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TURBINE BLADE EROSION AND THE USE OF WIND PROTECTION TAPE

BY

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THESIS

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Abstract

The aerodynamic performance of wind turbine airfoils with leading edge erosion was investigated in this research. The tests were conducted on 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. The airfoil was tested with simulated leading edge erosion by varying the type and severity of the erosion to determine the loss in performance for the different cases. As a method of leading edge protection of wind turbine blades, the impact of an experimental wind protection tape on the aerodynamic performance of the DU 96-W-180 airfoil was also investigated. The tape was wrapped around the leading edge of the airfoil with different chordwise extents on the upper and lower surfaces. For the taped airfoil cases, the tests were carried out at the same three Reynolds numbers between 1 and 1.85 million, as used for the erosion models. The ultimate aim was to make a comparison between the performance losses due to the use of the WPT and due to leading edge erosion in order to determine the feasibility of using the tape for practical purposes.
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<td>wind tunnel inlet settling section area</td>
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<td>$b$</td>
<td>model span</td>
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<td>airfoil chord</td>
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<td>$C_d$</td>
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<td>$C_{m}$</td>
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<tr>
<td>$C_p$</td>
<td>pressure coefficient</td>
</tr>
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<td>$C_{d,u}$</td>
<td>uncorrected drag coefficient</td>
</tr>
<tr>
<td>$D$</td>
<td>drag</td>
</tr>
<tr>
<td>$D'$</td>
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<tr>
<td>$F_A$</td>
<td>axial force</td>
</tr>
<tr>
<td>$F_N$</td>
<td>normal force</td>
</tr>
<tr>
<td>$h$</td>
<td>test-section height</td>
</tr>
<tr>
<td>$K_1$</td>
<td>body-shape factor</td>
</tr>
<tr>
<td>$L$</td>
<td>lift</td>
</tr>
<tr>
<td>$L'$</td>
<td>lift per unit span</td>
</tr>
<tr>
<td>$P_{atm}$</td>
<td>atmospheric pressure</td>
</tr>
<tr>
<td>$M$</td>
<td>pitching moment</td>
</tr>
<tr>
<td>$M_{c/4}$</td>
<td>quarter-chord pitching moment</td>
</tr>
<tr>
<td>$n_{rake}$</td>
<td>number of wake rake total pressurements</td>
</tr>
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</table>
**N** normal force from balance

**P_{0,\infty}** total pressure in the freestream

**P_{0,w}** total pressure in the wake

**P_{amb}** ambient air pressure

**P_{ss}** static pressure at wind tunnel inlet settling section

**P_{ts}** static pressure in wind tunnel test section

**q_\infty** dynamic pressure

**R** ideal gas constant for air

**Re** reynolds number

**S** projected model area

**s/c** normalized arc length

**T_{amb}** ambient air temperature

**U** characteristic velocity

**U_{ss}** inlet settling section velocity

**U_{ts}** test section velocity

**U_\infty** freestream velocity

**V_A** scaled axial force voltage

**V_M** scaled pitching moment voltage

**V_N** scaled normal force voltage

**x/c** normalized chordwise location

**x_0** chordwise displacement of model from balance center

**y_0** normal displacement of model from balance center

**\alpha** angle of attack

**\epsilon** total velocity increment

**\epsilon_{sb}** solid-blockage velocity increment

**\epsilon_{wb}** wake-blockage velocity increment

**\rho** air density

**\rho_{amb}** ambient air density

**\mu** dynamic viscosity
Abbreviations

AEP       Annual Energy Production
DU        Delft University
ESP       Electronically Scanned Pressure
LS        Lower Surface
PCU       Pressure Calibration Unit
PSI       Pressure Systems Incorporated
UIUC      University of Illinois at Urbana-Champaign
US        Upper Surface
WPT       Wind Protection Tape
Chapter 1

Introduction

Wind is perhaps the most abundant source of renewable energy. Due to the availability of flowing air in any and every location on the planet, the growth rate that has been predicted for the wind energy industry is close to 30% over the next decade making it a pivotal power contributor for the future [1].

One of the most important aspects of extracting energy from moving air is the design and efficiency of wind turbines. The performance of a wind turbine is primarily determined by the effectiveness of the turbine blades. The growing demand for wind power has led to the increase in the turbine installations in different climatic regions. Based on the location of the turbines, the blades are exposed to various environmental factors that create operational issues [1]. Of the numerous issues that persist with the turbine blades, the investigation of “leading edge erosion and accretion” and their effects on the performance of the wind turbine, was carried out as the first part of the research study.

Over the course of time, blades are degraded as a result of erosion of their surfaces. The primary cause of erosion is the exposure of the turbines to various forms of precipitation and abrasive airborne particles[2, 3]. It has been observed that surface degradation initiates at the leading edge and then propagates downstream gradually. In some environments the blades can form deposits and accretions due to collisions from insect and other cohesive airborne particle. A wind turbine blade extracts maximum energy from the outboard section which has approximately 15%–21% relative airfoil thickness[4]. Hence the combined phenomena of erosion and accretion especially near the rotor tip, leads to a drastic reduction in the aerodynamic performance particularly in the high-speed rotor tip region that is crucial to optimum blade performance and energy capture[5, 6]. Furthermore, for a turbine operating below the rated speed, the power output losses for a contaminated blade tend to increase with the increasing wind speed[7].

Figures 1.1 and 1.2 show damaged wind turbine blades as a result of leading edge erosion. The pictures are of blades that were removed from working wind turbines. Figure 1.1 shows a blade with early erosion features like pits and gouges near the leading edge, while Figure 1.2 shows a blade in operation for a longer time, with delamination over the entire leading edge.

High performance airfoils tend to have a greater vulnerability to surface irregularities and roughness
especially near the leading edge and require careful attention towards exact contour and smoothness of surface[4, 8]. Even though the detrimental effects of erosion are well known qualitatively, their quantification has not been carried out in the previous studies. The focus of earlier work has been on ice, dust and insect debris accretion on the wind turbine blades [2, 3, 5, 9]. The simulation of erosion in the previous studies was done using roughness strips or a zigzag tape applied near the leading edge [2, 10]. Though the use of roughness strips is a widely used and a simple method, it does not accurately model the leading edge erosion.

The initial part of the study was to develop a baseline understanding of the aerodynamic effects of different types and magnitudes of leading edge erosion and to quantify their relative impact on the airfoil performance. For this purpose, a wind turbine airfoil (DU 96-W-180) with simulated leading edge erosion was tested in the wind tunnel. The erosion was modeled using pictures of actual blades taken from wind turbines in operation. The erosion features included on the airfoil models used for testing were pits, gouges, delaminated leading edge and bug accretions.

The challenge that is faced by the industry is to develop optimal and economic methods to mitigate the problem of loss of blade performance due to environmental factors. To tackle the specific erosion/accretion related issues, there exists a simple and cost effective method: the application of a protective tape. The second part of the research was to study the impact of using a leading edge wind protection tape (WPT) on the airfoil. This was also done by testing the DU-96-W-180 airfoil in the wind tunnel, with the experimental tape wrapped around the leading edge. The cases were changed by varying the chordwise extents on the upper and lower surfaces of the airfoil.

The tape that can be used for practical purposes needs to be designed by taking into account a number of factors, for optimum performance. For example the best design has to be based on tape thickness, extent on the upper and lower surfaces of the airfoil, edge finish, etc. Further, the environmental factors like density, airborne particle distribution, average wind speeds and temperatures also need to be considered while designing the tape. Finally the rotor size and the speeds at various stations have to be included to arrive to an optimized tape configuration.

Taking the two objectives that have been discussed briefly in the preceding paragraphs, the ultimate goal was to compare the performance impacts of the wind protection tape and the leading edge erosion on wind turbines, so that the feasibility of using such a tape can be examined. The results can further be used to optimize the tape for application on wind turbine blades by making appropriate modifications to the size, geometry and placement of the tape.
Fig. 1.1: Photo of a wind turbine blade with pits and gouges courtesy of 3M.

Fig. 1.2: Photo of a wind turbine blade with a delaminated leading edge courtesy of 3M.
Chapter 2
Experimental Methodologies

All experiments and tests were carried out in the Aerodynamics Research Laboratory at University of Illinois Urbana-Champaign. The control room in the lab accommodates the data acquisition system whereas two subsonic wind tunnels are located in a test high bay.

2.1 Wind Tunnel Facility

The UIUC low-turbulence subsonic wind tunnel was used to carry out all the tests. Figure 2.1 shows the schematics of the tunnel. The wind tunnel is an open-return type with a contraction ratio of 7.5:1. The test section is rectangular with a cross section of $2.8 \times 4.0$ ft ($0.853 \times 1.219$ m) and a length of 8 ft (2.438 m). A thick boundary layer creates more blockage and tends to make the test section smaller [11]. Hence over the length of the test section, the width increases by approximately 0.5 in (1.27 cm) to account for the growth of the boundary layer along the tunnel side walls. Test-section speeds vary up to 160 mph (71.53 m/s) via a 125-hp (93.25 kW) alternating-current electric motor driving a five-bladed fan (Fig. 2.2). Four anti-turbulence screens and a 4-in (10.16-cm) thick honeycomb structure which are located in the tunnel settling chamber help in obtaining very low levels of turbulence in the wind tunnel (Fig. 2.3). The turbulence intensity with an empty test section was experimentally measured to be less than 0.1% [12].
Fig. 2.1: UIUC subsonic wind tunnel.
Fig. 2.2: Photograph showing the wind tunnel fan (taken by Gregory Williamson).

Fig. 2.3: Photograph of wind tunnel inlet showing the honeycomb (taken by Gregory Williamson).
Reynolds number is the primary factor that needs to be considered while carrying out analysis of subsonic airfoils. Reynolds number is a non-dimensional value represented by the ratio of inertia force to the viscous force for a fluid [13]. The equation used for calculating Reynolds number of the airfoil is given below:

\[
Re = \frac{\rho U_\infty c}{\mu}
\]  

(2.1)

In the above equation, \(\rho\) is the density of air which is treated as incompressible, \(U_\infty\) is the free stream velocity of the air, \(c\) is the chord length of the airfoil and \(\mu\) is the dynamic viscosity. The maximum Reynolds number that can be attained during the wind tunnel operation is 1.5 million/ft (4.92 million/m). During the tests, the Reynolds number was computer-controlled to within 2% error.

