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Prognostic Control to Enhance Offshore Wind Turbine Operations and Maintenance Strategies

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Abstract:

Offshore wind turbines are an attractive source for clean and renewable energy for reasons including their proximity to population centers and their potential for improved capacity factors with better wind resource. However, one obstacle to the more widespread utilization of offshore wind energy is that recent projections of offshore operations and maintenance (O&M) costs vary between 2 to 5 times the costs of onshore O&M. One way to reduce those costs is through a simple yet effective structural health monitoring (SHM) system as part of an overall condition based maintenance paradigm. This paper presents the results of studies that will improve the offshore O&M process and develop a cost-beneficial SHM system. Simulations of damage are performed at multiple model scales to characterize the sensitivity and localization of damage in a blade from operational responses. Concepts for prognostic control strategies are developed for smart load management. A successful SHM system would be able to reduce or eliminate unplanned or unnecessary maintenance as well as reduce logistic lead times and optimize supply chain management through the use of prognostic control operations (e.g. predictive control to mitigate component damage growth or avoid unfavorable operating conditions). Furthermore, by integrating the health of each turbine into the operation and control of the wind farm using a damage mitigating control strategy, the overall economic profit of the wind farm could be increased.

Keywords: prognostic control, operations and maintenance, O&M, structural health monitoring, operational measurements, damage mitigation, damage simulation, trailing edge disbond.

1. INTRODUCTION

Some of the drivers for the utilization of offshore wind include the proximity of the offshore resources to population centers and the potential for higher capacity factors due to higher resource winds [1, 2]. Because of these and other potential benefits of offshore wind, the DOE Offshore Wind Innovation and Demonstration initiative has developed an ambitious goal of deploying 10 GW of offshore capacity by 2020 at a cost of energy of only $0.10/ kWh [3].

1.1. **Drivers for Offshore SHPM**

Operations and maintenance (O&M) costs are expected to be significantly higher for offshore wind turbines than onshore wind turbines. Recent projections of O&M costs have ranged between $11 and $66 U.S. dollars per megawatt-hour with the majority of estimates being between 2 to 5 times the cost of onshore O&M [1]. These higher O&M costs represent a larger overall proportion of the cost of energy than for onshore turbines even when the large initial investment required for the installation of offshore turbines is included [4]. One of the reasons that O&M costs are likely to be higher offshore than onshore is that the offshore environment will bring with it increased loading which is relatively uncharacterized due to the lack of existing offshore installations. Offshore turbines will also have to be built to withstand the environmental harshness of the offshore environment. Lastly, access to the turbines will be difficult, costly, and occasionally not possible due to high sea states [1,5].

1.2. SHPM Benefits

One potential way in which these O&M costs could be addressed is through the use of a structural health and prognostics management (SHPM) system as part of a condition based maintenance (CBM) paradigm [5-11]. By continuously monitoring the health, or condition, of structural components in each wind turbine, required maintenance actions can be scheduled ahead of time and performed when they are needed at the remote site rather than on a preset schedule or only after failure has already occurred. The benefits of a CBM strategy are expected to include less regular maintenance, the reduction or avoidance of unscheduled maintenance and improved supply chain management [5, 8-10].

Furthermore, because wind turbines are active systems, monitoring the health of wind turbine components allows turbines to be operated based on their health so that smart turbine load management strategies (i.e. prognostic control) can be used to optimize the profit of the entire wind plant. For example, if a turbine blade becomes damaged and that damage is detected at an early stage by the SHPM system, the turbine could be derated so that smaller less costly repairs could be performed on the turbine. While this action would reduce the amount of power generated by the turbine in the short-term, it may allow for less extensive maintenance actions to be performed, extend the overall life of the turbine, and allow for multiple turbines to be serviced during the same visit to the plant in order to maximize the overall profit of the wind power plant.

