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Effects of Leading-Edge Protection Tape on Wind Turbine Blade Performance

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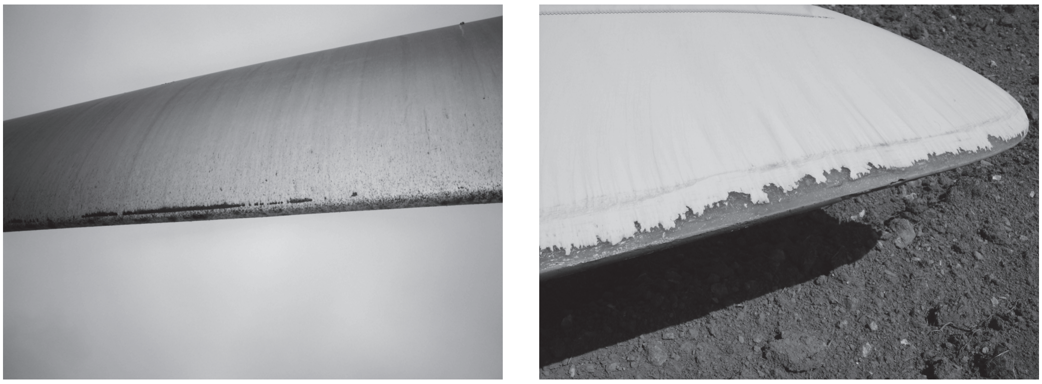
ABSTRACT
This paper presents results of a study to investigate the impact of using wind protection tape (WPT) to protect the leading edge of wind turbine airfoils from erosion. The tests were conducted on the DU 96-W-180 wind turbine airfoil at three Reynolds numbers between 1 and 1.85 million and angles of attack spanning the low drag range of the airfoil. Tests were run by varying the chordwise extent of the wind protection tape on the upper and lower surface in order to determine the relative impact of each configuration on the aerodynamics of the airfoil. The objective was to assess the performance losses due to the wind protection tape and compare them with losses due to leading-edge erosion in order to determine the potential benefits of using such tape to protect wind turbine blades. Results showed that the application of wind protection tape caused a drag increase of 5–15% for the various configurations tested and was significantly less detrimental to airfoil performance than leading edge erosion that could otherwise occur.

NOMENCLATURE

c	Airfoil chord
C_d	Drag coefficient
C_l	Lift coefficient
C_m	Moment coefficient
Re	Reynolds number
x/c	Normalized chordwise location
α	Angle of attack

1. INTRODUCTION
Wind turbine blades are exposed to myraid abrasive airborne particles and precipitation in a variety of forms that over the course of a few years can erode their surfaces, particularly at the leading edge. With time, these airborne particles can cause significant blade erosion damage that reduces aerodynamic performance and hence energy capture. Moreover, in some environments, insect debris and other airborne particles can accrete on the leading edges of wind turbine blades. Leading-edge blade erosion and debris accretion and contamination can dramatically

reduce blade performance particularly in the high-speed rotor tip region that is crucial to optimum blade performance and energy capture [1–5]. As an example, Fig. 1 shows the extent of damage that leading-edge erosion can cause on wind turbine blades in service. Figure 1(a) shows a blade with pits and gouges near the leading edge while Fig. 1(b) shows a blade with delamination over the entire leading edge.



(a) (b)

Figure 1. Photographs of wind turbine blades affected by leading-edge erosion with (a) pits and gouges, and (b) leading edge delamination (courtesy of 3M).

An earlier study by Sareen, et al. [6] examined the detrimental effect of leading-edge erosion that motivates the need for erosion mitigation strategies. It was shown that leading-edge erosion, even in small amounts, can be extremely detrimental to airfoil performance. Results from the study revealed that erosion can readily cause an 80–500% increase in drag, coupled with a significant reduction in lift. The losses in annual energy production due to the detrimental effect of erosion can be as high as ≈25% for multi-megawatt-class variable-speed wind turbines.