2.2 Setup

The following sections describe the experimental equipment used to obtain the airfoil performance data discussed in this thesis.

2.2.1 Pressure Measurement System

Static and total pressure measurements in the wake of the airfoil were made using a traversable wake survey system. The pressures were measured by a Pressure System Inc. (PSI) System 8400\textsuperscript{®}. A Central Control Module, a 14-bit 8420 Scanner Digitizer Unit, 1.0 and \(\pm\) 5.0 psid Pressure Calibration Units (PCU) and a Scanner Interface comprised the digital pressure acquisition system. The pressures were sampled at 50 Hz for two seconds by using Electronically Scanned Pressure (ESP) modules having 32 ports per module. Besides the 32 ports, each scanner module had one or two reference ports, a pressure calibration port, and two switch calibration ports C1 and C2. Each of the ports were connected to a pressure tap on the wake rake using a polyurethane or vinyl tubing.

The traversable wake rake used two 0.35-psid modules, one for static pressure measurements and the other for total pressure measurements. All modules were calibrated before each run using a computer program in LabView\textsuperscript{®}. The modules were switched between their run and calibration modes through the computer program which exerted a 100-psi burst of nitrogen gas from a nitrogen storage tank for a specified time. For this purpose, the specific C1 and C2 ports were used. In addition to the PCU, a vacuum pump was also used, in order to calibrate the scanners.
2.2.2 Flow Speed Measurement

The airspeed and dynamic pressure in the test section were determined by static pressure measurements in the wind tunnel contraction. The pressure difference ($\Delta P$) between the inlet settling section and test section ($P_{ss} - P_{ts}$) was measured using a Setra 239® differential pressure transducer. The average settling section static pressure $P_{ss}$ was provided by connecting a set of four pressure taps downstream on the anti-turbulence screens by a single tube to the pressure transducer. Just upstream of the test section were four more pressure taps which were also fed through a single tube to the pressure transducer to give the average test section static pressure, $P_{ts}$.

To calculate the test section airspeed, steady, inviscid flow was assumed. Hence by using the law of conservation of mass (Eq. 2.2) for incompressible fluids and the incompressible Bernoulli’s equation (Eq. 2.3) the airspeed was calculated.

\[ A_{ss} U_{ss} = A_{ts} U_{ts} \quad (2.2) \]

\[ \frac{1}{2} \rho U_{ts}^2 + P_{ts} = \frac{1}{2} \rho U_{ss}^2 + P_{ss} \quad (2.3) \]

\[ U_{ts} = \sqrt{\frac{2(P_{ss} - P_{ts})}{\rho_{amb} (1 - \left(\frac{A_{ts}}{A_{ss}}\right)^2}}} \quad (2.4) \]

In Eq. 2.4 the value of $\rho_{amb}$ which was the ambient air density, was calculated using the ideal gas law:

\[ \rho_{amb} = \frac{P_{amb}}{RT_{amb}} \quad (2.5) \]

In the above equation, $R$ is the ideal gas constant for air. Ambient temperature ($T_{amb}$) was measured using an Omega thermocouple and the ambient pressure ($P_{amb}$) using a Setra 270® pressure transducer, located in the tunnel high bay.

The difference between the test section and the settling section static pressures was measured. By using Bernoulli’s equation (Eq. 2.3) and conservation of mass (Eq. 2.2) for an incompressible fluid, the equation for $q_\infty$ (Eq. 2.6) was modified.

\[ q_\infty = \frac{1}{2} \rho U_\infty^2 \quad (2.6) \]
\[
q_\infty = \frac{1}{2} \rho_\infty U_{ts}^2 = \frac{(P_{ss} - P_{ts})}{\left[1 - \left(\frac{A_{ss}}{A_{ts}}\right)^2\right]^2}
\] (2.7)

In Eq. 2.6, \(\rho_\infty\) is the freestream air density which is assumed to be equal to \(\rho_{amb}\) as given in Eq. 2.4. The value of the dynamic pressure in terms of static pressure difference between the test section and the settling chamber was obtained by using the Setra model 239 pressure transducer.

2.2.3 Lift and Drag Measurements

A three-component external force and moment balance mounted underneath the test section and a wake rake were used to measure the performance parameters of the airfoil. The model was mounted with the spanwise axis in the vertical direction.

The normal force, axial force and the pitching moment were measured using the three-component balance. Lift and drag were calculated from the normal and axial forces, but the wake rake measurements were used for more accurate drag value calculations.

2.2.3.1 Force Balance Measurements

The three-component force balance mentioned previously was used to acquire the lift and pitching moment data for the airfoil model. The force balance built by Aerotech ATE Ltd., U.K. measured normal and axial forces on the airfoil as well as the pitching moments about the center of the balance using load cells. The load ranges are given in Table 2.1. For all the tests, the high range from the table was used. The load cells had a full-scale output voltage of \(\pm 20\) mV which was amplified to a full-scale voltage of 5 V and filtered at 1 Hz. At the beginning of the tests for the day, the force balance was tared. Besides at the start of the tests, whenever changes were made to the airfoil configuration, the balance was tared again. 200 voltage samples were acquired at the rate of 100 Hz and averaged for each force or moment measurement. As the experiments were carried out, the corresponding tare voltages were subtracted from the measurements for the three components taken by the balance. The difference \((V_{0i})\) was multiplied by a range ratio \((RR_i)\) as shown in Table 2.2, which depended on the load range setting. The product obtained was a scaled voltage \((V_i)\) as seen in Eq. 2.8. The voltages corresponding to the normal-component, the axial-component and the pitching-moment were represented by \(V_N\), \(V_A\) and \(V_M\) respectively. The final voltage was used to determine the normal and axial forces as well as the pitching-moments by plugging into the calibration matrix (Eq. 2.9). For all the tests, the airfoil model in the test section was mounted on a turn table which was a part of the force balance and was used to vary the angles of attack with an accuracy of 0.1 deg.
Table 2.1: Load Ranges of Force Balance

<table>
<thead>
<tr>
<th></th>
<th>High Range</th>
<th>Medium Range</th>
<th>Low Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Force</td>
<td>±450 lb</td>
<td>±225 lb</td>
<td>±90 lb</td>
</tr>
<tr>
<td>Axial Force</td>
<td>±90 lb</td>
<td>±55 lb</td>
<td>±18 lb</td>
</tr>
<tr>
<td>Pitching Moment</td>
<td>±45 ft-lb</td>
<td>±30 ft-lb</td>
<td>±15 ft-lb</td>
</tr>
</tbody>
</table>

Table 2.2: Range Ratios for Force Balance

<table>
<thead>
<tr>
<th></th>
<th>High Range</th>
<th>Medium Range</th>
<th>Low Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Force</td>
<td>1</td>
<td>0.4944</td>
<td>0.2046</td>
</tr>
<tr>
<td>Axial Force</td>
<td>1</td>
<td>0.6278</td>
<td>0.2173</td>
</tr>
<tr>
<td>Pitching Moment</td>
<td>1</td>
<td>0.6755</td>
<td>0.3413</td>
</tr>
</tbody>
</table>

\[ V_i = V_{0i} \cdot RR_i \] \hspace{1cm} (2.8)

\[
\begin{bmatrix}
F_N \\
F_A \\
M
\end{bmatrix} =
\begin{bmatrix}
37.7 & 0.01359 & -0.2095 & 0.01094 & 0 & -0.000865 \\
-0.1607 & 8.3125 & -0.01638 & 0.007084 & 0 & 0.007660 \\
-0.01299 & -0.005521 & 1.247 & -0.002122 & 0 & 0.0001497
\end{bmatrix}
\begin{bmatrix}
V_N \\
V_A \\
V_M \\
V_N^2 \\
V_A^2 \\
V_M^2
\end{bmatrix}
\] \hspace{1cm} (2.9)

The outputs obtained by substitution of the scaled voltages into the matrix (Eq. 2.9) were the normal force \( F_N \), axial force \( F_A \), and pitching moment \( M \). These measurements were used to calculate lift, drag and pitching moment at the quarter chord of the airfoil model by using the following equations:

\[ L = F_N \cos \alpha - F_A \sin \alpha \] \hspace{1cm} (2.10)

\[ D = F_N \sin \alpha + F_A \cos \alpha \] \hspace{1cm} (2.11)

\[ M_{c/4} = M + x_0 F_N + y_0 F_A \] \hspace{1cm} (2.12)

In Eq. 2.12, \( x_0 \) and \( y_0 \) represent the location of the quarter chord point of the airfoil with respect to the center of the force balance plate. To calculate the non-dimensional lift and drag coefficients, Eq. 2.10 and Eq. 2.11 were divided by dynamic pressure \( (q_{\infty}) \) and the reference area \( (S) \) as shown in Eq. 2.13 and
Eq. 2.14. To obtain the non-dimensional pitching moment coefficient about the quarter chord \( (C_m) \), Eq. 2.12 was divided by the quantity \( q_\infty S \) and the chord length of the airfoil \( (c) \) which gave Eq. 2.15. The equations for calculating the sectional coefficients of the airfoil are:

\[
C_l = \frac{L}{q_\infty S} \quad (2.13)
\]

\[
C_d = \frac{D}{q_\infty S} \quad (2.14)
\]

\[
C_m = \frac{M_{c/4}}{q_\infty Sc} \quad (2.15)
\]

The drag data obtained from the force balance was not used in the results. The reason for not incorporating the balance drag data is that the force balance includes an induced drag component in the values which typically makes them higher than the values obtained from the wake survey system as discussed in the next section. Drag values from the force balance were used only for comparison purposes.

### 2.2.3.2 Wake Survey System

For static and total wake pressure measurement, a traversable wake rake was used, which was located 1.17 chord lengths downstream of the airfoil model. The rake contained a total of 59 pressure probes with outer diameters 0.04 in, over a width of 9.75 in (24.77 cm). The probes were horizontally aligned parallel to the freestream flow direction to capture the pressure deficits in the wake generated by the model. The seven probes on each of the outer sides of the rake were spaced 0.27 in (6.86 mm) apart and the rest of the 45 probes were spaced 0.135 in (3.43 mm) apart. A Lintech traverse was used to control the movement of the wake rake so that it could take measurements at much finer resolutions as compared with a stationary wake rake. The traverse was capable of moving in both spanwise as well as chordwise directions. An IDC S6962 Stepper Motor Drive was used for controlling the movements. The Lintech traverse could be controlled manually as well as through the control room computers. During the course of the tests, a computer program was used for precisely controlling the traverse location.