1.3. Paper Overview

In this paper, we address the integration of SHPM into the O&M process for wind power plants in several ways. First, a multiscale simulation based methodology that is capable of determining the measurement channels that are the most sensitive to a representative form of damage in a cost-effective manner has been developed and can be extended to investigate the application of other potential health monitoring methods to a variety of damage or fault conditions. Second, the dependence of repair costs on damage size has been recognized and the utility of integrating the knowledge of these costs with the damage state of the turbine can be utilized not just to perform more cost-effective CBM but also to operate individual turbines to extend their life and maximize overall plant profit.

The initial approach of this research includes integration of multiple knowledge bases and perspectives for improved O&M strategies. The Sandia/DOE Blade Reliability Collaborative (BRC) is providing information regarding common defects and damage experienced in fielded utility-scale wind turbine blades. In addition, the Sandia/DOE Continuous Reliability Enhancement for Wind (CREW) project is providing a reliability database of wind farm operations including a characterization of operating performance at a system to component level. The CREW database uses high resolution Supervisory Control and Data Acquisition (SCADA) data. Data points cover the “heartbeat” of the turbine (e.g., operating state, rotor speed, power generated) as well as environmental conditions (e.g., wind speed, ambient temperature). The annual CREW public benchmark report focuses on characterizing the operations and maintenance (O&M) experience of the US fleet.

The hope is that BRC and CREW along with Sandia SHM researchers will provide a system-level strategy to identify and solve relevant O&M issues facing the wind industry. This paper will provide an initial case study for the integration of SHPM into the O&M process for a single blade damage mechanisim – a trailing edge (TE) disbond. A more comprehensive application considering component damage or operating faults including other blade damage types, rotor imbalance, and tower/foundation damage is the subject of ongoing and future work.

2. MULTISCALE SIMULATION OF DAMAGE APPROACH

2.1. Simulation Approach

To facilitate the investigation of SHPM systems for wind turbine blades using operational responses, a multiscale modeling approach was developed. A multiscale methodology was used because it allows for an investigation of the effects of damage on both the local and global model scales. Globally, the operational responses of the full turbine models can be analyzed for the development of health monitoring algorithms and identification of the

optimal measurement types and locations. The loads from these full turbine simulations can then be applied to high fidelity models in order to investigate the local effects of damage including residual strength, the effectiveness of alternative measurement methodologies & locations, and determination of appropriate prognostic control operations.
A simulation campaign was performed to identify operational response measurements that are sensitive to a representative form of damage. These simulations were an essential first step in identifying promising measurements for use in the operational monitoring of offshore wind turbines because of the scarcity of data from offshore wind turbines. The overall multiscale approach is shown in flowchart form in Figure 1.

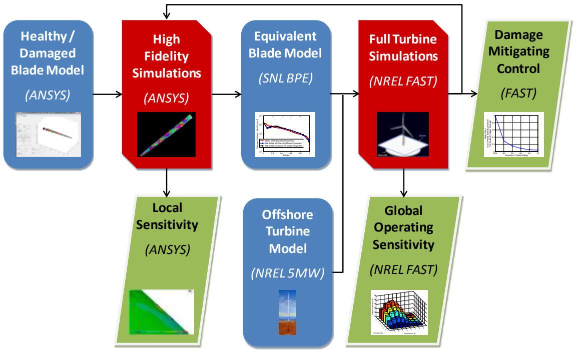

Figure 1. Multiscale simulation methodology for the identification of operational response measurements that are the most sensitive to damage.

In order to perform the desired simulations a variety of different software packages had to be integrated. The software packages that were used to obtain the results in this report are indicated in parenthesis in the Figure 1 flowchart. These include Sandia National Laboratories' NuMAD blade design software & BPE and ANSYS. Reduced order blade models were then integrated into a full turbine model for simulations of the damaged turbine in either FAST [12] or MSC.ADAMS [13]. Results from each stage of this modeling process can be used to assess the influence of damage on the response of the blade and the turbine as a whole.