Among various methods to mitigate erosion, the application of protective tape is a relatively low-cost method of protecting the blades from leading-edge erosion. In determining the optimum protective-tape configuration, there are many tradeoffs to consider. Key factors include the tape thickness, edge finish, chordwise extent on upper and lower surfaces, radial coverage, and airfoil shape change along the blade. Best application practice must also consider the environmental factors such as density and distribution of airborne particles together with the average wind speed and wind speed distribution for the particular site. Finally, the physical size of the rotor and physical speed of the blade are the ultimate factors to consider in optimizing tape configurations or otherwise determining the degree of damage and performance degradation that would accrue without protection. While there are many factors to consider as enumerated, there are specific wind turbine sizes produced in great number and optimized for specific average wind conditions, which are the focus of the research.

The objective of this study was to test different configurations of wind protection tape applied to the leading edge of an airfoil by varying the chordwise extent of the tape. The goal was to develop a baseline understanding of the aerodynamic effects of the wind protection tape and to compare the results with an earlier study on airfoils with leading-edge erosion. The relative impact of the wind protection tape and leading-edge erosion on airfoil performance could be used to examine the feasibility of using such tape and to optimize it for application on wind turbine blades by making modifications to the size, geometry and placement.

2. APPROACH AND EXPERIMENTAL METHODS

2.1. Wind Tunnel Facility

Testing was conducted in the UIUC low-turbulence subsonic wind tunnel shown schematically in Fig. 2. The wind tunnel is an open-return type with a 7.5:1 contraction ratio. The rectangular test section is 0.85 × 1.22 m (2.8 × 4.0 ft) in cross section and 2.44-m (8-ft) long. Over the length of the test section, the width increases by approximately 1.27 cm (0.5 in) to account for boundary-layer growth along the wind tunnel side walls. Test-section speeds are variable up to 71.53 m/s (160 mph) via a 93.25-kW (125-hp) alternating-current electric motor driving a five-bladed fan. The tunnel settling chamber contains a 10.16-cm (4-in) thick honeycomb and four anti-turbulence screens. The maximum Reynolds number that can be reached is 4.92 million/m (1.5 million/ft).

The airspeed and dynamic pressure in the test section were determined by static pressure measurements in the wind tunnel contraction. Ambient pressure was measured with an absolute pressure transducer. Ambient temperature was measured with a thermocouple. The axial force, normal force and pitching moment of the airfoil were measured using a three-component external force and moment balance mounted underneath the test section. The model was mounted with the spanwise axis in the vertical direction.

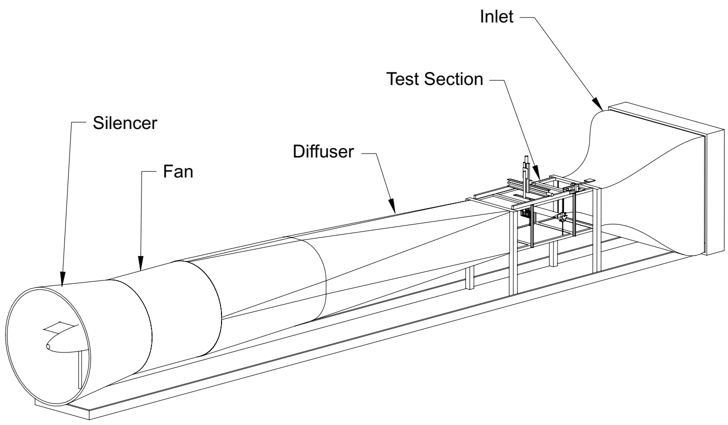


Figure 2. Schematic of the UIUC low-turbulence subsonic wind tunnel.

Lift and drag were calculated from the normal and axial forces, but a more accurate drag value was determined from wake rake measurements. The rake contained 59 total pressure probes over a total width of 24.77 cm (9.75 in). Seven probes on each of the outer sides of the rake were spaced 6.86-mm (0.27-in) apart, and the remaining inner 45 probes were spaced 3.43-mm (0.135-in) apart. The wake rake was positioned one chord length downstream of the airfoil trailing edge. Eight spanwise wake profiles were measured for each angle of attack starting 10.16-cm (4-in) above and ending 7.62-cm (3-in) below center span, and the resulting local drag values were averaged. The wake rake drag measurements are reported in this paper. All measurements were corrected for wind tunnel effects and validated by comparing data taken for an S809 airfoil model with data taken at Delft and The Ohio State University [1].