For each angle of attack, eight spanwise wake profiles were measured starting at 4 in (10.16 cm) above and ending at 3 in (7.62 cm) below the center span. A computer program precisely moved the wake rake to the center of the wake (region of the wake with minimum pressure). The program then moved the wake rake outward to the edge of the wake by detecting a region of constant pressure. As mentioned in Section 2.2.1, wake pressure measurements were taken using the PSI System 8400 and two \( \pm 0.35 \text{ psi} \) ESP modules. The
resulting drag values were averaged.

The momentum-deficit method discussed by Jones [14] and Schlichting [15] was used to calculate drag values from the pressures measured by the wake rake. The assumption is that the pressures that are being measured in a plane 1, perpendicular to the freestream and sufficiently far behind the airfoil and that the static pressure in the wake \((P_W)\) is equal to the freestream static pressure \((P_\infty)\). Applying the momentum equation to the appropriate control volume the drag per unit span can be given by Eq. 2.16:

\[
D' = \rho \int u_1 (U_\infty - u_1) \, dy_1
\]  

(2.16)

The wake rake measurements are taken in a second plane perpendicular to the freestream and closer to the model. By applying conservation of mass to a streamtube running between the two planes (Eq. 2.17) and substituting it in Eq. 2.16, Eq. 2.18 was generated.

\[
u_1 dy_1 = u_w dy
\]  

(2.17)

\[
D' = \rho \int u_w (U_\infty - u_1) \, dy
\]  

(2.18)

Equations 2.19–2.21 can be used for expressing the total pressures for the freestream, plane 1 and the wake plane respectively.

\[
\frac{1}{2} \rho U_\infty^2 + P_\infty = P_{0,\infty}
\]  

(2.19)

\[
\frac{1}{2} \rho u_1^2 + P_\infty = P_{0,1}
\]  

(2.20)

\[
\frac{1}{2} \rho u_w^2 + P_\infty = P_{0,w}
\]  

(2.21)

Equations 2.19–2.21 were solved and substituted into Eq. 2.18, to obtain the drag per unit span with the assumption that there were no pressure losses between wake plane and plane 1, i.e. \(P_{0,1} = P_{0,w}\):

\[
D' = 2 \int \sqrt{P_{0,w} - P_w} (\sqrt{P_{0,\infty} - P_\infty} - \sqrt{P_{0,w} - P_\infty}) \, dy
\]  

(2.22)

Combining Eq. 2.19 and Eq. 2.21 with the assumption that \(P_w = P_\infty\) gave the following equation:
\[ q_w = q_\infty - (P_{0,\infty} - P_{0,w}) \]  

(2.23)

Rearranging Eq. 2.22 and writing it in terms of dynamic pressure and by additionally substituting Eq. 2.23 gave the expression of drag per unit span as:

\[ D' = 2 \int \sqrt{q_\infty - (P_{0,\infty} - P_{0,w})} \sqrt{q_\infty - (P_{0,\infty} - P_{0,w})} \, dy \]  

(2.24)

The Eq. 2.24 has the pressure difference term \((P_{0,\infty} - P_{0,w})\) which can be directly calculated from the wake survey system, making it easier to obtain the value of drag per unit span \(D'\). The pressure difference \((P_{0,w} - P_{\text{atm}})\) was measured by the wake survey system, as the \(\pm 0.35\) psid ESP units were referenced to the atmospheric pressure. At the edge of the wake a pressure difference \((P_{0,\infty} - P_{\text{atm}})\) was measured by the wake survey due to assumption that the total pressure was equal to the freestream total pressure. Hence to calculate \((P_{0,\infty} - P_{0,w})\) the following equation was used:

\[ P_{0,\infty} - P_{0,w} = (P_{0,\infty} - P_{\text{atm}}) - (P_{0,w} - P_{\text{atm}}) \]  

(2.25)

Eq. 2.24 was solved numerically using the trapezoidal method which resulted in the following equation for calculating incremental sectional drag:

\[ \Delta D' = \left[ \sqrt{q_\infty - (P_{0,\infty} - P_{0,w})} \sqrt{q_\infty - (P_{0,\infty} - P_{0,w})} \right] \]  

(2.26)

\[ + \left[ \sqrt{q_\infty - (P_{0,\infty} - P_{0,w+i})} \sqrt{q_\infty - (P_{0,\infty} - P_{0,w+i})} \right] (y_i - y_{i+1}) \]  

(2.27)

The incremental sectional drag \(\Delta D'\) was summed over the total number of probes \((n_{\text{rake}})\) used to measure the wake, to acquire the total sectional drag per unit span given by Eq. 2.28. The measurements from outside the wake of the model, where the total pressure was equal to the freestream total pressure, were not considered as they did not have any contribution to the drag calculation.

\[ D' = \sum_{i=1}^{n_{\text{rake}}} \Delta D'_i \]  

(2.28)

The drag coefficient was then calculated using:

\[ C_d = \frac{D'}{q_\infty c} \]  

(2.29)
2.3 Airfoil Geometry

All the tests were carried out on the DU 96-W-180 which is an 18%-thick airfoil designed at Delft University. For the DU airfoils the designation is DU yy-W-xxx, in which DU stands for Delft University, followed by the last two digits of the year in which it was designed. The W represents the application of the airfoil to wind energy operations [16]. It was designed to be used at the 75% blade station and is actively used for wind energy research found in the literature [17, 18]. The span of the airfoil was 33.5 in (0.851 m) with an 18-in (0.457-m) chord. The various erosion cases and tape configurations were developed and tested by applying them to the DU 96-W-180 airfoil.

2.4 Erosion Models

To test the various leading edge erosion cases, the type and severity of erosion were changed for the different models. The DU 96-W-180 airfoil was used to develop the various models. For reference, the pictures showing actual eroded wind turbine blades, provided by 3M® were used to generate the different models. The pictures and the available literature revealed that the process of erosion of wind turbine blades starts with the development of small pits on the surface near the leading edge. With time the pits slowly increase in number which leads to formation of gouges as a result of merging of the pits. The gouges further tend to grow larger and deeper with time, combining to form delamination of the entire leading edge. The other important observations that were made were:

• The density of pits and gouges was maximum near the leading edge and decreased in the chordwise direction.

• There was a greater impingement and hence greater erosion on the LS due to the angle of the attack at which the blade operated.

To account for the differences in the number and chordwise extent of the erosion features on the upper and lower surfaces, an upper-to-lower surface impingement ratio of 1:1.3 was chosen to model the various erosion cases. The difference in both the magnitude and chordwise extent of erosion on the upper and lower surfaces due to angle of attack when the blade is operational, is taken care of by the impingement ratio. The erosion cases comprised of the following three features: pits, gouges and leading edge delamination. Based on the impingement ratio, the chordwise extent of the different erosion features was fixed for all the cases at \( s/c = 10\% \) on the US and \( s/c = 13\% \) on the LS. The number of pits and gouges on the LS was set to be 1.3 times that on the US. The limits for leading edge delamination were set to \( s/c = 1\%, 2\% \) and \( 3\% \) on the
Fig. 2.4: Extent of leading edge erosion (bold line) on the DU 96-W-180 airfoil at $s/c = 10\%$ on the upper surface and $s/c = 13\%$ on the lower surface.

Table 2.3: Specifications of the Erosion Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Depth/Diameter</th>
<th>Leading Edge Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pits</td>
<td>0.02 in (0.51 mm)</td>
<td>0–2 in (0–50.8 mm)</td>
</tr>
<tr>
<td>Gouges</td>
<td>0.10 in (2.54 mm)</td>
<td>0–2 in (0–50.8 mm)</td>
</tr>
<tr>
<td>Delamination</td>
<td>0.15 in (3.81 mm)</td>
<td>0–0.18/0.36/0.72 in (0–4.57/9.14/18.29 mm)</td>
</tr>
</tbody>
</table>

US and $s/c = 1.3\%$, 2.6\% and 3.9\% on the LS. Figure 2.4 is a graphical representation of the section of the airfoil model that was eroded.

The effect of surface roughness on an airfoil performance is highly dependent on the nature and size of the roughness features relative to the boundary layer thickness [19, 20]. For the wind tunnel tests the features were carefully added on the airfoil models. Table 2.3 lists the various erosion features that were modeled along with the respective sizes and extent from the leading edge. Using the pictures of eroded wind turbine blades as reference, the sizes and depths of the pits, gouges and leading edge delamination were scaled down. After scaling down, the average depth of the pits, gouges and leading edge delamination was set to 0.02 in, 0.1 in and 0.15 in respectively. The average diameter of the pits and gouges was set to be the same as the depth.

Based on the different features listed in Table 2.3, there were three types of models that were generated. Type A which had just pits, Type B with pits and gouges and Type C with pits, gouges and leading edge delamination. For each model, tests were conducted by varying the severity of erosion in stages. Each successive stage was set to have almost twice the number of pits, gouges and extent of delamination as compared to the previous one. The test sequence that was adopted was based on the natural erosion process mentioned previously.

Besides the three types of erosion cases, accumulation of debris on the airfoil was also tested. Particularly, the effects of accretion due to bug and insect strikes were researched and have been described in Section 2.5.