Even if a SHPM system proves effective in detecting damage, in order to utilize the information most effectively, the cost of repairing the damage and risk of damage progression should be taken into account in the CBM framework. This allows the health information to be used not just for the scheduling and optimization of the maintenance procedures but also to optimize the operation (i.e. prognostic control) of the slightly damaged turbines. Using smart turbine load management strategies with damage mitigating control could allow for the productive life of blades to be extended while slowing the propagation of damage until the appropriate maintenance can be performed in the most cost effective manner. This stage of the process is indicated in the rightmost box in Figure 1.

2.2. Five Megawatt Offshore Turbine Model Description

The NREL offshore 5-MW baseline wind turbine was developed in order to support concept studies aimed at assessing offshore wind technology [14]. This model was selected for this study due to its availability and relevant power rating. An image of the MSC.ADAMS model of the offshore wind turbine, with 20m monopole foundation, is shown in Figure 2.

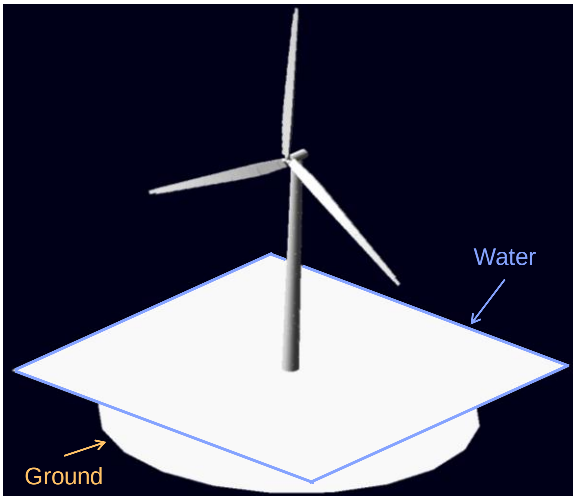

Figure 2. An image of the offshore 5-MW wind turbine model in MSC.ADAMS.

2.3. Five Megawatt Blade Model Development

A high-fidelity blade model was needed for our multiscale modeling and simulation studies. The publicly available NREL 5-MW turbine aeroelastic model and associated report do not contain detailed information about the blade design; therefore, Sandia's NuMAD blade design software was used to create the detailed blade model for the current work.

The blade model used existing blade geometry data from the DOWEC study and composite layup information from the UpWind project in a preliminary 5-MW baseline blade model. A preliminary composite layup (using all-glass materials) produced a blade that was too heavy compared to the blade weight specified for the NREL 5-MW (25,630 kg vs. 17,740 kg). Thereafter, carbon fiber spar caps were substituted while preserving the specified span-wise distribution of blade stiffness. Material properties for uni-directional (UD) carbon fiber (Newport 307) were obtained from the Sandia-MSU Materials Database [15]. Figure 3 shows a picture of the completed finite element model in ANSYS.

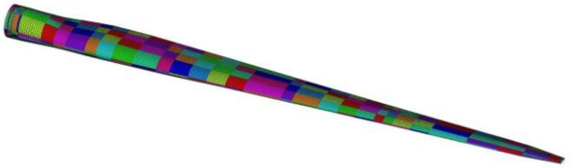

Figure 3. ANSYS finite element mesh for SNL 5-MW blade model

The Sandia Beam Property Extraction (BPE) tool was used to determine the equivalent beam property distributions for this blade model [16]. The inclusion of the carbon spar cap in the SNL 5-MW blade resulted in good agreement with the span-wise mass and stiffness properties of the NREL 5-MW baseline. In addition, the blade weight was in good agreement (16,381 kg with carbon spar caps). This Sandia 5-MW blade model has not yet undergone a comprehensive set of analyses to demonstrate acceptance to design loads (e.g. buckling, fatigue, or tip deflection) although the current model is deemed suitable for preliminary simulations of damage studies.

