerodynamics and performance characteristics of horizontal axis wind turbines. Comparisons have been done in the past against measurements for the radial variation of chordwise and normal force coefficients, and the power production. The blade element-momentum theory is employed to assess the use of a rotating leading edge as a circulation control device. Previously published 2-D calculations for airfoils with a rotating cylinder are used to generate the airfoil lift and drag characteristics of the airfoil as a function of angle of attack, leading edge cylinder radius, and the device angular velocity. It is found that the rotating device greatly increases maximum lift coefficient, stall angle of attack, and the lift to drag ratio. The 2-D data are used in the 3-D BEM analysis to compute the integrated loads (torque, power) with and without the rotating device. It is observed that power production may be significantly enhanced. Because of its ability to delay stall, this device also has the potential for reducing vibratory airloads.

1. INTRODUCTION

Wind is one of the cleanest forms of energy resources available to humankind. Unlike other methods of energy production that require fossil fuel or nuclear fission material, with abundant water supply for cooling purposes, wind energy only requires 7 m/sec to 15 m/sec winds to produce significant amounts of useful power. Wind turbines have a very small footprint and may be placed on farms or fields without impacting their operations. Because wind turbine availability and reliability is approaching 90% or more, operating and maintenance costs are also reasonably low.

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Wind turbines employ laminar airfoils that have high lift/drag ratio over a broad range of wind angles of attack. This allows for efficient power production. However, there may be situations where the local wind velocity exceeds the wind speeds over which the blade is designed to operate. This would lead to increased local angles of attack that exceed stall limit, causing the blade section to lose power. In other situations, the wind velocities may be high enough to cause structural damage. To avoid these two scenarios (blade stall, extreme wind loads), large-scale wind turbines are designed to operate with a variable pitch control that reduces the blade section angles of attack to avoid stall. Pitch control is also used to set the blades at a pitch that will result in the lowest possible airloads, minimizing the extreme wind loads.

Pitch control, yaw control and, in some cases, RPM control, are common ways of extracting maximum power from a wind turbine and alleviating extreme wind loads. Pitch control requires individual motors for each blade, while the yaw control rotates the entire nacelle housing the generator and the blade system to face the wind. These control systems are costly to implement and maintain, and cannot be justified for small wind turbines.

Various forms of individual blade control and system control have been explored (Barlas 2007; Berg 2007; Johnson 2008) for enhanced power production. These include aeroelastically tailored blades (Lobitz, 2001), variable diameter rotor (DOE 2005), trailing edge devices that include flaps, Gurney flaps, and microtabs (Chow 2007; Migliore 1995; Miller 1995 and 1998; Standish 2005; Tongchitpakdee 2006; van Dam 2007), vortex generators (Lin 2002), blowing and suction including synthetic jets and circulation control (Englar 2000; Liu 2004; Tongchitpakdee 2006), plasma control (Moreau 2007; Post 2004; Santhanakrishnan 2005), flexible and morphing surfaces (Basualdo 2005; Magla 2004), higher harmonic control (Yu et al., 1997, 2000), and individual pitch control (Larsen 2004).

One concept that has not received widespread attention is rotating leading edge devices. These are small circular cylinders placed in the leading edge of a rotor blade section and rotated at a fixed RPM. If the cylinder is not rotating, the blade section behaves like the baseline shape. If the blade section is rotating, the motion of the solid surface allows the boundary layer to negotiate the adverse pressure gradient near the leading edge, alleviating static stall (Alvarez-Calderon, 1961; Cinchy 1972; Cook 1974; Johnson 1975). An excellent set of flow visualization data demonstrating the usefulness of this device are presented by Al-Garni et al. (2000), and a sketch of the device used is shown in Figure 1. This device thus has the potential of reducing the stall encountered by wind turbines when locally high angles of attack are caused by high winds, or atmospheric turbulence.