The erosion process is very random and has several factors responsible for it. To take into account the randomness of the location and spread of the various erosion features, Gaussian distribution was used with maximum impingement frequency near the leading edge of the airfoil. Figures 2.5–2.21 show erosion
Fig. 2.5: Illustration showing the Type A/Stage 1 (A1) nominal erosion pattern with pits on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

distribution of pits, gouges and leading edge delamination for the various stages over an 8-in span on the upper and lower surfaces of the airfoil. A MATLAB® script was written and used in order to generate these figures depicting the different erosion features. Figures 2.22–2.29 are pictures showing the different airfoil models with various erosion features on them used for wind tunnel testing.
Fig. 2.6: Illustration showing the Type A/Stage 1 (A1) nominal erosion pattern with pits on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.7: Illustration showing the Type A/Stage 2 (A2) nominal erosion pattern with pits on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.8: Illustration showing the Type A/Stage 2 (A2) nominal erosion pattern with pits on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.9: Illustration showing the Type A/Stage 3 (A3) nominal erosion pattern with pits on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.10: Illustration showing the Type A/Stage 3 (A3) nominal erosion pattern with pits on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.11: Illustration showing the Type B/Stage 2 (B2) nominal erosion pattern with pits and gouges on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.12: Illustration showing the Type B/Stage 2 (B2) nominal erosion pattern with pits and gouges on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.13: Illustration showing the Type B/Stage 3 (B3) nominal erosion pattern with pits and gouges on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.14: Illustration showing the Type B/Stage 3 (B3) nominal erosion pattern with pits and gouges on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.15: Illustration showing the Type B/Stage 4 (B4) nominal erosion pattern with pits and gouges on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.16: Illustration showing the Type C/Stage 3 (C3) nominal erosion pattern with pits, gouges and leading-edge delamination on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.17: Illustration showing the Type C/Stage 3 (C3) nominal erosion pattern with pits, gouges and leading-edge delamination on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.18: Illustration showing the Type C/Stage 4 (C4) nominal erosion pattern with pits, gouges and leading-edge delamination on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.19: Illustration showing the Type C/Stage 4 (C4) nominal erosion pattern with pits, gouges and leading-edge delamination on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.20: Illustration showing the Type C/Stage 5 (C5) nominal erosion pattern with pits, gouges and leading-edge delamination on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.21: Illustration showing the Type C/Stage 5 (C5) nominal erosion pattern with pits, gouges and leading-edge delamination on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.22: Picture of the DU 96-W-180 erosion model with stage-1 pits (Type A/Stage 1).

Fig. 2.23: Picture of the DU 96-W-180 erosion model with stage-2 pits (Type A/Stage 2).
Fig. 2.24: Picture of the DU 96-W-180 erosion model with stage-2 pits and gouges (Type B/Stage 2).

Fig. 2.25: Picture of the DU 96-W-180 erosion model with stage-3 pits and gouges (Type B/Stage 3).
Fig. 2.26: Picture of the DU 96-W-180 erosion model with stage-4 pits and gouges (Type B/Stage 4).

Fig. 2.27: Picture of the DU 96-W-180 erosion model with stage-3 pits, gouges and delamination (Type C/Stage 3).
Fig. 2.28: Picture of the DU 96-W-180 erosion model with stage-4 pits, gouges and delamination (Type C/Stage 4).

Fig. 2.29: Picture of the DU 96-W-180 erosion model with stage-5 pits, gouges and delamination (Type C/Stage 5).
2.5 Accretion

Besides erosion the turbine blades also face a problem of accretion. One of the causes of accretion is accumulation of insect debris as a result of impact and rupture of bugs on the surface of the blade.

There are several factors that are critical to the accumulation phenomena like, the wind speed, angle of impact, size and mass of the bug etc. To simulate a general effect of bugs on the airfoil performance, small pieces of a scaled down version of the 3M® leading edge protection tape (Product Number: FV1222) having 0.0035-in (0.09-mm) thickness, were cut and added to the airfoil models. Initially bugs were added to the clean airfoil in two stages, the first stage having 35 bugs and the second having 75. To assess the combined effect of positive impingement and erosion, bugs were added to the model with pits also (Type A/Stage 1 with 35 bugs and Type A/Stage 2 with 75 bugs). Again Gaussian distribution was used for applying the bugs on the upper and lower surfaces of the airfoil. Figures 2.30–2.33 show the distribution of bugs for the clean airfoil, model Type A over an 8-in span, on the upper and lower surfaces. Figures 2.38–2.40 are pictures showing the different airfoil models with simulated bugs on them used for wind tunnel testing.
Fig. 2.30: Illustration showing stage-1 bugs on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.31: Illustration showing stage-1 bugs on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.32: Illustration showing stage-2 bugs on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.33: Illustration showing stage-2 bugs on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.34: Illustration showing the Type A/Stage 1 (A1) nominal erosion pattern with pits and bugs on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.35: Illustration showing the Type A/Stage 1 (A1) nominal erosion pattern with pits and bugs on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.36: Illustration showing the Type A/Stage 2 (A2) nominal erosion pattern with pits and bugs on the upper surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.

Fig. 2.37: Illustration showing the Type A/Stage 1 (A1) nominal erosion pattern with pits and bugs on the lower surface of the DU 96-W-180 erosion model over an 80-mm (3.15-in) span from 0–13% s/c.
Fig. 2.38: Picture of the clean DU 96-W-180 airfoil with bugs (clean with bugs).

Fig. 2.39: Picture of the DU 96-W-180 erosion model with stage-1 pits and bugs (Type A/Stage 1 with bugs).
Fig. 2.40: Picture of the DU 96-W-180 erosion model with stage-2 pits and bugs (Type A/Stage 2 with bugs).
2.6 Wind Protection Tape

A wind protection tape (WPT) used on wind turbines has been developed by the 3M Renewable Energy Division®. It is a polyurethane tape 7.8-in (20-cm) wide and 0.014-in (0.36-mm) thick. The tape is currently used for a variety of turbine blade sizes in the wind power industry. The tape thickness scales with the wind turbine blade chord. For the tests, the tape that was used (Product Number: FV1222) on the DU 96-W-180 airfoil was a scaled down version with a thickness of 0.0035 in (0.09 mm). The scaling factor was calculated by assuming a full-scale chord of 6 ft (1.83 m) at the 75% spanwise station where in full scale the tape thickness is 0.014 in (0.36 mm). The tape was wrapped around the leading edge of the DU 96-W-180 airfoil for testing the effect on the aerodynamic performance of the airfoil. The chordwise extent of the tape (backedge location) on the upper and lower surfaces was varied to generate the different configurations for the tests. The US limits were fixed at $x/c = 10\%$, 20\% and 30\% while the LS limits were fixed at $x/c = 10\%$ and 20\%. Figures 2.41–2.46 graphically represent a section of the airfoil with the WPT wrapped around the leading edge in various tape configurations. The different tape configurations that were tested have been listed below:

- US @ 10\% , LS @ 10\%
- US @ 10\% , LS @ 20\%
- US @ 20\% , LS @ 10\%
- US @ 20\% , LS @ 20\%
- US @ 30\% , LS @ 10\%
- US @ 30\% , LS @ 20\%
Fig. 2.41: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.

Fig. 2.42: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface.

Fig. 2.43: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.

Fig. 2.44: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 2.45: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface.

Fig. 2.46: Position of the vinyl tape (red line) on the DU 96-W-180 airfoil at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
2.7 Trips

Trip strips were used on the airfoils with the assumption that they would have the same effect on the performance of the airfoils as that of WPT. Tape strips with a small width were cut for covering the entire span of the airfoil. The thickness of the strips was the same as that of the scaled down version of the WPT described in Section 2.6.

The strips were placed at locations on the airfoil which corresponded to the extents of the tape on the upper and lower surfaces with the assumption that they would act as flow trips having backward facing steps just like the actual WPT. A trip tends to create an inflection point in the boundary layer [21]. This inflection point further creates instabilities which transition the flow and render it turbulent. The increase in drag value for the airfoil was primarily due to the flow tripping at the backward facing step of the tape. So it was assumed that trip strips placed at the WPT backward facing step locations on the airfoil would have the same effect on the drag value as the whole tape wrapped around the leading edge.

The positions of the trips on the upper and lower surfaces of the airfoil were set to the various backedge locations of the WPT, as specified in Section 2.6. For the upper surface the limits were fixed at $x/c = 10\%$, $20\%$ and $30\%$. For the lower surface the limits were fixed at $x/c = 10\%$ and $20\%$. Figures 2.47–2.49 graphically represent a section of the airfoil with the trips on the upper and lower surfaces corresponding to the different backedge locations of the WPT.
Fig. 2.47: Position of the vinyl trips (red lines) on the DU 96-W-180 airfoil at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.

Fig. 2.48: Position of the vinyl trips (red lines) on the DU 96-W-180 airfoil at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface.

Fig. 2.49: Position of the vinyl trips (red lines) on the DU 96-W-180 airfoil at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
2.8 Aerodynamic Test Procedure

A computer code in LabVIEW® was used for controlling the data acquisition equipment and hardware. At the start of the test, the power supply to the wind tunnel and the pressurized nitrogen supply for the PSI system were turned on. A manual check run was carried out after installing and fastening the airfoil model and the ceiling of the test section, at different fan speeds so that any loose nuts, bolts or other components could be re-tightened. As mentioned earlier the balance was tared automatically through a computer code. The balance was turned through a range of angles of attack and zero airspeed lift, drag and pitching moment voltages were recorded.

The wind tunnel tests were classified as lift runs and drag runs. All the airfoil models were tested at three Reynolds numbers: $1 \times 10^6$, $1.5 \times 10^6$ and $1.85 \times 10^6$. Hence for each airfoil model, there was a total of six cases: three lift runs and three drag runs. To ensure repeatability of the data, all the cases were run twice. For the lift runs, the wake rake was fixed at one spanwise location to capture the wake. The airfoil was turned through angles of attack spanning the range $(-10$ to $18 \text{ deg})$. The lift value at each angle of attack was obtained using the three-component balance. For the drag runs the wake rake took measurements at 8 spanwise stations in order to obtain accurate drag values at the different angles of attack. The angles of attack ranged between $(-4$ to $10 \text{ deg})$.

2.8.1 Erosion Tests

A Test Matrix incorporating all the erosion cases was created (Table 2.4). The table lists the number of pits, gouges, and the degree of leading edge delamination on the US of the airfoil for each case (Type and Stage) tested. Moving from left to right in the table changes the type of erosion features on the airfoil model as described in Section 2.4. Moving down the table column from a lower to a higher stage corresponds to an increase in the severity of erosion. The natural process of erosion follows very closely to the Test Matrix generated. For the different stages, the number of pits, gouges and the extent of delamination are separated by the slash symbol. All of the configurations were tested at the three Reynolds numbers for the lift and drag runs.

