Leading edge erosion of wind turbine blades

Hasager, Charlotte Bay; Bech, Jakob Ilsted; Kusano, Yukihiro; Sjöholm, Mikael; Mikkelsen, Torben Krogh; Bak, Christian; Skrzypinski, Witold Robert; Fæster, Søren; Tilg, Anna-Maria; Vejen, Flemming; Madsen, Martin Bonde; Bayar, Mertcan; Pedersen, Morten Saldern; Halling, Kaj M.

Publication date:
2018

Document Version
Peer reviewed version

Citation (APA):
Leading Edge Erosion of Wind Turbine Blades

Charlotte Hasager, Jakob Ilsted Bech, Yukihiro Kusano, Mikael Sjöholm, Torben Mikkelsen, Christian Bak, Witold Skrzypinski, Søren Fæster, Anna-Maria Tilg (DTU)
Flemming Vejen (DMI)
Martin Bonde Madsen (R&D)
Mertcan Bayar (E.ON)
Morten Saldern (Vattenfall)
Kaj M. Halling (Vestas)
Leading Edge Erosion of Wind Turbine Blades

• Wind turbine blades erosion: Reducing the largest uncertainties (EROSION project)

• Extension of the life of blade leading edges by reducing the tip speed during extreme precipitation events

• The meteorological perspectives in rain erosion at leading edges of wind turbine blades
Content

- The EROSION project in brief
- Reducing tip speeds during rain events to extend the life time of blades
- Meteorological perspectives
- Conclusion
The EROSION project in brief

www.rain-erosion.dk
1. **Research hypothesis:** Erosion damage is mainly generated during heavy precipitation (big drops of rain or hail), which occurs in a very little fraction of the turbines operation time. By reducing the tip speed of the blades in these few hours a significant extension of the leading edge lifetime can be obtained with negligible loss of production.

2. **Methodology:** Define rain and hail erosion classes to quantify leading edge blade in-field and in lab testing. Correlations between rain intensity, droplet size, impact speed, materials properties, etc. will be established.

3. **Measurement Device:** Low-cost prototype for precipitation measurement on site and real time warning device enabling modern control of wind turbines.

4. **Erosion safe mode:** A safe mode control based on the erosion classes to control the wind turbine, reducing the tip speed under severe conditions – preventing aerodynamic degradation and reducing maintenance costs.
Rain Erosion Tester by R&D Test Systems

Example of specimen
**First results**

RET test results for EROSION specimen.
Damage is the first visual damage point of erosion.

- **3.5 mm droplets**
  - Rain intensity 58 mm/hour
- **2.4 mm droplets**
  - 29 mm/hour
- **3 (4) different velocities**
- **3 blades**

Stop frequently and map the new point damages each time.

DTU Wind Energy, Technical University of Denmark
First results

![Graph showing kinetic energy vs. impacts to failure for two droplet sizes: 3.5 mm and 2.4 mm. The graph includes fitting lines and confidence intervals.](image-url)
Rain erosion test samples with different degradation have been investigated by electron microscopy.

The erosion appears to start at the surface where the surface roughness increase. However at the same time as the top-coating and the filler slowly degrades microscale damage can be observed within the laminate. Cracks have been observed at the position of the peel fly as well as within the laminate.

Electron microscopy provide a snapshot of the degradation in a polished cross section.
Rain erosion specimen testing map

EROSION test campaign

Leading edge configurations

“conventional coating”
LEP
Filler
Layer thicknesses

v1, v2, v3, v4, v5
Speed
d1, d2, d3
droplet size
sq1
sq2
sq3

Test parameters

Characterisation

Failure modes

Pre test
Post test

X CT
US
SEM

Light Microscopy

surface cracks
debonding of layers
crushing of filler
sub surface cracks

X CT: X-ray Computed Tomography
US: Ultrasonic Scanning
SEM: Scanning Electron Microscopy
Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events

Extending the life of wind turbine blade leading edges by reducing the tip speed during extreme precipitation events

Jakob I. Bech¹, Charlotte B. Hasager¹, Christian Bak¹

¹Department of Wind Energy, Technical University of Denmark, Roskilde, 4000, Denmark

Correspondence to: Jakob Ilisted Bech (jakb@dtu.dk)
Rain erosion test data plotted as a Wöhler curve

![Graph showing rain erosion test data plotted as a Wöhler curve. The x-axis represents time to removed coating in hours, ranging from 0.1 to 10.0. The y-axis represents local rotor speed in m/s, ranging from 60 to 160. The graph shows a downward trend indicating the relationship between time and speed.]
Rain erosion test data plotted as a Wöhler curve: Impacts per unit area to failure as function of the kinetic energy for each impact

\[ E_k = \frac{1}{12} \rho \pi D^3 v_t^2 \ [J] \]
Wöhler curves for droplet diameters of 1.5, 2.0 and 2.5 mm

![Graph showing Wöhler curves for droplet diameters of 1.5, 2.0, and 2.5 mm. The x-axis represents impacts/area to removed coating in cm$^{-2}$, and the y-axis represents local rotor speed in m/s. Different curves are shown for each droplet diameter, with markers indicating RET results.]
Control of turbine

Turbine follows pitch-RPM table until rated power and adjusts pitch not to exceed rated power afterwards.

Power = Torque * Rotational Speed
Erosion safe-mode

In an erosion-safe mode the turbine would be downrated meaning that it would act as its rated power was lower than default. That would effectively decrease the rated RPMs.