2.4. Damage Modeling Methodology

A trailing edge (TE) disbond was selected as a representative damage for this initial study. To model the presence of a TE disbond on a wind turbine blade, the NuMAD blade model was modified so that nodes at the TE were split into two different nodes (i.e. TE nodes were unequivalenced). This effectively split the blade model at the TE in a similar way to how the blade is physically constructed by bonding two shells. To simulate a healthy bond across the blade, the top and bottom TE nodes were connected using constraint equations in all six degrees of freedom. In the area of the blade in which the TE disbond existed the constraints were removed so that there was no connection between the top and bottom of the blade. Figure 4 shows an example of the influence of this disbond on the blade’s dynamics where the separation of the 1.25 meter long disbond extending from max chord is readily apparent in the first torsional mode shape of the cantilevered blade. While the separation of the TE is clearly visible in the mode shape, it resulted in a decrease in natural frequency of less than 0.01 Hz.

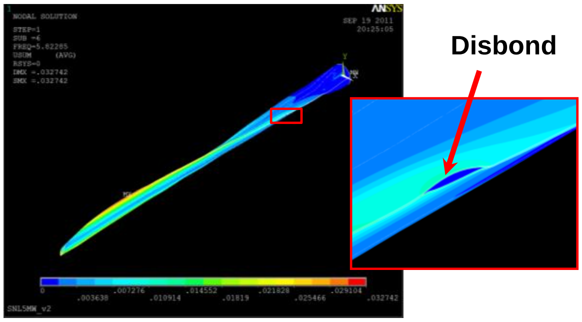

Figure 4. An image of the first torsional mode shape of a cantilevered blade with a disbond extending 1.25 m towards the tip of the blade from max chord.

While this modeling disbond methodology is effective in modeling a disbond in which the two sides do not come into contact, it fails to take into account the possible interaction of the top and bottom surfaces of the disbond. For large cracks in which interaction between the top and bottom of the blade may have a significant influence, the relative decrease in stiffness due to the disbond is likely over-estimated because the added stiffness due to the disbond face interaction was not taken into account. Modeling the interaction between the two surfaces could be achieved using nonlinear surface contact constraints on both sides of the blade but this was not attempted during this initial investigation and remains as future work.

3. DAMAGE SENSITIVITY CASE STUDY

As an illustrative example of how the developed modeling and simulation based methodology could be used to evaluate measurements for a potential offshore health monitoring system, the effects of the TE disbond on a 5-MW offshore wind turbine were investigated. This damage mechanism was identified through the Sandia/DOE BRC project.

The multiscale modeling methodology (Figure 1) is demonstrated to investigate the sensitivity of a wide range of potential operational measurements to the presence of a TE disbond. For this initial investigation all of the disbonds were assumed to initiate at max chord of the blade (14.35 meters along the span from the root) and propagate outboard toward the tip of the blade providing a series of damaged blade models with increasing severity.

This section summarizes a variety of different sensitivity analyses that were conducted at various stages throughout the modeling process. Initially, the sensitivity of the span-wise stiffness properties was evaluated. Here it was found that only the torsional stiffness (GJ) was significantly affected while the flap-wise, edge-wise and axial stiffnesses were not significantly affected.

Next, operational responses were analyzed to characterize each response's sensitivity to the damage. Due to the large potential benefits of SHPM a large amount of research in this field has been done in recent years [9, 17-19]. A large portion the prior work, however, has focused on the application of specific methods or methodologies to a wide range of potential problems. Rather than taking this approach to the problem of monitoring offshore wind turbines for damage using operational response measurements, this paper approached the problem more generally by attempting to use simple time domain methods to identify which responses are the most sensitive to the presence of damage. This approach was taken because if the response measurements that are used by the SHPM system are completely unaffected by the presence of damage, damage will not be able to be detected regardless of the sophistication of the damage detection algorithm that is used.