The airfoil models were tested for accretion effects in two stages: with 35 bugs and 75 bugs. Bugs were added to the clean airfoil as well as models A1 (35 bugs) and A2 (75 bugs) to assess the combined effect of both erosion and accretion. The different lift and drag runs were carried out at the three Reynolds number values mentioned previously. Table 2.5 describes the different accretion cases that were tested. Data reduction and obtainment of the performance plots was done using a script written in MATLAB®.
Table 2.4: Test Matrix with the Number of Pits (P), Number of Gouges (G), and Magnitude of Leading Edge Delamination (DL) on the Upper Surface of the Erosion Model for Each Case Tested

<table>
<thead>
<tr>
<th></th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>100P</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Stage 2</td>
<td>200P</td>
<td>200P/100G</td>
<td>–</td>
</tr>
<tr>
<td>Stage 3</td>
<td>400P</td>
<td>400P/200G</td>
<td>400P/200G/DL</td>
</tr>
<tr>
<td>Stage 4</td>
<td>–</td>
<td>800P/400G</td>
<td>800P/400G/DL+</td>
</tr>
<tr>
<td>Stage 5</td>
<td>–</td>
<td>–</td>
<td>1600P/800G/DL++</td>
</tr>
</tbody>
</table>

Table 2.5: Various Bug Accretion Cases Tested

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of Bugs</th>
<th>Pits/Bugs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>35</td>
<td>0/35</td>
</tr>
<tr>
<td>Clean</td>
<td>75</td>
<td>0/75</td>
</tr>
<tr>
<td>A1</td>
<td>35</td>
<td>100/35</td>
</tr>
<tr>
<td>A2</td>
<td>75</td>
<td>200/75</td>
</tr>
</tbody>
</table>

### 2.8.2 Wind Protection Tape Tests

The tape was wrapped around the leading edge of the DU 96-W-180 airfoil. The chordwise extent of the wind protection tape was varied on both the surfaces to account for the different configurations mentioned in Section 2.6 which were then tested.

For the chordwise location of $x/c = 20\%$ on the LS, the US extent was changed to $x/c = 10\%, 20\%$ and $30\%$ respectively. Next the LS location was changed to $x/c = 10\%$ and again the US locations were fixed at the three previously mentioned values. So, overall the tests were carried out for 6 configurations. As in the case of erosion models, the tests were conducted at the three Reynolds numbers for the lift and drag runs.

### 2.9 Wind Tunnel Corrections

The wind tunnel tests were carried out in order to simulate real world wind turbine performance losses due to erosion and accretion. As the tests were performed in the laboratory conditions with scaled down airfoil models and wind protection tape, fabricated erosion features and specific flow conditions, the exact state of an operating wind turbine in a specific environment and climate could not be duplicated perfectly. The wind tunnel walls altered the flowfield past all the models. To improve the accuracy of the data, the measurements from all tests were corrected. The three most important effects on the flow are solid blockage, wake blockage and reduced streamline curvature. Corrections for these effects are based on the work done by Barlow, Rae
Solid blockage is reduction in the effective test section area due to the presence of a model, seen commonly at high angles-of-attack and for large models. To maintain the mass flow rate across the test section, the airspeed must be increased, as the area of the model perpendicular to the flow direction becomes larger. The increase in velocity is a function of the angle of attack of the model, thickness \( t \), shape factor \( \lambda \) and test section width \( W \). The correction factor for solid blockage can be estimated using equation:

\[
\epsilon_{sb} = \frac{K_1 (model\text{volume})}{C^2}
\]  

In the above equation, \( \epsilon_{sb} \) is the solid-blockage velocity increment, \( K_1 \) is a factor with value 0.52 for a model spanning the wind tunnel height [22]. The test section area is represented by \( C \).

Another correction effect that needs to be considered is the wake blockage, which is an increase in flow velocity in a closed wind tunnel outside the wake. The flow upstream of the airfoil is uniform but non-uniform downstream. Inside a wake the velocity is lesser than the freestream velocity. Hence for conservation of mass the flow velocity outside of the wake becomes higher than the test section freestream velocity. The following equation can be used to estimate the correction factor for wake blockage due to an airfoil:

\[
\epsilon_{wb} = \frac{1}{2} \frac{c}{h} C_{d,u}
\]  

In the above equation \( \epsilon_{wb} \) is the wake-blockage velocity increment, \( h \) is the test-section height and \( C_{d,u} \) is the uncorrected value for drag coefficient of the airfoil. To obtain the total increase in flow velocity \( \epsilon \) the solid-blockage and the wake-blockage increments were added as shown in the following equation:

\[
\epsilon = \epsilon_{sb} + \epsilon_{wb}
\]  

The natural curvature of the streamlines is affected by the walls. The presence of the wind tunnel walls leads to a distortion of the natural streamlines which is known as streamline curvature. The airfoil in a closed wind tunnel appears to have more camber than it actually has, leading to an increase in lift and quarter-chord pitching moment. This effect is accounted for by applying the following equation for the variable \( \sigma \):

\[
\sigma = \frac{\pi^2}{48} \left( \frac{c}{h} \right)^2
\]  

The correction factors discussed in equations above are used to obtain more accuracy in the airfoil angles of attack, lift, drag and pitching moment coefficients. The angles of attack were corrected using the uncorrected lift and pitching moment data. These corrections were applied to both balance and pressure...
The following equations were used for acquiring the different corrected parameters:

\[ \alpha_{\text{cor}} = \alpha_u + \frac{57.3\sigma}{2\pi} (C_{l,u} + C_{m,u}) \]  
(2.34)

\[ C_{l,\text{cor}} = C_{l,u} (1 - \sigma - 2\epsilon) \]  
(2.35)

\[ C_{d,\text{cor}} = C_{d,u} (1 - 3\epsilon_{sb} - 2\epsilon_{wb}) \]  
(2.36)

\[ C_{m,\text{cor}} = C_{m,u} (1 - 2\epsilon) + \frac{1}{4} \sigma C_{l,u} \]  
(2.37)
Chapter 3

Results and Discussion

In this section, the data that was obtained by testing the various erosion models described previously and the models with different wind protection tape configurations, was analyzed and compared to the performance of the clean DU 96-W-180 airfoil under the same test conditions. The results further shed light on the how various degrees of erosion hamper the wind turbine performance and the applicability and feasibility of using the WPT for an operational wind turbine blade.

3.1 Clean Airfoil Case

The baseline results used for all comparisons were obtained by testing the clean DU 96-W-180 airfoil. Figures 3.1–3.2 show the performance plots and drag polars of the clean airfoil at the three specific Reynolds numbers. With increasing Reynolds number, the drag polars shifted to the left indicating a reduction in drag, which is the expected trend. To measure the changes in drag values for all other cases, the clean airfoil dataset was used as the reference.

3.2 Leading Edge Erosion and Accretion

For any airfoil perform efficiently, the flow should remain attached and laminar over the entire surface of the airfoil till it leaves from the trailing edge [23]. Whenever there is an imperfection on the surface of an airfoil in the form of additional roughness, the flow either transitions from laminar to turbulent permanently, or there is an early separation off the surface. In both cases there is a significant drag rise which leads to a loss in performance. The erosion and accretion features like pits, gouges, bugs and leading edge delamination are the different types of surface imperfections that disrupt the flow leading to performance losses. Theoretically, an increase in the number of erosion features over the surface of any airfoil should lead to a degradation of the performance, which is the result found in the tests.

The various erosion cases were tested by following the test matrix mentioned in Section 2.8.1. Figures 3.3–3.20 show the coefficients of lift and pitching moment of the various eroded airfoil models at different angles of
attack. For each of the erosion cases the drag polars were also plotted. For each model, the plots correspond to the three Reynolds numbers at which the tests were carried out. For the initial stage of erosion (model A1) the drag polar (see Fig. 3.3) followed the normal trend and shifted to the left with the increase in Reynolds number. But as soon as we moved to the next higher stage in the test matrix, the shifting trend of the drag polar seemed to change. For the case of model A2 (Fig. 3.5) between the $C_l$ values of 0.3 and 1.1, the drag polar shifted to the right instead of shifting to the left with increasing values of Reynolds number. The observation was that for A2 and all other models corresponding to the higher stages of the test matrix (A3, B2, B3, B4, C3, C4, and C5), the drag polar shifted to the right with an increase in the Reynolds number. The drag value for the severely eroded cases got larger as compared to the clean case. The reason for the sudden rise in drag values is the early transition and possible separation of the flow due to the surface irregularities, as discussed earlier.

The goal of the research was to obtain an estimate in the performance degradation of a wind turbine blade for the various erosion cases replicating the practical scenario. For this purpose, the drag polars and lift curves at each Reynolds number test conditions for the various erosion models were co-plotted with that of the clean case. Figures 3.45–3.71 give a comparison of all the erosion models individually to the clean airfoil at the three specific Reynolds number values. The plots show a loss in lift coefficient and an increase in the drag coefficient values for the different models. As the severity of erosion is increased, the performance loss is magnified.

Figures 3.21–3.26 are plots showing the effect of bug strikes and the eventual accretion over the surface, on the airfoil. Figure 3.21 and Figure 3.22 show the drag polar and lift curve for the clean DU 96-W-180 with just bugs on it. Figures 3.23–3.26 show the combined effect of accretion and leading edge erosion on the airfoil. Bugs also hamper the performance severely in terms of lift and drag. The performance plots of the four cases of airfoils with accretions at the different test conditions have also been co-plotted with the clean case (see Fig. 3.72–3.80). The results point to a heavier loss in performance due to the combined effect of erosion and accretion as compared to just the erosion cases.

The performance plots of all the stages of the same model were depicted together along with the baseline plots of the clean case. A separate set of plots was used showing the percentage increase in drag values [$\Delta C_d(\%)$] of the different cases as compared to the clean airfoil. Figures 3.99–3.101 show the drag polars and lift curves for the models A1, A2 and A3 compared with the clean airfoil at the three Reynolds numbers. Figures 3.102–3.104 show the percentage rise in drag due to leading edge erosion for the above mentioned cases as compared to the clean airfoil polar. The plots clearly show that the first stage of Type A erosion has very little impact on the performance of the airfoil. As we increase the severity of the erosion and progress to stages 2 and 3, the detrimental effect of the erosion on the airfoil is clearly visible, with an almost double
value of the drag for case A3. With increase in Reynolds number, the drag values go up. There is a dip in the lift values for the latter cases at higher angles of attack.

Figures 3.105–3.107 and Figures 3.111–3.113 are the comparison plots for different stages of models with pits and gouges (B2, B3, B4) and pits, gouges and leading edge delamination (C3, C4, C5) respectively. The trend that can be observed for these cases is very similar to the Type A models. The performance degradation is magnified as the erosion features (pits and gouges) increase in number. The drag rise for each stage is clearly indicated in Figures 3.108–3.110 and Figures 3.114–3.116.

Figures 3.117–3.118 give a comparison of the different erosion and accretion cases with the clean airfoil performance plots.