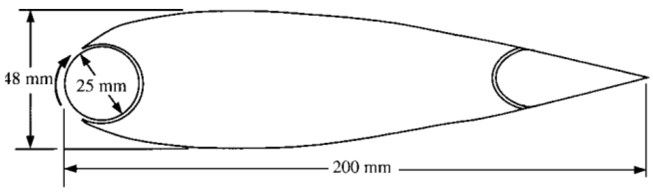


Figure 1 Sketch of a NACA 0024 Airfoil with a Leading Edge Device (Al-Garni, 2000)

The present authors conducted one of the first 2-D Navier-Stokes analyses of this concept (Hassan et al., 1992). It was found that stall was postponed. Because flow over the airfoil was attached, pressure drag was also reduced. If the device was not smoothly interfaced with the airfoil, a small step jump in the surface contour would occur, which was found to trip the boundary layer and increasing the drag relative to the baseline airfoil. Several other authors have subsequently numerically studied the aerodynamic behavior of such devices in isolation and in wind turbines (e.g. Zhuang, 2012) and demonstrated that these devices have the potential for enhanced power production.

2. NUMERICAL APPROACH

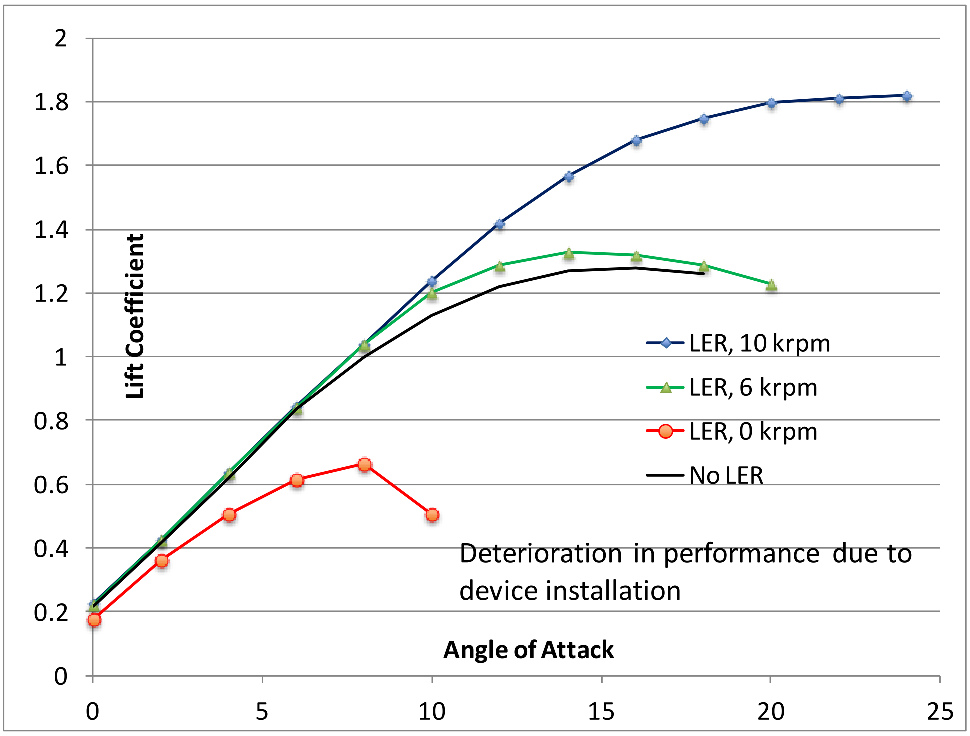
In an effort to assess the benefits of rotating leading edge devices on wind turbines, a 10 m diameter two bladed wind turbine called the NREL Phase VI rotor has been considered. This rotor was designed by Giguère et al. (1999). A wealth of experimental data including surface pressure distributions at selected radial locations and associated sectional normal and tangential forces are available for this rotor (Fingersh et al., 2001; Hand et al., 2001; Simms et al., 2001) for a broad range of wind conditions. The present authors (Xu, 2002; Tongchitpakdee, 2006) have modeled this rotor using a hybrid Navier-Stokes / free wake methodology and obtained very good agreement with the test data.