3.1. Operational Response Damage Sensitivity

To identify the effects of a TE disbond on the operational response characteristics of an offshore wind turbine, both FAST [12] and ADAMS [13] models of the turbine were used in conjunction with seven different blade models. The seven different blade models used in these simulations included one healthy blade model as well as models that included disbonds with length 0.625, 1.25, 1.875, 2.5, 4 and 6 meters. All of the input parameters to the model were kept consistent between the data sets other than the parameters used to model the damage in the blade. Consequently, the same input wind data file with a mean wind speed of 11.4 m/s and IEC turbulence characteristic A (generated using TurbSim [20]) was used in all of the simulations. The simulations were conducted for one hour and the first 30 seconds of response was discarded so that only the turbine's steady-state response was analyzed.

Several different sensitivity measures were investigated for application to the operational response measurements. These include statistical moments, standardized RMS difference, and time domain changes in the rotationally resampled and synchronously averaged responses.

The first data measure that was used to assess the sensitivity of operational response measurements to the disbond were the statistical moments of the data. These parameters were tracked because changes in the moments are correlated to changes in the underlying distribution of the data which may be caused by the damage. The investigated moments included the mean, variance, skewness and kurtosis of the data [21]. While the mean and variance of the data are well known measures of the expected value of the data and the spread of the data respectively, the skewness and kurtosis are less well known but effective statistical moments that can be used to help describe the shape of the distribution. Kurtosis is a widely used damage detection measure in the field of rotating machinery [22].

In addition, a simple root mean square (RMS) of the difference between the healthy time histories and the damaged time history was computed for each channel.

Thirdly, rotational resampling and synchronous averaging was applied to the operational response measurements so that changes in the average response of the turbine with respect to rotor position could be investigated. Rotational resampling is the process of fitting and interpolating the data so that rather than having data points that are spaced equally in time, the acquired data points are spaced equally with respect to the rotor position (or azimuth angle) and occur at the same rotor position during each rotation. Once the time histories were resampled, the average responses over an integer number of rotations of the turbine were calculated using synchronous averaging. In synchronous averaging blocks of data are averaged together in which each data point coincides with the same rotor position. This a common practice in the health monitoring of rotating machinery because responses that are repeated every rotation of the system constructively interfere, while random noise and transient events destructively interfere and their influence is minimized.

3.2. ADAMS Simulation Results

For the aeroelastic simulations, a large number of responses were analyzed to determine the measurements' sensitivity to the TE disbond. A variety of different measurements were obtained on the turbine's rotor including the local accelerations and moments in three directions along the blade span. A variety of measurements that were not on the rotor were also acquired including the local tower accelerations and loads at 4 different locations along the tower. A variety of measurements from the turbine's drive train were also measured including the nacelle IMU translations and rotations, the generator speed, power and torque, as well as a variety of forces and moments from the low speed shaft.

Initially FAST simulations were performed; however, it was found that these FAST simulations were inadequate to assess the sensitivity of operational measurements with a TE disbond because FAST does not account for the torsional flexibility of the blades. This confirmed initial studies focused on analysis of sensitivities in the span-wise stiffness properties where only the torsional stiffness demonstrated any significant sensitivity to the TE disbond.

The FAST preprocessor was used to create an offshore ADAMS model of the turbine which models both the pitching and span-wise degrees of freedom of the blade. As with the FAST simulations, 30 seconds of start-up data at the beginning of each simulation was discarded and the remaining hour of response data was acquired and analyzed. Furthermore, because ADAMS has no limit on the number of requested outputs a much larger candidate set of output responses could be investigated. A total of 1,007 different responses were recorded using a 100 Hz sampling rate for each of the simulations. These measurements included the translational and rotational accelerations of all 17 lumped masses for each blade as well as the local forces and moments in each direction. The locations of the response measurements along the span of the blade are shown in Figure 5. The translational and rotational forces and accelerations were also recorded along the height of the tower and a variety of other generator, nacelle, and other measurements were recorded. The most sensitive measurements are described.

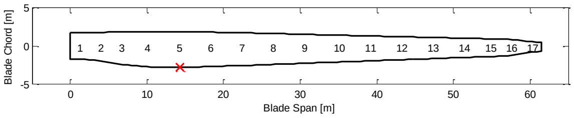

Figure 5. The 17 measurement locations on each of the blades used for the ADAMS models. All of the investigated disbonds extend outboard from max chord which is indicated with a red "X".