### 3.3 Wind Protection Tape and Trips

The DU airfoil was tested with the WPT wrapped around the leading edge having the different configurations mentioned earlier. The purpose of the tests was to find out the effect of the tape on the airfoil performance which could be then extended to an actual turbine blade operating with tape applied on it. The performance of the airfoil does get affected due to the backward facing steps created at the locations where the tape terminates on the upper and lower surfaces. The step tends to trip the flow thereby increasing the value of the drag. The results of the tests are to be used in determining the feasibility of the WPT usage.

To simulate the effect of the backward facing step created due to the WPT, some tests were run with vinyl trips applied to the airfoil at the same locations. The reason behind these tests was that if simple trips produced the same effect on the drag as full tape coverage, then trips could be used for future tests. Figures 3.27–3.32 show the performance plots and the drag polars for the trip at $x/c = 20\%$ on the lower surface and $x/c = 10, 20$ and $30\%$ on the upper surface respectively. It was seen that there was a mismatch in the performance of the airfoil with wind protection tape, and with just the trips at the corresponding tape edge locations. So further testing of the trips was not carried out. The reason for a mismatch may have been additional imperfections on the tape surface which was fully covering the leading edge, arising due to bubbles trapped under the tape or due to manufacturing irregularities.

Figures 3.33–3.44 show the coefficients of lift and pitching moment of the airfoil with tape wrapped around the leading edge ending at $x/c = 10, 20$ and $30\%$ on the upper surface and $x/c = 10$ and $20\%$ on the lower surface at different angles of attack. For each of the configurations the drag polars were also plotted. For each case, the plots correspond to the three Reynolds number at which the tests were carried out. For better comparison the drag polars and lift curves at specific Reynolds number test conditions for the various tape configurations were co-plotted with that of the clean case (Figures 3.81–3.98). These results point to a
small drag rise which can be further minimized by using some methods explained in the next chapter.

Figures 3.119–3.127 compare the airfoil cases with different tape extents to the performance plots of the clean airfoil. Another set of plots show the percentage increase in drag values of the different cases as compared to the clean DU airfoil. The $\Delta C_d$ values were calculated by using the clean airfoil as the baseline.

The plots show a small increment in the drag values due to the usage of the tape which is a consequence of the backward facing step as discussed earlier. As the edge of the tape is moved closer to the leading edge, there is more turbulent flow over the airfoil and hence greater drag. So if the protection tape covers greater area on the airfoil, the drag value will be lower.

The plots show similar trends with a greater degradation in performance for the tape ending closer to the leading edge on the upper surface. The magnitude of drag increase is greater, as the tape ends closer to the leading edge on the lower surface. The trend that is observed in the plots is that with increasing Reynolds number, the difference in the drag value of any taped case and the clean case becomes larger.
3.4 Performance Figures and Graphs

Fig. 3.1: Lift and pitching moment for the clean DU 96-W-180.
Fig. 3.1: (continued) Lift and pitching moment for the clean DU 96-W-180.
Fig. 3.2: Drag polar for the clean DU 96-W-180.
Fig. 3.3: Lift and pitching moment for the DU 96-W-180 erosion model A1.
DU 96-W-180 erosion type A, stage 1  
Re=1,850,000 (1434cs)  

Fig. 3.3: (continued) Lift and pitching moment for the DU 96-W-180 erosion model A1.
Fig. 3.4: Drag polar for the DU 96-W-180 erosion model A1.
Fig. 3.5: Lift and pitching moment for the DU 96-W-180 erosion model A2.
DU 96-W-180 erosion type A, stage 2
Re=1,850,000 (1470cs)

Fig. 3.5: (continued) Lift and pitching moment for the DU 96-W-180 erosion model A2.
Fig. 3.6: Drag polar for the DU 96-W-180 erosion model A2.
Fig. 3.7: Lift and pitching moment for the DU 96-W-180 erosion model A3.
Fig. 3.7: (continued) Lift and pitching moment for the DU 96-W-180 erosion model A3.
DU 96-W-180 erosion type A, stage 3

Fig. 3.8: Drag polar for the DU 96-W-180 erosion model A3.
Fig. 3.9: Lift and pitching moment for the DU 96-W-180 erosion model B2.
Fig. 3.9: (continued) Lift and pitching moment for the DU 96-W-180 erosion model B2.
DU 96-W-180
erosion type B, stage 2
\(\Re = 1,000,000\) (1491sn)
\(\Re = 1,500,000\) (1493sn)
\(\Re = 1,850,000\) (1495cs)

Fig. 3.10: Drag polar for the DU 96-W-180 erosion model B2.
Fig. 3.11: Lift and pitching moment for the DU 96-W-180 erosion model B3.
Fig. 3.11: (continued) Lift and pitching moment for the DU 96-W-180 erosion model B3.
Fig. 3.12: Drag polar for the DU 96-W-180 erosion model B3.
Fig. 3.13: Lift and pitching moment for the DU 96-W-180 erosion model B4.
DU 96-W-180 erosion type B, stage 4
Re=1,850,000 (1488cs)

Fig. 3.13: (continued) Lift and pitching moment for the DU 96-W-180 erosion model B4.
Fig. 3.14: Drag polar for the DU 96-W-180 erosion model B4.
Fig. 3.15: Lift and pitching moment for the DU 96-W-180 erosion model C3.
DU 96-W-180 erosion type C, stage 3
Re=1,850,000 (1506sn)

Fig. 3.15: (continued) Lift and pitching moment for the DU 96-W-180 erosion model C3.
Fig. 3.16: Drag polar for the DU 96-W-180 erosion model C3.
Fig. 3.17: Lift and pitching moment for the DU 96-W-180 erosion model C4.
Fig. 3.17: (continued) Lift and pitching moment for the DU 96-W-180 erosion model C4.
Fig. 3.18: Drag polar for the DU 96-W-180 erosion model C4.
Fig. 3.19: Lift and pitching moment for the DU 96-W-180 erosion model C5.
Fig. 3.19: (continued) Lift and pitching moment for the DU 96-W-180 erosion model C5.
Fig. 3.20: Drag polar for the DU 96-W-180 erosion model C5.
Fig. 3.21: Lift and pitching moment for the clean DU 96-W-180 with bugs.
Fig. 3.21: (continued) Lift and pitching moment for the clean DU 96-W-180 with bugs.
Fig. 3.22: Drag polar for the clean1 DU 96-W-180 with bugs.
DU 96-W-180
erosion type A, stage 1 with bugs
Re=1,500,000 (1444sn)

DU 96-W-180
erosion type A, stage 1 with bugs
Re=1,500,000 (1444sn)

Fig. 3.23: Lift and pitching moment for the A1 type eroded DU 96-W-180 with bugs.
DU 96-W-180 erosion type A, stage 1 with bugs $\text{Re} = 1,850,000$ (1446sn)

Fig. 3.23: (continued) Lift and pitching moment for the A1 type eroded DU 96-W-180 with bugs.
DU 96–W–180 erosion type A, stage 1 with bugs

Fig. 3.24: Drag polar for the A1 type eroded DU 96-W-180 with bugs.
Fig. 3.25: Lift and pitching moment for the A2 type eroded DU 96-W-180 with bugs.
DU 96-W-180 erosion type A, stage 2 with bugs $Re=1,850,000$ (1482as)

Fig. 3.25: (continued) Lift and pitching moment for the A2 type eroded DU 96-W-180 with bugs.
DU 96-W-180 erosion type A, stage 2 with bugs

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Fig. 3.26: Drag polar for the A2 type eroded DU 96-W-180 with bugs.
Fig. 3.27: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.27: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.28: Drag polar for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.29: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at \( x/c = 20\% \) on the upper surface and \( x/c = 20\% \) on the lower surface.
Fig. 3.29: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.30: Drag polar for the DU 96-W-180 with 0.0035-in vinyl trip at \( x/c = 20\% \) on the upper surface and \( x/c = 20\% \) on the lower surface.
Fig. 3.31: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.31: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.32: Drag polar for the DU 96-W-180 with 0.0035-in vinyl trip at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.33: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.33: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.34: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.35: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.35: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
DU 96-W-180
0.0035" vinyl tape u.s. x/c=10%, l.s. x/c=20%

Fig. 3.36: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.37: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.37: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.38: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.39: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.39: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
DU 96-W-180

0.0035" vinyl tape u.s. x/c=20%, l.s. x/c=20%

○ Re = 1,000,000 (1347as)
□ Re = 1,500,000 (1349cs)
○ Re = 1,850,000 (1351cs)

Fig. 3.40: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at x/c = 20% on the upper surface and x/c = 20% on the lower surface.
Fig. 3.41: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.41: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.42: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface.
Fig. 3.43: Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.43: (continued) Lift and pitching moment for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.44: Drag polar for the DU 96-W-180 with 0.0035-in vinyl tape ending at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface.
Fig. 3.45: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A1 at $Re = 1,000,000$. 

DU 96-W-180
erosion type A, stage 1
$Re=1,000,000$

erosion (1431as)
clean (1275as)
Fig. 3.46: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A1 at $Re = 1,500,000$. 

DU 96-W-180
erosion type A, stage 1
$Re$=1,500,000
© clean (1277as)
erosion (1433as)
Fig. 3.47: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A1 at $Re = 1,850,000$. 
Fig. 3.48: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A2 at $Re = 1,000,000$. 
Fig. 3.49: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A2 at $Re = 1,500,000$. 
DU 96-W-180
erosion type A, stage 2
Re=1,850,000

Fig. 3.50: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A2 at Re = 1,850,000.
Fig. 3.51: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A3 at $Re = 1,000,000$. 

DU 96-W-180 erosion type A, stage 3
Re = 1,000,000

clean (1275as)
erosion (1419sn)
Fig. 3.52: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A3 at $Re = 1,500,000$. 
Fig. 3.53: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A3 at $Re = 1,850,000$. 

DU 96-W-180 erosion type A, stage 3 $Re = 1,850,000$

clean (1279as) erosion (1423sn)

Fig. 3.53: Performance comparison of the clean DU 96-W-180 airfoil and erosion model A3 at $Re = 1,850,000$. 

DU 96-W-180 erosion type A, stage 3 $Re = 1,850,000$

clean (1279as) erosion (1423sn)
Fig. 3.54: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B2 at $Re = 1,000,000$. 
Fig. 3.55: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B2 at $Re = 1,500,000$. 
Fig. 3.56: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B2 at $Re = 1,850,000$. 
Fig. 3.57: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B3 at $Re = 1,000,000$. 