2.2. Airfoil Model

With wind turbines being the primary application for the wind protection tape in this particular study, the DU 96-W-180 airfoil was chosen for the tests. The DU 96-W-180 is an 18%-thick airfoil designed at Delft University [7]. It was designed to be used at the 75% blade station. In addition to being used on wind turbines in operation, it is actively used in wind energy research and found in the literature [7–9]. The airfoil model had a span of 0.85 m (33.5 in) with a 0.46-m (18-in) chord.

In order to determine the accuracy of the wind-tunnel model, it was digitized using a Brown & Sharpe coordinate measuring machine (CMM) to determine the actual airfoil shape. Approximately 80 points were taken around the airfoil model at the midspan position. The point spacing was more or less proportional to the local curvature. Figure 3 shows the true airfoil as designed (solid line) compared with the actual digitized airfoil (dotted line). The two different line types are hardly discernible because the lines nearly coincide. The model accuracy plot depicts the differences between the true airfoil and actual airfoil coordinates for the upper surface (solid line) and lower surface (dotted line) of the airfoil. A displacement above or below the axis indicates that the digitized model surface lies above or below the true airfoil, respectively. In this case, the actual model was for the most part slightly thicker than the true airfoil, and the average error was 0.089 mm (0.0035 in).

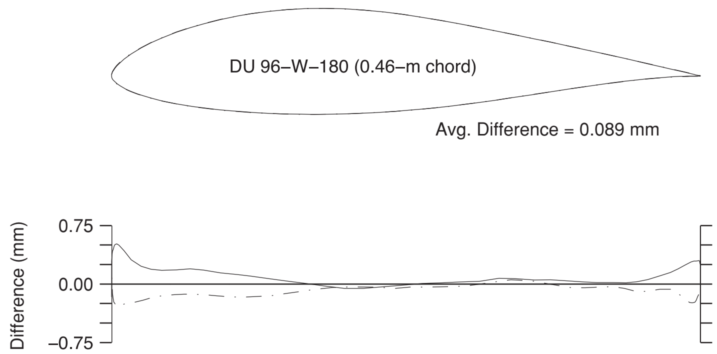


Figure 3. Comparison of the true DU 96-W-180 airfoil and the digitized wind tunnel model.

2.3. Wind Protection Tape

The wind protection tape that was used in these experiments is manufactured by the 3M Renewable Energy Division. 3M produces a polyurethane wind protection tape (WPT) that is 20-cm (7.8-in) wide by 0.36-mm (0.014-in) thick. This tape is used in the wind turbine industry across a spectrum of wind turbine sizes. Since the tape thickness scales with the wind turbine blade chord, the tape used for the tests was a scaled-down variant that was 0.09-mm (0.0035-in) thick. The scaling factor was calculated by assuming a full-scale chord of 1.83 m (6 ft).

2.4. Test Plan

Testing of the wind protection tape was done by varying the chordwise extent on the upper and lower surface at three Reynolds numbers: *Re* = 1,000,000, 1,500,000 and 1,850,000. The first set of tests were run with the tape wrapped around the leading edge of the airfoil, ending on the lower surface at *x/c* = 10% and ending on the upper surface at three different locations: *x/c* =10%, 20%, and 30%. The tests were then repeated with the tape ending at *x/c* = 20% on the lower surface and the same three locations on the upper surface. Figure 4 shows a graphical representation of the case with tape ending at *x/c* = 20% on the lower surface and *x/c* = 30% on the upper surface.

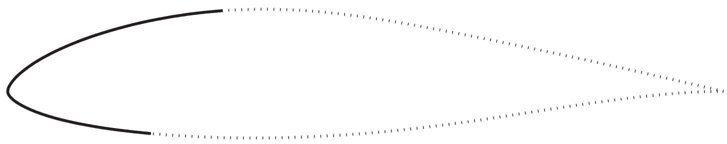


Figure 4. Position of the wind protection tape (bold line) on the DU 96-W-180 airfoil ending at x/c = 30% on the upper surface and x/c = 20% on the lower surface.

