Abstract title: Leading Edge Protection Lifetime Prediction Model Creation and Validation
Abstract type: Science & research

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Presenting author bio: Drew Eisenberg, design and innovation engineer, at Siemens Wind Power, focuses on wind turbine blade aerodynamics. He develops tools for aeroelastic loading analysis and business case development of new technologies. He leverages his expertise in power curve creation and validation to develop software for determining wind turbine platform configurations and cost modeling. Drew has most recently developed wind turbine leading edge erosion models which can predict leading edge degradation. He has a masters degree in aerospace engineering and a bachelors degree in meteorology, both from Cornell University in New York, USA.

Abstract:

Introduction:

This paper describes how Siemens Wind Power has developed an analytical surface fatigue model to predict the initiation of leading edge erosion due to rainfall. Leading edge erosion on wind turbine blades is an industry wide problem as it may reduce the aerodynamic efficiency of wind turbines. The industry has developed multiple leading edge protection coatings intended to reduce the degradation of wind turbine blades due to this erosion. Most leading edge protection coatings are evaluated in controlled and isolated rain erosion tests in which they are subjected to a high speed whirling arm and simulated heavy rainfall. These tests are good at comparing the relative protection that the coating provides, however, they fail to predict the life time of the coating that would be expected in the field operation of a wind turbine. This paper addresses the impact physics of rain droplets in these tests and in the field to create a model to predict leading edge erosion progression at any site.

In this research, Siemens Wind Power has used rain erosion whirling arm tests to determine the surface impact fatigue resistance of different coatings used in the field. With a large database of photos of wind turbine blades, leading edge erosion observations in the field are used to validate the analytical model to accurately predict the initiation of leading edge erosion. The aerodynamic impact of the erosion has also been modeled and been used to determine the expected sectional efficiency loss of the damaged airfoils. Combining the leading edge erosion forecast model with the efficiency loss model, we have predicted the AEP loss over time on different sites due to rain induced leading edge erosion.

Approach:

The approach of this research was to start with the basic physics of liquid impact. We observed an

exponential relationship between rain erosion testing speed and the time to damage the coating. Thus, a modeling scheme similar to a traditional fatigue S-N curve based concept is suggested. We performed a literature review of surface fatigue physics and decided to develop a leading edge erosion model based upon “Erosion by Liquid Impact” by George Springer [1]. In this paper, we describe the steps taken to develop an erosion model, and how we have applied existing research to determine the degradation of AEP over time. A rough outline of the steps taken:

1. Erosion damage model developed based on research
2. Erosion model applied to rain erosion test data and the erosive strength of test materials is determined
3. Modeled erosion on field turbines using measured erosive strength, turbine operation, and rain drop distribution
4. Validated computed results against measured observations from an extensive leading edge picture database
5. Modified airfoil data corresponding to varying levels of erosion according to existing erosion research [2]
6. Simulated wind turbine efficiency over time combining erosion model with aerodynamic polar modification to determine expected AEP reduction over time

Main body of abstract:

The erosion process has multiple stages. There is initially a period of incubation in which damage is occurring to the material without noticeable change in the material. After a sufficient amount of fatigue damage has accumulated, the material starts to fail and begins to lose mass. This marks the end of the incubation period and start of the steady weight loss rate period [1]. The following figure shows the traditional erosion process:

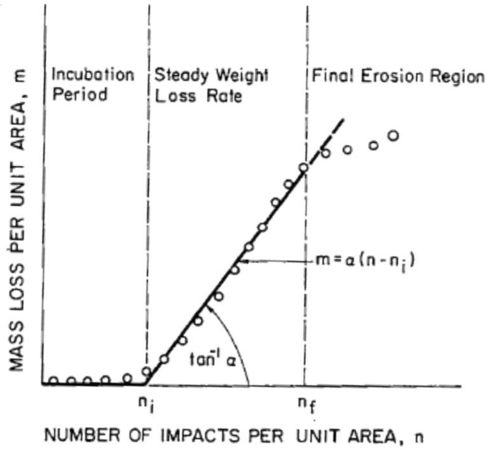


Figure 1. Mass loss verses number of droplet impacts [1]