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Fig. 3.58: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B3 at $Re = 1,500,000$. 
DU 96-W-180
erosion type B, stage 3
Re=1,850,000
clean (1279as)
erosion (1459as)

Fig. 3.59: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B3 at Re = 1,850,000.
Fig. 3.60: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B4 at $Re = 1,000,000$. 
DU 96-W-180
erosion type B, stage 4
Re=1,500,000

© clean (1277as)

Fig. 3.61: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B2 at Re = 1,500,000.
Fig. 3.62: Performance comparison of the clean DU 96-W-180 airfoil and erosion model B4 at $Re = 1,850,000$. 
Fig. 3.63: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C3 at $Re = 1,000,000$. 

DU 96-W-180
erosion type C, stage 3
$Re=1,000,000$

clean (1275as)
erosion (1503sn)

© clean (1275as)
erosion (1503sn)
Fig. 3.64: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C3 at $Re = 1,500,000$. 
Fig. 3.65: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C3 at $Re = 1,850,000$. 

DU 96-W-180
erosion type C, stage 3
Re=1,850,000

clean (1279as)
erosion (1507sn)
Fig. 3.66: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C4 at $Re = 1,000,000$. 

DU 96-W-180
erosion type C, stage 4
$Re=1,000,000$

© clean (1275as)
 erosion (1497as)
Fig. 3.67: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C4 at $Re = 1,500,000$. 

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Fig. 3.68: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C4 at $Re = 1,850,000$. 
Fig. 3.69: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C5 at $Re = 1,000,000$. 


d (deg)

C_d

C_l
clean (1275as) erosion (1609as)
DU 96-W-180 erosion type C, stage 5

Re=1,000,000

° clean (1275as)

° erosion (1609as)

DU 96-W-180 erosion type C, stage 5

Re=1,000,000

° clean (1275as)

° erosion (1609as)
Fig. 3.70: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C5 at $Re = 1,500,000$. 
Fig. 3.71: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C5 at $Re = 1,850,000$. 

Fig. 3.72: Performance comparison of the clean DU 96-W-180 airfoil and erosion model C5 at $Re = 1,850,000$. 

DU 96-W-180
erosion type C, stage 5
$Re=1,850,000$
clean (1279as)
erosion (1613as)
Fig. 3.72: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with stage-1 bugs at $Re = 1,000,000$. 

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Fig. 3.73: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with stage-1 bugs at $Re = 1,500,000$. 
Fig. 3.74: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with stage-1 bugs at $Re = 1,850,000$. 

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Fig. 3.75: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-1 with bugs at
$Re = 1,000,000$. 
Fig. 3.76: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-1 with bugs at $Re = 1,500,000$. 
Fig. 3.77: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-1 with bugs at $Re = 1,850,000$. 

DU 96-W-180
erosion type A, stage 1 with bugs
Re=1,850,000
© clean (1279as)
© erosion (1435cs)
bugs (1447sn)

$\alpha$ (deg)
$C_d$
$C_l$
clean (1279as)
erosion (1435cs)
bugs (1447sn)
DU 96-W-180erosion type A, stage 1 with bugs
$Re=1,850,000$

0.00 0.005  0.01 0.015  0.02 0.025
−0.5
 0.0
 0.5
 1.0
 1.5

2.0
−10   0  10  20

$\alpha$ (deg)
$C_d$
$C_l$
clean (1279as)
erosion (1435cs)
bugs (1447sn)
DU 96-W-180erosion type A, stage 1 with bugs
$Re=1,850,000$

0.00 0.005  0.01 0.015  0.02 0.025
−0.5
 0.0
 0.5
 1.0
 1.5

2.0
−10   0  10  20
Fig. 3.78: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-2 with bugs at $Re = 1,000,000$. 

DU 96-W-180
erosion type A, stage 2 with bugs
$Re=1,000,000$

clean (1275as)
erosion (1467as)
bugs (1479as)
Fig. 3.79: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-2 with bugs at $Re = 1,500,000$. 
DU 96-W-180 erosion type A, stage 2 with bugs
Re = 1,850,000

Fig. 3.80: Performance comparison of the clean DU 96-W-180 airfoil and Type A, stage-2 with bugs at $Re = 1,850,000$. 
Fig. 3.81: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,850,000$. 
Fig. 3.82: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,500,000$. 
Fig. 3.83: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,850,000$. 
Fig. 3.84: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,000,000$. 
Fig. 3.85: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,500,000$. 
Fig. 3.86: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 10\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,850,000$. 
Fig. 3.87: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,000,000$. 
Fig. 3.88: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,500,000$. 
Fig. 3.89: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 20\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,850,000$. 
Fig. 3.90: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at \( x/c = 20\% \) on the upper surface and \( x/c = 20\% \) on the lower surface at \( Re = 1,000,000 \).
Fig. 3.91: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,500,000$. 
Fig. 3.92: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 20\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,850,000$. 

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Fig. 3.93: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at \(x/c = 30\%\) on the upper surface and \(x/c = 10\%\) on the lower surface at \(Re = 1,000,000\).
Fig. 3.94: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,500,000$. 
Fig. 3.95: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 30\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,850,000$. 
Fig. 3.96: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,000,000$. 

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Fig. 3.97: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,500,000$. 

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Fig. 3.98: Performance comparison of the clean DU 96-W-180 airfoil and the airfoil with 0.0035-in vinyl tape at $x/c = 30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,850,000$. 

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Fig. 3.99: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models A1, A2 and A3 at $Re = 1,000,000$
Fig. 3.100: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models A1, A2 and A3 at $Re = 1,500,000$. 
Fig. 3.101: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models A1, A2 and A3 at $Re = 1,850,000$
Fig. 3.102: Comparison of the percentage drag rise due to the three stages of Type A leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,000,000$

Fig. 3.103: Comparison of the percentage drag rise due to the three stages of Type A leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,500,000$
Fig. 3.104: Comparison of the percentage drag rise due to the three stages of Type A leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,850,000$
Fig. 3.105: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models B2, B3 and B4 at $Re = 1,000,000$. 

DU 96–W–180
Erosion Comparison (Type B)

$Re=1,000,000$

Clean
Stage 2
Stage 3
Stage 4

$C_d$

$\alpha$ (deg)
Fig. 3.106: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models B2, B3 and B4 at $Re = 1,500,000$
Fig. 3.107: Comparison of the drag polar and lift curve of clean the DU 96-W-185 airfoil and erosion models B2, B3 and B4 at $Re = 1,850,000$. 

DU 96–W–180
Erosion Comparison (Type B)

$Re=1,850,000$

Clean
Stage 2
Stage 3
Stage 4
α (deg)

$C_d$

$C_l$
Fig. 3.108: Comparison of the percentage drag rise due to the three stages of Type B leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,000,000$

Fig. 3.109: Comparison of the percentage drag rise due to the three stages of Type B leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,500,000$
Fig. 3.110: Comparison of the percentage drag rise due to the three stages of Type B leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,850,000$
Fig. 3.111: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models C3, C4 and C5 at $Re = 1,000,000$. 
Fig. 3.112: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models C3, C4 and C5 at $Re = 1,500,000$
Fig. 3.113: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models C3, C4 and C5 at $Re = 1,850,000$
Fig. 3.114: Comparison of the percentage drag rise due to the three stages of Type C leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,000,000$

Fig. 3.115: Comparison of the percentage drag rise due to the three stages of Type C leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,500,000$
Fig. 3.116: Comparison of the percentage drag rise due to the three stages of Type C leading edge erosion on the DU 96-W-180 airfoil at $Re = 1,850,000$
Fig. 3.117: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and airfoil with stage 1 and stage 2 bugs at $Re = 1,500,000$
Fig. 3.118: Comparison of the drag polar and lift curve of the clean DU 96-W-180 airfoil and erosion models A1 and A2 with and without bugs at $Re = 1,500,000$
Fig. 3.119: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,000,000$. 
Fig. 3.120: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,500,000$.
Fig. 3.121: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface at $Re = 1,850,000$.
Fig. 3.122: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,000,000$

Fig. 3.123: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,500,000$
Fig. 3.124: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 20\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,850,000$
Fig. 3.125: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,000,000$
Fig. 3.126: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,500,000$
Fig. 3.127: Comparison of the drag polar and lift curve for DU 96-W-180 airfoil with WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 10\%$ on the lower surface at $Re = 1,850,000$
Fig. 3.128: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 10\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,000,000$

Fig. 3.129: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%, 20\%$ and $30\%$ on the upper surface and $x/c = 10\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,500,000$
Fig. 3.130: Comparison of the percentage drag rise due to WPT ending at $x/c = 10\%$, 20\% and 30\% on the upper surface and $x/c = 10\%$ on the lower surface on the DU 96-W-180 airfoil at $Re = 1,850,000$
3.6 Effect of Leading Edge Erosion and Accretion

The DU 96-W-180 airfoil was tested with different types and levels of leading edge erosion. The results obtained from testing the various simulated leading edge erosion cases showed that erosion can severely hamper the performance of the airfoil. The detrimental effect of the leading edge erosion on the performance of DU 96-W-180 airfoil has been tabulated (Table 3.1). The table lists the percentage increase in drag and the loss in lift due to the different erosion cases. For the three cases A2, B3 and C4 the annual loss in energy has also been shown. The results are derived from an analysis for estimating and assessing the possible loss in performance of a wind turbine with similar erosion features on its blades. The design and performance analysis was carried out using PROPID, a wind turbine design code [24, 25]. Modeling of the wind turbine was based on a 2.5-MW class turbine. Analysis in clean and rough conditions was done to estimate the loss in the annual energy production (AEP) due to erosion and soiling. Even though the degradation in airfoil performance was applied along the entire blade a major part of AEP shown in the table is primarily from the outer part of the blade.

The tabulated data shows that there is an increase in $\Delta C_d$ value from 6% to 500% as the severity of erosion is intensified. A significant loss in lift coefficient, of almost 0.17, can be observed for Type C/Stage 5 along with drag magnification. The drag rise and loss in lift hamper the overall performance of the wind turbine. The energy loss estimate revealed that the smallest of leading edge erosion can lead to losses close to 400 MWh/yr. For Type C cases that were tested, AEP losses can reach a high value of approximately 2000 MWh/yr, which is equal to the energy generated through the continuous operation of a 2.5-MW turbine for a month at peak power.