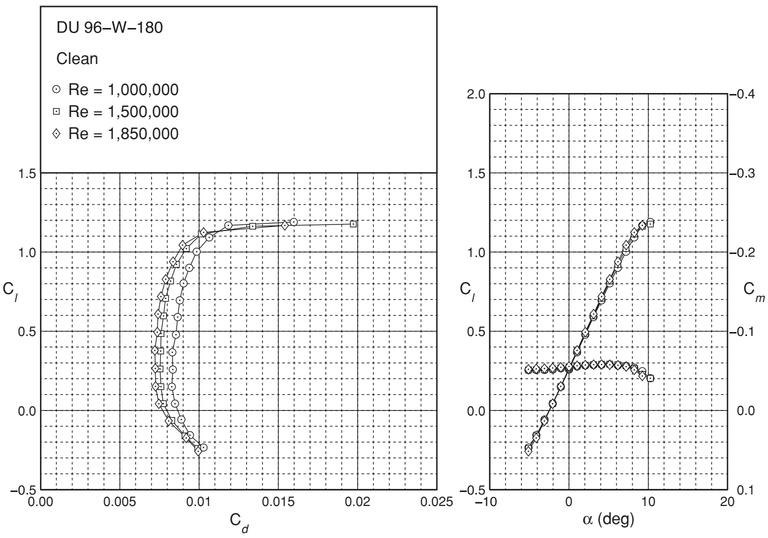


Figure 5. Drag polars for the clean DU 96-W-180 at the three Reynolds numbers.

3. RESULTS AND DISCUSSION

This section discusses results of the wind protection tape tests on the DU 96-W-180 airfoil. Drag polars, lift curves, and pitching-moment data for the different cases along with the percentage increase in drag for each case are shown.

3.1. Clean Airfoil

Before testing the DU 96-W-180 airfoil with leading-edge erosion, a baseline needed to be determined against which the effect of the leading-edge erosion would be compared. Figure 5 shows the performance of the clean DU 96-W-180 airfoil for the three Reynolds numbers. This dataset provided the baseline used to measure the effect of leading-edge erosion on the airfoil performance.

3.2. Wind Protection Tape

After testing the clean airfoil to obtain the baseline, the DU 96-W-180 airfoil was tested with the wind protection tape applied to the leading edge based on the previously discussed test plan. Figures 6–11 show the drag polars, lift curves and quarter-chord pitching moment coefficients for the various tape configurations tested at the three Reynolds numbers. The figures also show the percentage increase in drag due to the wind protection tape for the different cases. The ΔC_d values as a function of the lift coefficient were calculated by using the clean airfoil as the baseline.

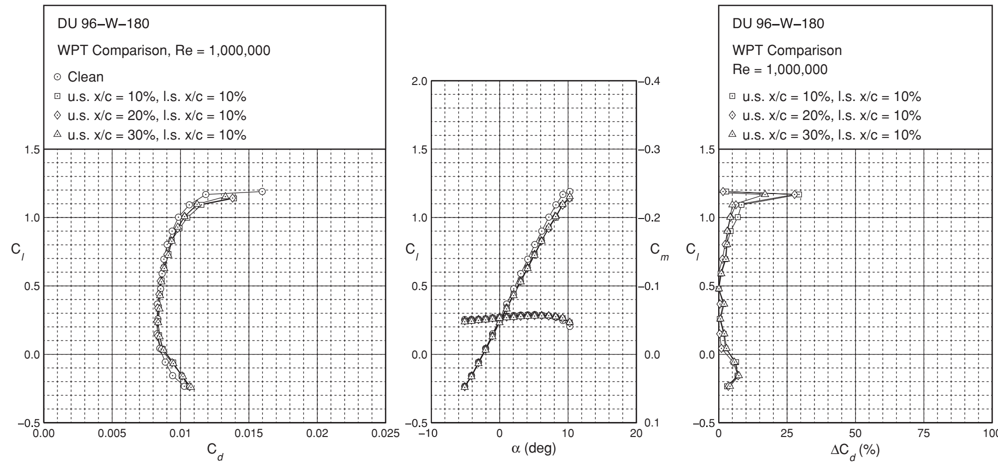


Figure 6. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 10% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,000,000.