During incubation there is no mass loss until there are enough impacts per unit area, N. After N_i impacts mass loss occurs at a steady rate. The non-dimensional number of impacts required until erosion begins is:

$$N_i^* = 7 * 10^{-6}\left(\frac{S}{P}\right)^{5.7}$$

Where S is the erosive strength of the material that has been determined through rain erosion testing and the P is the pressure of the water droplet impact. This paper will describe the process of determining the S parameter of a material and how the pressure of water droplet impact varies by coating characteristics. The rate of damage is determined in the paper as a function of droplet diameter:

$$\dot{D}_\iota = \frac{q * V_s * \beta(d)}{\frac{8.9}{d}\left(\frac{S}{P}\right)^{5.7}}$$

Where q is the number of droplets per cubic meter of air, V_s is velocity of the material in m/s, $\beta(d)$ is the impingement frequency as a function of droplet diameter, and d is the droplet diameter in mm.

Once the material properties are determined, we investigate the distribution of impact pressure on blades in the field. To do this we must determine the rain drop size distribution as a function of rain rate [3]:

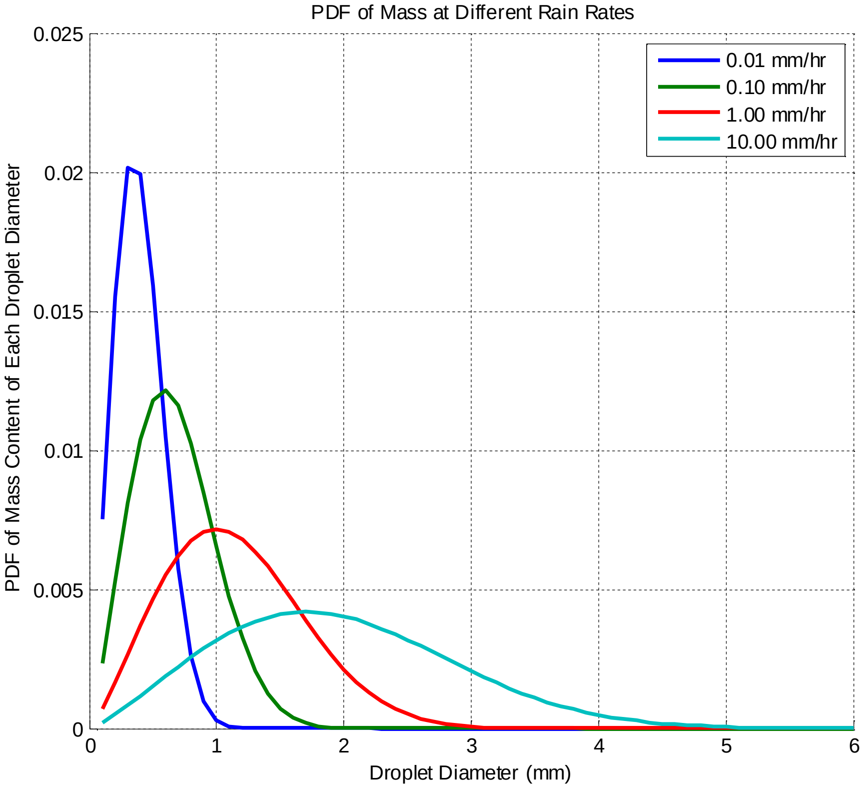


Figure 2. Probability distribution of rain droplets of given diameter for different rain rates

Given these distributions, we can solve for the amount of damage as a function of velocity and rain rate:

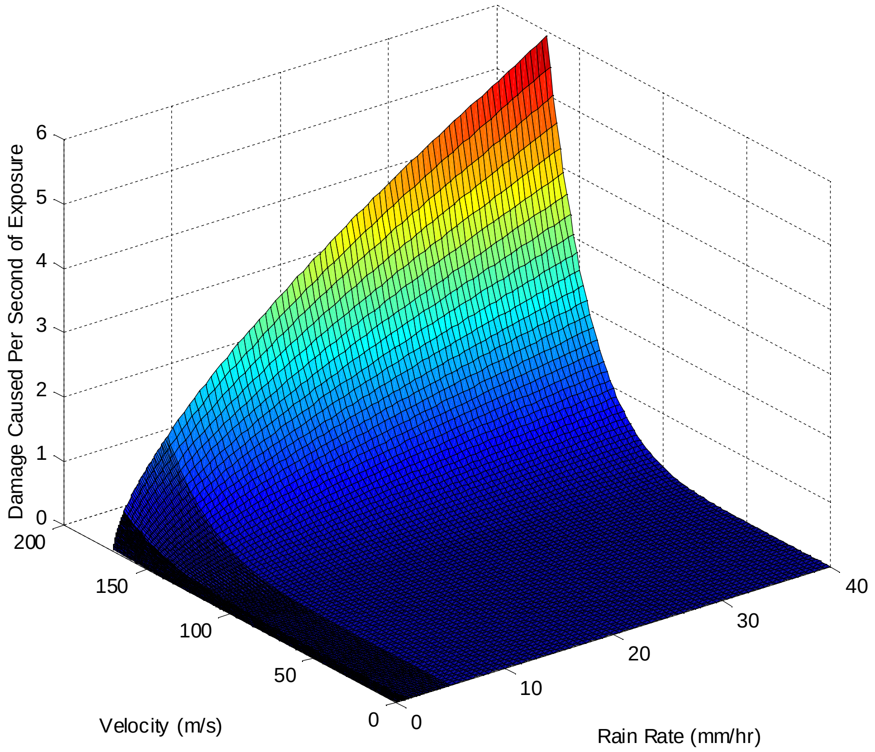


Figure 3. Non-dimensional fatigue damage as a function of blade velocity and rain rate

Using observed rainfall at each site and measured RPM for each turbine we can predict the extent of erosion on each turbine. This predicted result has been compared against turbines that have been measured in the field:

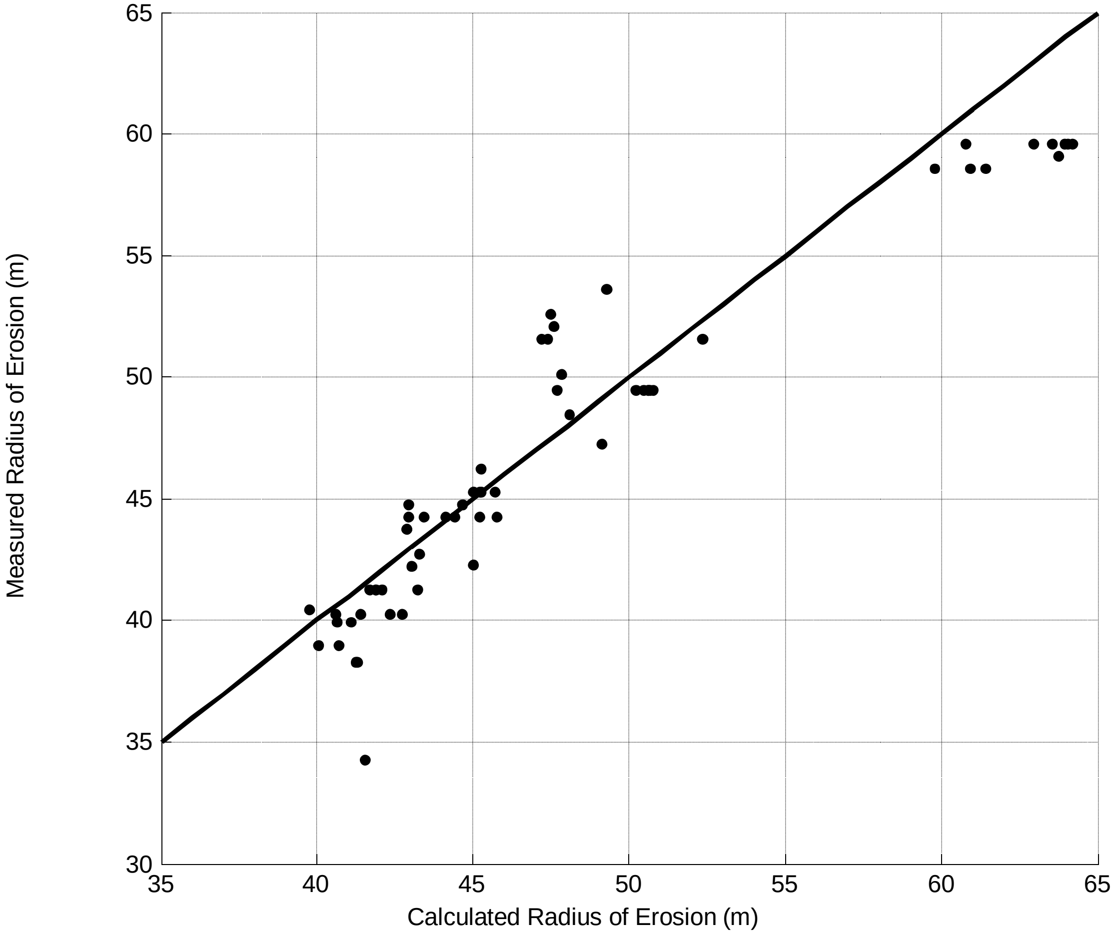


Figure 4. Measured initiation of erosion verses modeled initiation of erosion

After the surface has been fatigued to initiate erosion, there is steady material loss on the blade. The steady mass loss erosion modeling uses the same erosive strength parameter as the initiation modeling described above. Due to limited data and size scaling between the rain erosion tests and field observation, there is greater uncertainty with predictions on erosion progression. We have begun to compare the modeled steady weight loss against field observations. The erosion damage observed was then classified depending on severity with progressively degraded airfoil data according to existing research.

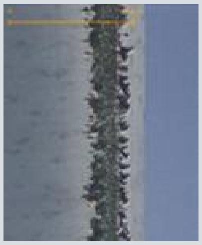
Severity Level	1	2	3	4
Example Picture				

Figure 5. Examples of leading edge erosion severity on one blade

By combining the erosion progression model with aerodynamic simulations, we are able to predict AEP loss over the lifetime of the turbine:

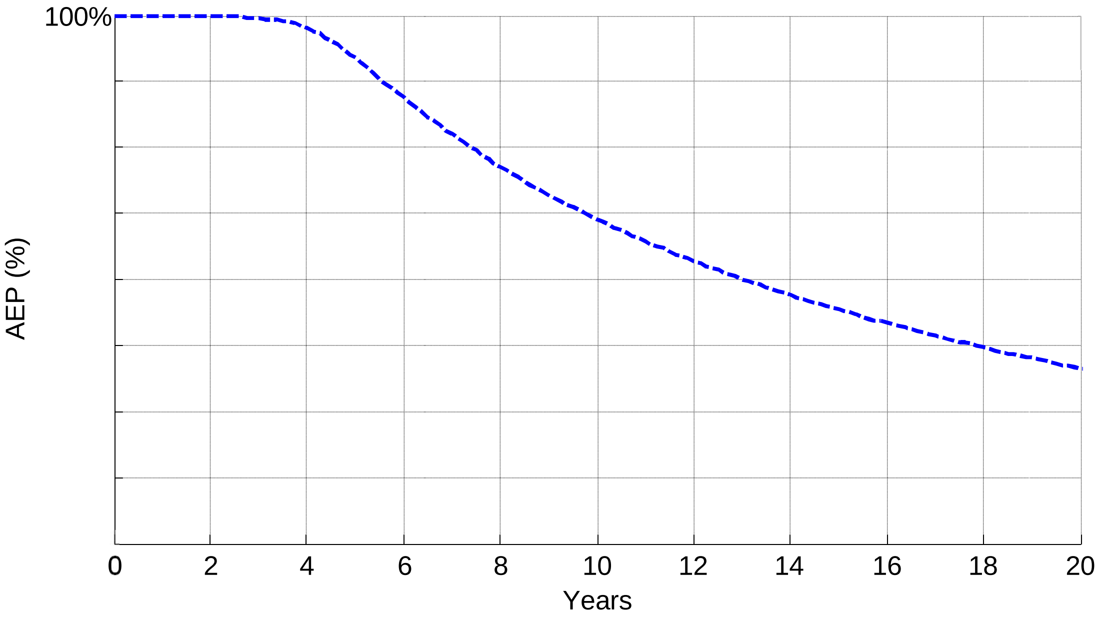


Figure 6. Example of modeled AEP percent verses years of operation.

Conclusion:

Siemens Wind Power believes that the presented modelling framework can be an accurate wind turbine leading edge erosion model. We are working with certification bodies to create wind turbine erosion standards based upon it. We have uniquely combined laboratory testing, analytical physics modeling, field results, and existing aerodynamic research to create a robust model that predicts erosion initiation and turbine AEP loss over time.

Learning objectives:

Leading edge erosion is an industry wide problem. By presenting this research, we are able to share the progress we have made in analyzing the progression, prevention, and effects of erosion. We also hope that a physics based approach will define the industry standard for determining coating lifetime from rain erosion testing.

References:

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