For the simplest and the earliest stage of erosion involving a small number of pits on and around the leading edge (simulated by Type A/Stage 1), the percentage drag rise was close to 6%, which can be considered to be in the acceptable range. The progressive increase in the erosion severity while moving to higher stages, points to a steep rise in drag values. For the models A2 to C5 the data from the tests showed a drag increase of 80–500% due to leading edge erosion. Besides the drag rise, a significant reduction in lift coefficient is also observed especially at higher angles of attack that are experienced by wind turbine blades during operation. The 80% drag rise in the initial erosion stages could lead to an annual energy production loss of 5% as predicted by PROPID. The cases with 400–500% drag rise coupled with loss of lift can have the annual energy production losses of up to 24%.

During the normal operation, wind turbine blades are likely to develop both erosion and accretion features on the surfaces. Hence, simulated insect accretion cases were also tested as described in Section 2.5. These simulated insect contamination cases pointed to high losses in performance. The models A1 and A2 when
tested with bugs on them showed a far worse performance than the simple erosion cases. The test results also point to a greater energy loss due to the combined effects of erosion and accretions.

Table 3.1: Effect of Leading Edge Erosion on Wind Turbine Blade Performance as Estimated by PROPID [24, 25]

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\Delta C_d$</th>
<th>$\Delta C_l$</th>
<th>Avg Wind Speed (m/s)</th>
<th>AEP Loss (MWh/yr)</th>
<th>AEP Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>+6%</td>
<td>-0.07</td>
<td>7.05</td>
<td>383</td>
<td>-4.85%</td>
</tr>
<tr>
<td>A2</td>
<td>+80%</td>
<td>-0.12</td>
<td>7.93</td>
<td>392</td>
<td>-4.10%</td>
</tr>
<tr>
<td>A3</td>
<td>+150%</td>
<td>-0.15</td>
<td>8.81</td>
<td>384</td>
<td>-3.49%</td>
</tr>
<tr>
<td>B2</td>
<td>+150%</td>
<td>-0.16</td>
<td>7.05</td>
<td>902</td>
<td>-11.42%</td>
</tr>
<tr>
<td>B3</td>
<td>+200%</td>
<td>-0.14</td>
<td>7.93</td>
<td>930</td>
<td>-9.73%</td>
</tr>
<tr>
<td>B4</td>
<td>+400%</td>
<td>-0.15</td>
<td>8.81</td>
<td>917</td>
<td>-8.33%</td>
</tr>
<tr>
<td>C3</td>
<td>+150%</td>
<td>-0.16</td>
<td>7.05</td>
<td>1,858</td>
<td>-23.53%</td>
</tr>
<tr>
<td>C4</td>
<td>+400%</td>
<td>-0.15</td>
<td>7.93</td>
<td>1,948</td>
<td>-20.38%</td>
</tr>
<tr>
<td>C5</td>
<td>+500%</td>
<td>-0.17</td>
<td>8.81</td>
<td>1,947</td>
<td>-17.68%</td>
</tr>
</tbody>
</table>
3.7 Effect of Wind Protection Tape and Trips

The DU 96-W-180 airfoil was tested with the wind protection tape wrapped around the leading edge. The different cases were based on the changes in the extent of the tape on the upper and lower surfaces. The results pointed to a small to moderate increase in drag which depended on the extent of the tape on the upper and lower surfaces. Based on the performance analysis using the test data, a drag rise of 5–15% was observed due to the wind protection tape. PROPID analysis of a particular case with upper and lower surface tape extents of \( x/c = 20\% \) showed a drag rise of 8% resulting in a loss of 0.38% in annual energy production [24, 25].

Trips were used in order to induce the effect of the backward facing step of the WPT which is responsible for the drag rise due to tripping of the flow. However the results of the airfoil with trips and with WPT were not matching perfectly. Hence further testing of airfoils with trips was discontinued.

The estimated energy losses due to the tape are lesser as compared to even the light leading edge erosion. The performance loss due to the usage of the WPT can be minimized by moving the tape edge further back towards the trailing edge.

The overall effect of the WPT on the performance of the DU 96-W-180 airfoil has been tabulated (Table 3.2). The table provides the percentage increase in drag and loss in lift due to the various tape configurations that were tested. For a particular tape configuration of \( x/c = 20\% \) on both upper and lower surfaces, the annual loss in energy has been shown in the table. The tabulated data is derived from PROPID analysis carried out to estimate the potential loss in performance of a wind turbine operating with a similar WPT applied to its surface [24, 25]. Similar to the erosion cases, the modeling of the wind turbine was based on a 2.5-MW class turbine. The analysis was carried out for the clean conditions along with the different tape configurations for estimating the loss in annual energy production (AEP) due to the WPT. It was observed that the maximum AEP loss was incurred from the outer part of the wind turbine.

The tabulated data shows that there is an increase in drag of 5–21% depending on the extent of the tape on the upper and lower surfaces. There is also a small loss in the lift coefficient at higher angles of attack. For the particular configuration of tape chosen (\( x/c = 20\% \) on upper and lower surfaces), the annual energy loss is estimated to be approximately 36 MWh/yr. This value is insignificant when compared to the losses due to erosion which is far more detrimental to the turbine performance.
Table 3.2: Effect of Wind Protection Tape on Wind Turbine Blade Performance as Estimated by PROPID [24, 25]

<table>
<thead>
<tr>
<th>Configuration (upper / lower)</th>
<th>$\Delta C_d$</th>
<th>$\Delta C_l$</th>
<th>Avg Wind Speed (m/s)</th>
<th>AEP Loss (MWh/yr)</th>
<th>AEP Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% / 20%</td>
<td>+5%</td>
<td>-0.00</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>30% / 10%</td>
<td>+6%</td>
<td>-0.01</td>
<td>7.05</td>
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Chapter 4

Conclusions and Recommendations

4.1 Summary

The experimental investigation was carried out in order to determine and quantify the detrimental effects of erosion and accretion on the performance of a wind turbine. A wind protection tape was also tested and its effects on the wind turbine performance were determined. The airfoil that was chosen for the tests was the DU 96-W-180. The models were tested in the UIUC 3 × 4 ft low-speed, low turbulence wind tunnel at Reynolds numbers of $1 \times 10^6$, $1.5 \times 10^6$ and $1.85 \times 10^6$. The performance of the clean airfoil was used as a baseline for all measurements. The simulated leading edge erosion included the following features: pits, gouges and leading edge delamination. The extent of these features was based on an upper-to-lower surface impingement ratio of 1:1.3 following a Gaussian distribution. Bugs made up of small pieces of the scaled down version of the 3M WPT were added on the clean airfoil and models A1 and A2 to simulate the effect of insect contamination. Additionally, the performance of the airfoil was measured with different extents of the leading edge WPT. Using a traversable wake rake and a three-component force balance, steady-state lift, drag and quarter-chord pitching moment data was taken. Trends in the lift and drag data were used to identify the effects of erosion, bugs and WPT on the aerodynamic characteristics and performance of the airfoil.

4.2 Conclusion and Recommendations

The aim of the research was to estimate and quantify the performance deterioration of wind turbine blades due to erosion near the leading edge and to compare it with the changes in performance that arise when a Wind Protection Tape is applied to protect the leading edge. For the initial part of the study, DU 96-W-180 airfoil was tested with various types and magnitudes of leading edge erosion. It was seen that even small amounts of irregularities and imperfection in the smoothness of the leading edge can have adverse effects on the performance of the blade airfoil. The increase in drag due to leading edge erosion spanned over a range of 6–500% (light-to-heavy erosion cases). The quantification of the drag rise was done by measuring
the shift in drag polars of the different erosion models to the higher side as compared to the clean case. The loss in lift due to erosion was substantial especially at higher angles of attack which are experienced by the turbine blades during normal operation. Similar to leading edge erosion, simulated bugs also resulted in a significant loss in performance. PROPID analysis estimated that an 80% increase in drag, which was caused by a relatively small degree of leading edge erosion, can result in approximately 5% loss in the annual energy production [24, 25]. For a drag rise of 400–500% this loss in annual energy production can be as high as 25%.

As an erosion mitigation method, analysis of the use of Wind Protection Tape was carried out during the study. The effect of using WPT wrapped around the leading edge, on the blade performance was quantified by testing the DU 96-W-180 airfoil with varying extents of the leading edge protection tape on the upper and lower surfaces. The results that were obtained indicate a relatively small drag rise depending on the extent of the tape on the upper and lower surfaces. The rise in drag values due to the use of the WPT spanned a range of 5–15%. The loss in lift due to the tape usage was insignificant. For a particular case of the tape extending up to 20% on both upper and lower surfaces, the predicted annual energy loss was close to 0.38%.

The results point to a need for new and efficient erosion mitigation strategies. The ultimate goal of the study was to compare the results of the erosion and Wind Protection Tape tests and their relative impacts on the blade performance. The highly detrimental nature of erosion is evident from the performance loss values that were obtained from the test results. Compared to erosion, the use of WPT has less than significant effect on the airfoil performance. Even very light leading edge erosion can reduce the annual energy production by many times of that due to the usage of WPT. The cost of replacing and using WPT, taking into account the minute performance changes, is considerably lower as compared to the cost of running the turbine with eroded blades or replacing an eroded blade all together. Furthermore there are methods through which the performance deterioration due to the WPT can be reduced. As observed from the experimental results, moving the tape end further towards the trailing edge of the airfoil leads to a reduction in the drag rise value. The backward facing step created due to the tape aft edge, which is the cause of tripping of the flow and the drag rise, can be totally eliminated if the tape is integrated with the airfoil. Besides integration with the airfoil, another method through which the drag rise can be alleviated is by tapering and thinning the WPT near the aft edge so as to have a smaller thickness of the backward facing step. In order to develop an ideal method for preventing erosion, optimization of the operation and maintenance costs along with the performance is required. The challenge lies in determining the most effective tape configuration for a specific wind turbine blade. There are a number of factors that need to be looked into for the optimum design like tape thickness, edge finish, chordwise coverage, radial coverage etc. Based on the test results that were
obtained, it is safe to conclude that using a WPT is a simple, feasible and cost effective method to protect a wind turbine blade from erosion and contamination occurring after just a few years of operation.
Chapter 5

References