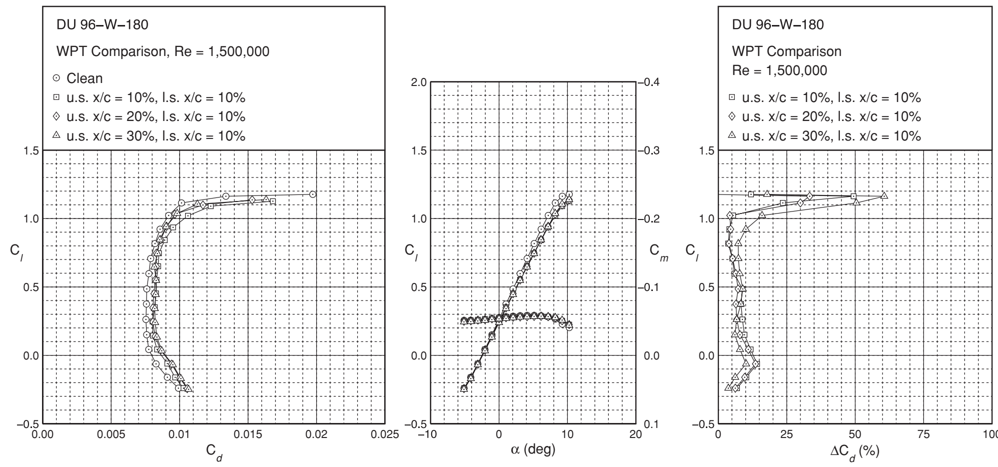


Figure 7. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 10% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,500,000.

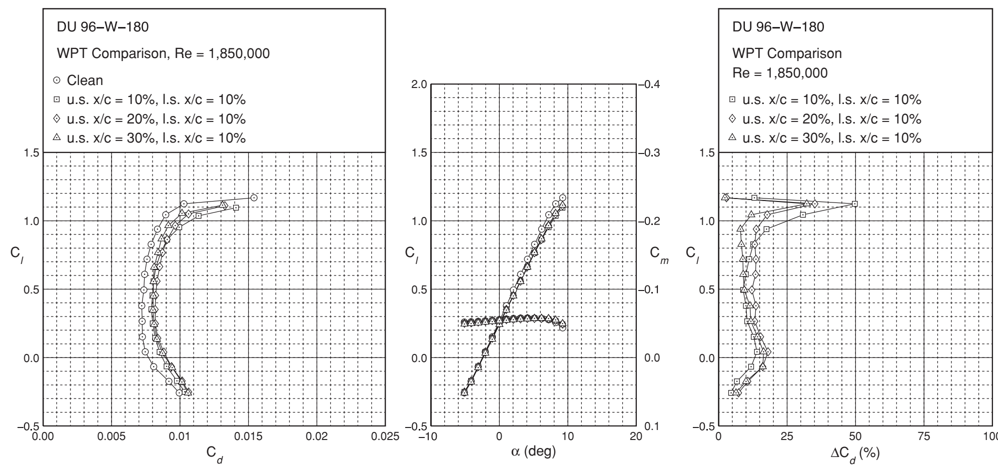


Figure 8. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 10% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,850,000.