Although most of the responses were not sensitive to the TE disbond, the statistical moments of the pitching moments on the damage blade were well correlated with the presence and extent of the TE disbond and displayed significant percent changes in some cases. The mean pitching moments on the element centered at 15.85 meters down the span of the damaged blade changed up to 4% due to the disbond and in general the changes in the mean seemed to generally increase with increasing length disbonds. In addition to changes in the mean, the changes in the standard deviation, skewness, and kurtosis of the damaged blade's pitching moments were also well correlated with the size of the disbond.

To focus the sensitivity analysis on the operational response of the turbine, the rotational resampling and synchronous averaging technique was performed on the ADAMS response measurements. When the standardized RMS difference of the average waveforms was utilized to determine the influence of the disbond on the models' responses, the responses with the largest percent changes between simulations were not correlated with the size of the disbond in the model. However, out of the channels of data whose standardized RMS difference was correlated with the disbond size, the pitching moments in the damage blade demonstrated by far the most significant differences.

When the sensitivity of the time histories was quantified using the distribution of data at different rotation angles, the most sensitive measurements were once again found to be the pitching moment near the location of the disbond. In this case the largest difference between the average waveforms is over 0.6 times the standard deviation of the healthy data, which occurs in the blade section at 15.85 meters when the rotation is approximately 1/4 complete as can be seen in Figure 6. Figure 6 also demonstrates, however, that relatively small changes are seen in this time history due to smaller length disbonds. However, the pitching moments in the next outboard section (centered around 19.95 meters) show differences even for the smallest disbond and these differences increase relatively consistently as the length of the disbond grows (Figure 7).

Using a variety of different methods the sensitivity of the local pitching moments around the damage location to the presence of a TE disbond has been demonstrated and consequently these measurements would be advantageous to have in any SHPM designed to detect the presence of these disbonds. This example has illustrated the utility of the developed multiscale modeling methodology in the identification of measurements that are sensitive to a particular form of damage and the construction of an SHPM system. Characterization of operational measurement sensitivity can be performed in a similar fashion for other types of damage or fault conditions in the turbine or blades.

Finally, to investigate the effects of the TE disbond further, the aerodynamic loads from the aeroelastic simulations were mapped onto the more refined ANSYS blade model so that the change in the distributed strain field due to the TE disbond could be assessed. This analysis demonstrated that the changes in the strain field were highly localized around the location of the disbond which supports the localized changes in the pitching moment around the damage location seen in the ADAMS simulations. These simulation results illustrated the ability of the multiscale modeling approach to identify the physical manifestations of damage in the laminates and determine which measurement types, locations, and directions could be most suitable for the implementation of a SHM system.

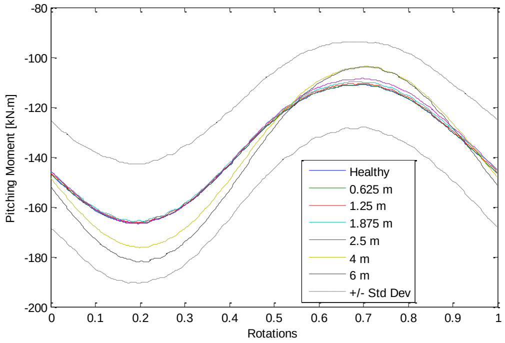

Figure 6. The average net pitching moment during one rotation of the turbine for a section centered around 15.85 m down the span of the damaged blade for all disbond lengths. The dotted lines are the healthy average pitching moment plus and minus one standard deviation.