In the present study, since the rotating leading edge devices are expected to maintain attached flow over a broad range of wind speeds, a computationally less expensive approach based on blade element-momentum theory is used. The analysis, coded in Matlab as a classroom exercise for a wind energy course at the authors' institution, is based on the well-known NREL analysis YawDyn (Moriarty et al., 2005). In this approach, the blade is divided into a number of elements. At each such element, the induced velocity and swirl velocity are computed using combined blade element-momentum theory. The rotational velocity, wind velocity, normal induced velocity, and the tangential swirl velocity are combined into a total velocity vector. A table-look up procedure is used to compute the resulting airloads. Since the airloads affect the induced velocity and swirl, and vice versa, an iterative procedure is needed. The iterative process quickly and reliably converges. Once the sectional forces have converged, they are numerically integrated to obtain torque, sectional bending moments, thrust, and other quantities of interest.

In order to assess the effects of rotating devices, it is first necessary to generate the lift and drag characteristics of the airfoil equipped with the rotating cylinder, for various angular velocities. This may be done experimentally or numerically (e.g. Hassan, 1992; Zhuang, 2012). For the present application, digitized data extracted from the recent studies of Zhuang et al. (2012) with a state of the art solver were used.

Figure 2 shows the variation of lift and drag coefficients with angle of attack. When no leading edge rotation is present, the geometric irregularities associated with the placement of the device in the leading edge region cause the airfoil to stall quickly at an angle of attack around 8 degrees. The clean airfoil without the device has a high maximum lift coefficient of 1.28 and did not stall until 16 degrees of angle of attack. The leading edge device, in the absence of rotation also has a higher drag compared to the baseline airfoil. Thus, it appears that the use of rotating leading edge devices, in the absence of rotation, would be detrimental to the performance of an otherwise well behaved airfoil, unless they are carefully integrated into the airfoil surface.

As the angular velocity of the leading edge increases, lift quickly recovers. At an RPM of 10000, the maximum lift coefficient is as high as 1.8. As may be expected, at low angles of attack, the rotating device does not provide any incremental lift and the airfoil behaves like a conventional airfoil. An examination of the drag coefficient as a function of alpha indicates that the rotating device also reduces the drag significantly, particularly at high angles of attack when the baseline airfoil experiences separated flow and stall.