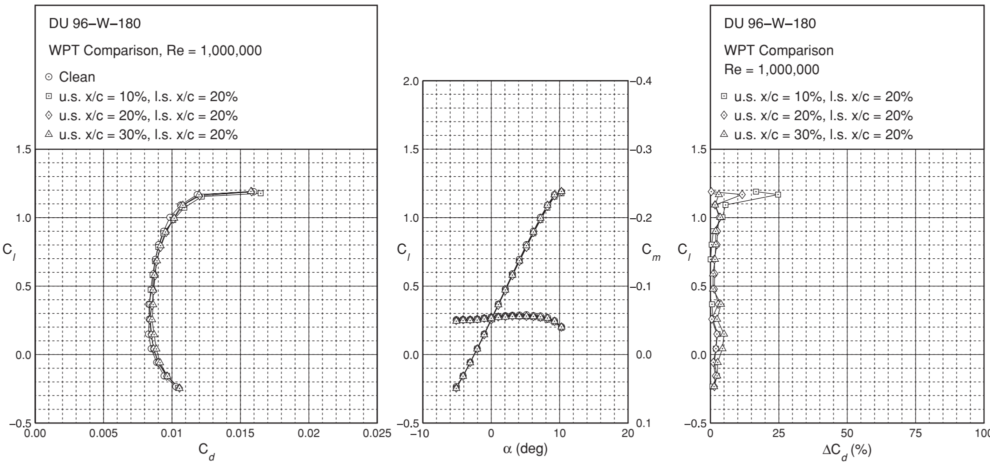


Figure 9. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 20% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,000,000.

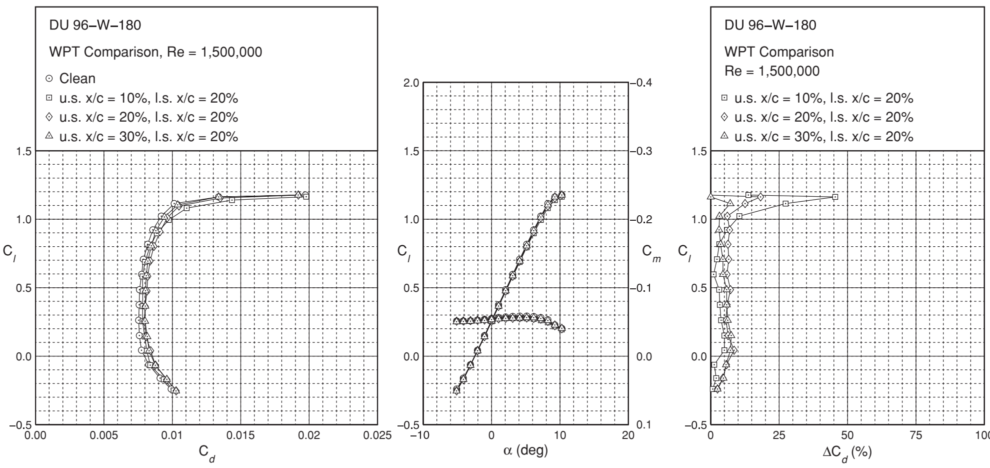


Figure 10. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 20% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,500,000.

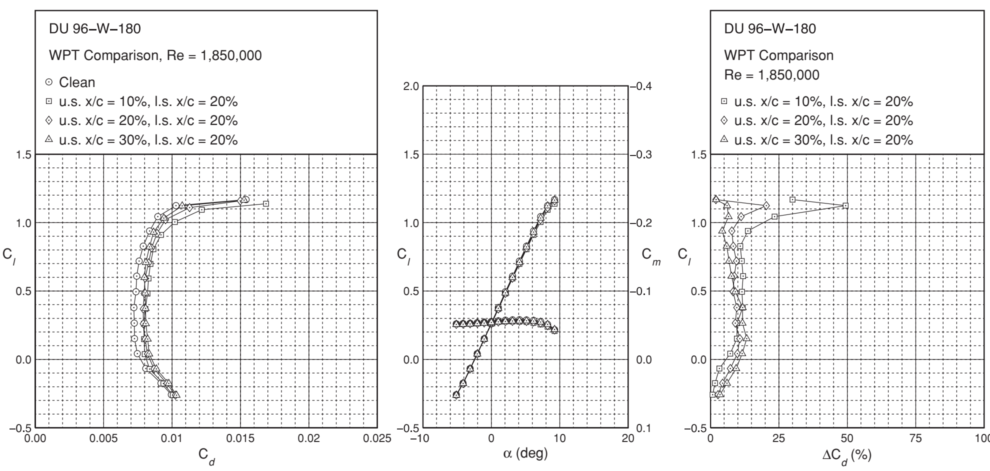


Figure 11. Effect of wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 20% on the lower surface on the performance of the DU 96-W-180 airfoil and the resulting percentage increase in drag at Re = 1,850,000.

