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Aerodynamics of Leading-Edge Protection Tapes for Wind Turbine Blades

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1 Introduction

One of the primary sources of blade damage is erosion of the blade surface at the leading edge from the impact of particles such as sand, rail, or hail over time [1]. High rotational speeds and a high impact count make the leading edge in the blade tip region the most susceptible to severe damage [2]. Beside posing structural concerns [1], leading-edge erosion notably increases sectional profile drag as much as 500%, which results in Annual Energy Production (AEP) losses of up to 25% for utility-scale wind turbines [3]. To avoid these losses and protect the blades, leading-edge protection (LEP) tapes have so far proven to be a reliable and affordable solution. Standard LEP tapes on the market today are made from a polyurethane-based material and are of constant 350 µm thickness for sufficient erosion protection [4]. There are still losses associated with standard LEP tape application due to the backward-facing step at the tape edge, which transitions the boundary layer. Depending on the tape, blade geometry, and wind turbine operating conditions, drag increases anywhere from 8% to 15%, resulting in a 0.45% AEP loss for standard LEP tapes [3].

The aerodynamics of the backward-facing step of an LEP tape is not a well-studied phenomenon on utility-scale wind turbines. To investigate and reduce the aerodynamic impact of LEP tape on wind turbine performance, numerical models are developed to estimate the effect of both standard and new tape designs on cl and cd of a NACA 64-618 airfoil – a representative wind turbine tip section airfoil – at Re = 3×10^6. Down-selected designs are experimentally verified in a wind tunnel on a full-chord tip section of a utility-scale wind turbine blade. A wind turbine design and analysis code, XTurb [5], is used to predict the power output of a representative utility-scale 1.5 MW wind turbine for the tape designs of interest to verify whether the proposed tape design reduces AEP losses compared to standard tapes currently in production.

2 Numerical Analysis

Combining boundary-layer theory and the need for erosion protection, the proposed new tape design is a tapered profile that is thick in the middle and thin at the edges, reducing the height of the backward-facing step, T_{edge} in Figure 1.

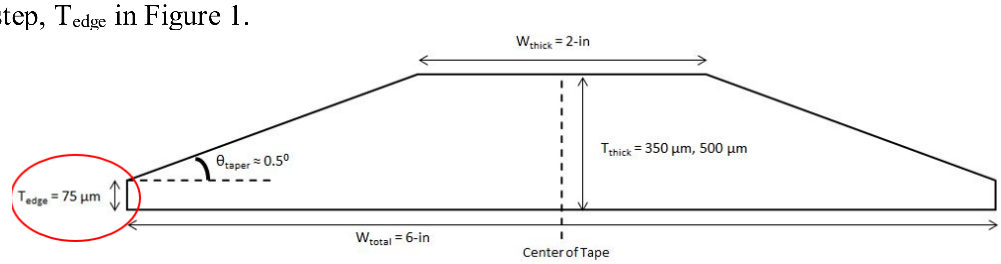

Figure 1 Schematic of a proposed tapered LEP tape design (*not to scale)

Performance of an airfoil with LEP tape applied is numerically estimated using Computational Fluid Dynamics. The flow field around a NACA 64-618 airfoil with LEP tape applied is computed in STAR-CCM+ using the 2-D, incompressible Reynolds-Averaged Navier Stokes equations. The two-equation k-ω SST turbulence model and the modified Gamma transition model are applied for all simulations. Two-dimensional c_l and c_d are computed for each tape configuration at Re = $3x10^6$ and for $\alpha = -2^\circ$ to 8° (the operational angle of attack range for a tip-section airfoil). Each tape configuration is compared to the clean airfoil to determine relative performance changes.

Numerical simulations show distinct boundary-layer transition at the backward-facing step for standard tapes due to high local pressure gradients, Figure 2 (left). Forward movement of the transition point by the standard LEP tape resulted in Δc_d = 40% - 90% across the operating range. By tapering the LEP tape, the adverse pressure gradient at the tape step is significantly reduced and boundary-layer transition occurs at x/c = 45%, Figure 2 (right). By moving the transition point downstream, Δc_d = 0% - 20%, notably reducing aerodynamic losses.

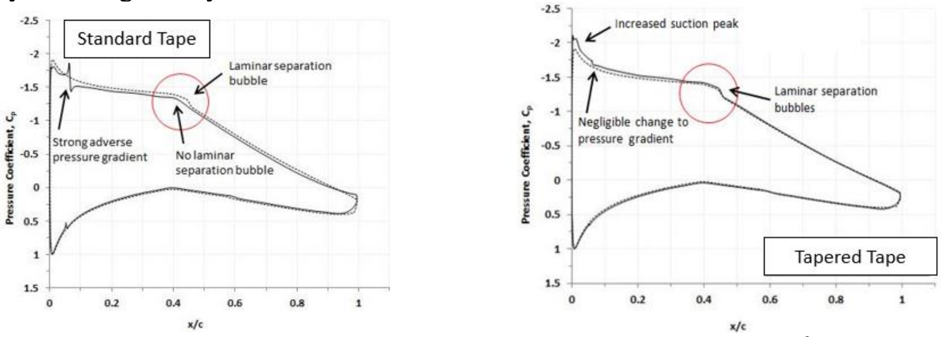

Figure 2 c_p distribution over the NACA 64-618 airfoil at Re = $3x10^6$ and $\alpha = 6^\circ$.

3 Experimental Validation

Numerical results are verified with experiments conducted in the Pennsylvania State University Low-Speed, Low-Turbulence wind tunnel. Standard and prototype tapered LEP tapes were applied to a full-scale chord tip section of a wind turbine blade. Drag coefficients are measured at Re = $3x10^6$ and $\alpha = 0^\circ$ using a wake probe. Results are compared the clean blade to verify CFD estimates of Δc_d.

Experiments indicate that, at $\alpha = 0^\circ$, the change in drag coefficient notably improves for tapered LEP tapes, compared to the drag coefficient increase observed for standard tapes. Oil visualization of the flow over the blade also verifies CFD predictions that standard tapes move the boundary-layer transition forward to the tape edge. For tapered LEP tapes, where cleanly applied, oil visualization shows that the boundary layer remains undisturbed by the backward-facing step.

4 Conclusions

By reducing the backward-facing step height of an LEP tape below some critical value, above which the boundary layer transition point moves upstream to the tape edge, CFD and experimental data indicate that the aerodynamic impact of an LEP tape can be notably reduced. Performance of a 1.5 MW wind turbine with LEP tape applied to the outboard 40% of the rotor is estimated using CFD aerodynamic data as an input to XTurb [5]. AEP losses are on the order of 5% for a standard tape. XTurb estimates that AEP losses are nearly eliminated for a tapered LEP tape, indicating that it is possible to design an LEP tape that reduces the aerodynamic losses on wind turbines.

Bibliography

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