Power = Torque * Rotational_Speed
Control strategies

Apart from a reference case where it is assumed that there is no erosion, six different control strategies are investigated based on the model for expected lifetime for the blade leading edge:

- Control strategy 1 with expected life time of 1.6 years
- Control strategy 2 with expected life time of 10.4 years
- Control strategy 3 with expected life time of 24.4 years
- Control strategy 4 with expected life time of 53.9 years
- Control strategy 5 with expected life time of 106.5 years
- Control strategy 6 with expected life time of infinite many years
Calculation of the life time of the blade leading edge with no reduction of the tip speed. Control strategy 1

<table>
<thead>
<tr>
<th>Rain intensity [mm/hr]</th>
<th>Droplet size [mm]</th>
<th>Percent of time [%]</th>
<th>Hours pr year [hrs/year]</th>
<th>Blade tip speed [m/s]</th>
<th>Hours to failure [hrs]</th>
<th>Fraction of life spent pr year [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.5</td>
<td>0.02</td>
<td>1.8</td>
<td>90</td>
<td>3.5</td>
<td>51</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>0.1</td>
<td>8.8</td>
<td>90</td>
<td>79</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>1</td>
<td>88</td>
<td>90</td>
<td>3606</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>3</td>
<td>263</td>
<td>90</td>
<td>745710</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>438</td>
<td>90</td>
<td>2830197826</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Sum of fractions [%]: 64

Expected life [years]: 1.6
Calculation of the life time of the blade leading edge with reduction of the tip speed to 70m/s and 80m/s, respectively: Control strategy 2

<table>
<thead>
<tr>
<th>Rain intensity [mm/hr]</th>
<th>Droplet size [mm]</th>
<th>Percent of time [%]</th>
<th>Hours pr year [hrs/year]</th>
<th>Blade tip speed [m/s]</th>
<th>Hours to failure [hrs]</th>
<th>Fraction of life spent pr year [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.5</td>
<td>0.02</td>
<td>1.8</td>
<td>70</td>
<td>46</td>
<td>3.8</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>0.1</td>
<td>8.8</td>
<td>80</td>
<td>263</td>
<td>3.3</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>1</td>
<td>88</td>
<td>90</td>
<td>3606</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>3</td>
<td>263</td>
<td>90</td>
<td>745710</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>438</td>
<td>90</td>
<td>2830197826</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Sum of fractions [%]: 9.6

Expected life [years]: 10.4
Calculation of the life time of the blade leading edge with reduction of the tip speed to 55m/s, 65m/s and 70m/s, respectively: Control strategy 5

<table>
<thead>
<tr>
<th>Rain intensity [mm/hr]</th>
<th>Droplet size [mm]</th>
<th>Percent of time [%]</th>
<th>Hours pr year [hrs/year]</th>
<th>Blade tip speed [m/s]</th>
<th>Hours to failure [hrs]</th>
<th>Fraction of life spent pr year [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.5</td>
<td>0.02</td>
<td>1.8</td>
<td>55</td>
<td>541</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>0.1</td>
<td>8.8</td>
<td>65</td>
<td>2215</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>1</td>
<td>88</td>
<td>70</td>
<td>47514</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>3</td>
<td>263</td>
<td>90</td>
<td>745710</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>5</td>
<td>438</td>
<td>90</td>
<td>2830197826</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Sum of fractions [%]: 0.9

Expected life [years]: 107
Simulated power curves for the Vestas V52 for different leading edge roughness levels
Simulated power curves for the Vestas V52 for different maximum tip speeds

- Clean, max tip speed = 90 m/s
- Clean, max tip speed = 80 m/s
- Clean, max tip speed = 70 m/s
- Clean, max tip speed = 60 m/s
Cost of operation and maintenance

- Energy price:
  - 50 €/MWh
  - 250 €/MWh
- Inspection cost:
  - 500 €/rotor
  - 1500 €/rotor
- Repair cost:
  - 10000 €/rotor
  - 20000 €/rotor
- Control strategy 1: 10 inspections and 9 repairs
- Control strategy 2: 10 inspections and 1 repairs
- Control strategy 3: 5 inspections and 0 repairs
- Control strategy 4: 5 inspections and 0 repairs
- Control strategy 5: 2 inspections and 0 repairs
- Control strategy 6: 2 inspections and 0 repairs

Stand still of 1 day inspected
Stand still of 2 days repaired
AEP relative to AEP with no erosion

![Bar chart showing AEP relative to AEP with no erosion for different control strategies and wind speeds.]
Loss of income due to erosion, inspection and repair

Power: 50€/MWh. Repair: 10000€/rotor. Inspection: 500€/rotor
Meteorological perspectives
Raindrop size distribution through a horizontal plane with the rain fall intensity as a parameter (from Kubilay et al., 2013, based on Best, 1950)
Average rainfall rate-frequency relationships for four rain climates (Jones and Sims, 1978) ©American Meteorological Society. Used with permission.
Meteorological observation instruments
EROSION disdrometer network
Size-Velocity histogram for year 2012 to 2017 at Voulund
DMI’s weather radar network shown with an example from 6 June 2017 at 15:20 UTC. The unit dBZ indicates the relative rain rate.
Radar QPE (quantitative precipitation estimate) field on 16 June 2016 at 0900 UTC versus raingauge at Vejle Pumpestation.
Annual rain in Denmark

The average yearly precipitation in Denmark in the reference period 1961-1990 measured in mm.

Annual rain offshore

At offshore sites there are no rain gauges thus approximation and/or extrapolation is necessary.

The new offshore disdrometer data may prove useful for radar-based rain mapping offshore.
Conclusions

The extension of blade life time using erosion safe mode is calculated based on assumptions on erosion related to rain events.

The erosion safe mode control strategy is outlined and the expected reduction in operational cost is estimated.

First tests in rain erosion tester have been completed and preliminary results on damage in specimen are available.

Precipitation data will be collected during next one year.