Table 1: Effect of Leading-Edge Protection Tape on the DU 96-W-180 Airfoil Performance

Configuration (upper / lower)	ΔC_d	ΔC_l
10% / 10%	+15%	–0.03
20% / 10%	+12%	–0.02
30% / 10%	+6%	–0.01
10% / 20%	+13%	–0.03
20% / 20%	+8%	–0.02
30% / 20%	+5%	–0.00

Table 2: Effect of Leading-Edge Protection Tape on the Annual Energy Production of a Wind Turbine as Estimated by PROPID

Avg Wind Speed (m/s)	AEP Loss (MWh/yr)	AEP Loss (%)
7.05	36	–0.45%
7.93	37	–0.38%
8.81	36	–0.32%

Figures 6–8 show results for the airfoil with wind protection tape ending at x/c = 10%, 20%, and 30% on the upper surface and 10% on the lower surface. The plots show a small increase in drag due to the tape, which can be primarily attributed to early flow transition due to the backward facing step of the film. The closer the edge of the tape is to the leading edge, the greater the turbulent flow over the airfoil, and hence, the greater the drag.

Figures 9–11 show results for the airfoil with tape ending at the same locations on the upper surface but at x/c = 20% on the lower surface. The plots show similar trends, with the degradation in performance increasing progressively as the tape on the upper surface ends closer to the leading edge. The magnitude of the drag increase, however, is reduced because the tape on the lower surface extends further back from the leading edge.

Table 1 summarizes the effects of the wind protection tape on the performance of the DU 96-W-180 airfoil. The table lists the percentage increase in drag and the decrement in lift coefficient for the different wind protection tape configurations tested. These losses correspond to a typical variable-speed wind turbine operating condition, i.e. near the clean $C_l / C_{d\ max}$ operating point. Table 2 shows the predicted loss in annual energy production (AEP) for the case with the tape ending at x/c = 20% on both the upper and lower surfaces. The data is based on an analysis carried out to estimate the potential loss in performance for a wind turbine with similar wind protection tape on its blades. The design and analysis was done using the wind turbine design code PROPID [10]. The wind turbine was modeled on a 2.5-MW class turbine and analyzed in clean and protected conditions to estimate the loss in AEP due to the wind protection tape. The degradation in airfoil performance was applied along the entire blade, but the majority of the AEP loss shown in the the table primarily derives from the outer part of the blade.

The tabulated data shows that the measured loss in performance ranges from a 5–15% increase in drag (Table 1) depending on the extent of the tape on the upper and lower surface. The data also shows that the increase in drag is coupled with a small loss in the lift coefficient. The estimated annual energy loss (Table 2) reveals that tape ending at x/c = 20% on the upper and lower surfaces would result in a loss of ≈0.3–0.5%. Annual energy losses of this magnitude would be small in comparison with losses due to leading-edge erosion that can grow significantly over time and approach ≈25% as shown by the previous study [6].

4. CONCLUSION

The DU 96-W-180 airfoil was tested with various extents of leading-edge protection tape on the upper and lower surfaces. Results revealed that while the tape can cause a small-to-moderate increase in drag depending on the extent on the upper and lower surfaces, the effect of the tape on airfoil performance is far less detrimental than leading-edge erosion that could otherwise occur. For a typical operating point near $C_l / C_{d\,max}$, data from the tests showed a drag increase of 5–15% due to the wind protection tape. This increase in drag can be attributed to an early transition from laminar-to-turbulent flow caused by the aft edge of the tape. The tape did not have a significant effect on the lift coefficient of the airfoil. Based on the analysis performed using PROPID, it was estimated that an 8% increase in drag, which was caused by the tape ending x/c = 20% on both the upper and lower surfaces of the airfoil, would result in a 0.38% loss in annual energy production at an average wind speed of 7.93 m/s (17.74 mph). This energy loss is significantly less than the estimated losses due to even light leading-edge erosion. When compared with previous estimates for many of the moderate-to-heavy erosion cases, the performance loss due to the tape is insignificant. Furthermore, the degradation in performance due to the tape can be minimized by extending it further back from the leading edge and possibly integrating it with the blade (during manufacture) to eliminate the backward facing step otherwise created at the tape aft edge.

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