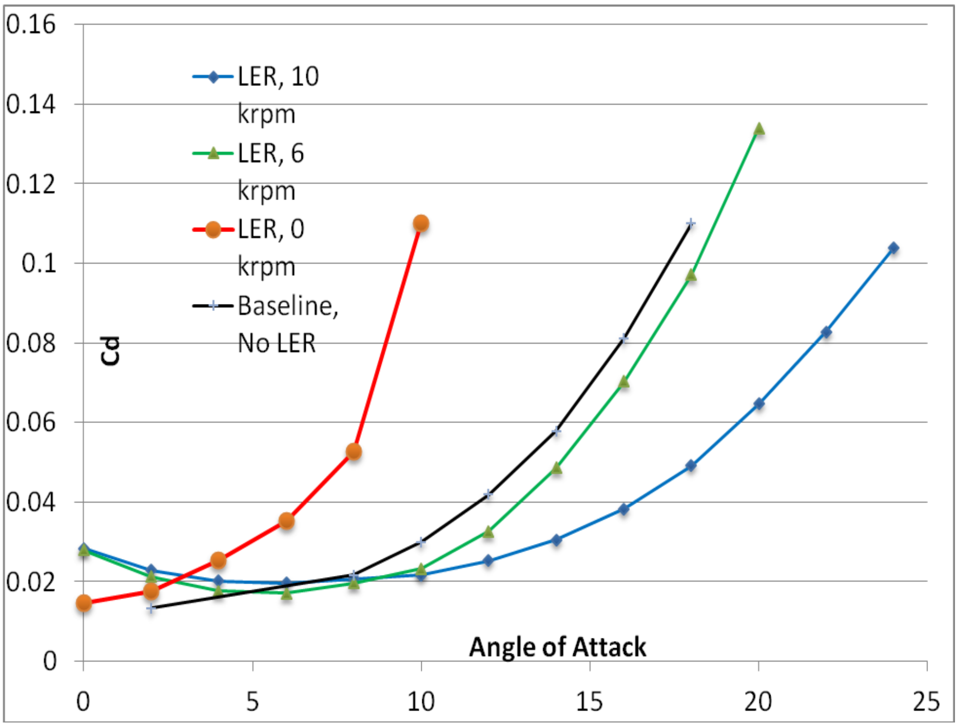


Figure 2 Variation of Lift and Drag Coefficient with Angle of Attack as a Function of Device Angular Velocity (Digitized Data from Zhuang, 2012)

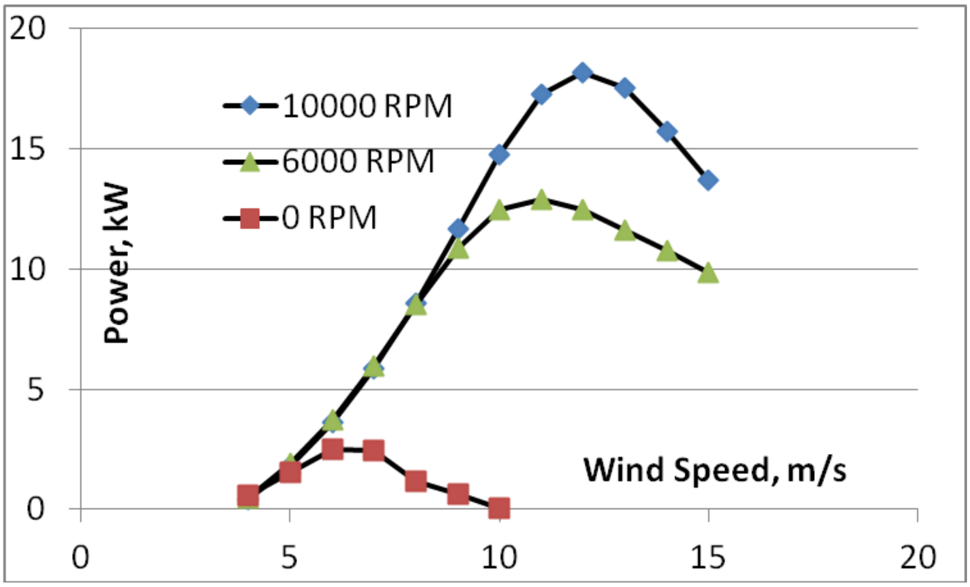


Figure 3. Predicted Effects of Leading Edge Rotation on Power Production

Figure 3 shows the effects of leading edge rotation on power production. The baseline rotor with no leading edge devices employed a low drag airfoil named S 809. At a blade rotational RPM of 72, experimental data and our numerical studies indicate that the power production peaks around 10 KW and the rotor stalls at higher wind speeds. When the leading edge device is installed, power production first suffers because the airfoil with the rotating device has poor L/D characteristics when the device is not spinning. When the device RPM is increased the rotor is able to produce a peak power of 17 kW. This peak power is well in excess of the baseline Phase VI rotor.

The ability of the rotor to operate at high wind speeds, and local sectional angles of attack also means that this concept will mitigate and even alleviate the large vibratory loads that invariably arise when the rotor is stalled.

3. CONCLUSIONS

Combined blade element-moment theory has been used to explore the power generation of horizontal axis wind turbines. A baseline NREL Phase VI rotor was modified by replacing the low drag S809 airfoils with an airfoil equipped with a rotating leading edge device. When the RPM of the rotating device is sufficiently high, stall was postponed at wind velocities where the baseline rotor would normally stall and exhibit vibratory loads. The airfoil sections exhibited higher lift and lower drag and generated higher power.

Additional studies are underway at this writing to assess the behavior of the rotor under yaw conditions, and on the use of segmented rotating devices along the span to provide localized flow control.

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