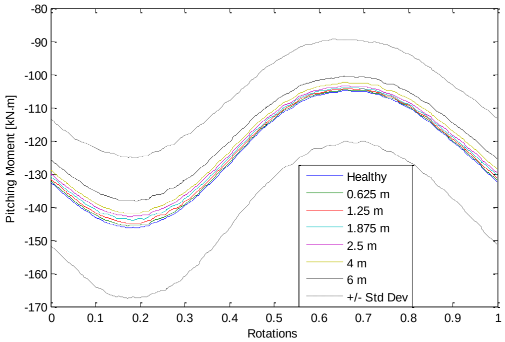

Figure 7. The average net pitching moment during one rotation of the turbine for a section centered around 19.95 m down the span of the damaged blade for all disbond lengths. The dotted lines are the healthy average pitching moment plus and minus one standard deviation.

4. OPERATIONS AND MAINTENANCE OF A SMART OFFSHORE WIND FARM

4.1. Progressive Damage and Cost Function Model

To effectively integrate an SHPM system into the overall O&M strategy for an offshore wind energy plant the repair costs associated with damage should be characterized. While some investigations of CBM implementations [23, 24] use a constant repair cost for each component, the likely repair cost versus defect size function is expected to be more similar to a piecewise function where different types of repairs have different costs associated with them. Such a curve is shown for blade repairs in Figure 8 and will be employed in future cost-benefit analysis for structural health monitoring.

There are four distinct regions of the cost model:

1. Small defects which do not need to be repaired
2. Moderate defects which can be repaired up-tower
3. Large defects which require the blade to be removed
4. Very large defects which require blade removal and replacement

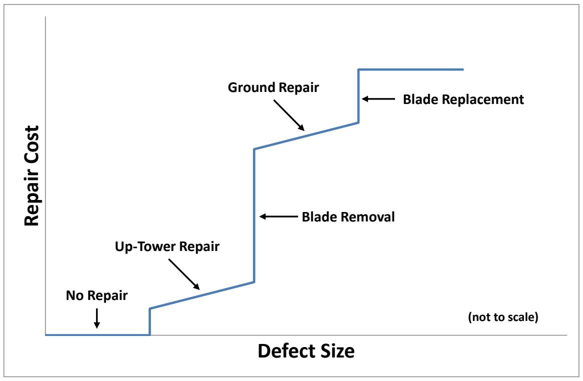

Figure 8. Example defect-cost model demonstrating the piecewise nature of defect size versus repair cost.

The exact numbers for this model have not been determined to date, nor has the relationship between repair cost and such factors as defect location, blade size, etc. However, the impact of this cost model in the SHPM cost-benefit analysis would be to show that knowledge of the damage state and the expected future loads would allow an intelligent controller to limit damage growth and keep it within the lower cost regions of the above curve until low-cost repairs can be accomplished. Furthermore, if a damage mitigating control strategy can be developed the turbine could continue to produce revenue even in this degraded state.

4.2. Mitigation of Damage Growth by Turbine Derating – Prognostic Control

Next we consider a simple example to evaluate the potential of mitigation of wind blade damage through derating the turbine. The presence of a crack, or similar damage, in the blade can cause a stress concentration which, if high enough, will become the dominant failure point in the blade structure. Due to the cyclic nature of wind blade loads, with time the higher stresses near the crack will exceed allowable levels and will lead to more rapid damage propagation.

4.2.1. Stress Increase Due To Blade Damage

A very simplified example is shown here in order to demonstrate the concept of stress amplification resulting from the presence of blade damage, in this case a simple crack. If one assumes that a crack is present in the blade such that the crack has an elliptical shape, is oriented perpendicular to applied stress, and is a relatively long crack with small crack tip radius of curvature, then the stress concentration factor associated with the crack is represented by Equation (1)

$$K_t = \frac{\sigma_{\max}}{\sigma} = 2\left(\frac{a}{\rho}\right)^{1/2} \tag{1}$$

where ρ is the crack tip radius of curvature and a is the half length of internal crack.

Making these assumptions about the crack tip radius, one can get a basic sense of the trends and magnitude of stress concentration factors associated with the damage. Stress concentration factor is highly dependent on the crack tip geometry and increases most rapidly at smaller crack lengths as seen in Figure 10. This trend highlights the importance of detecting cracks at early stages.

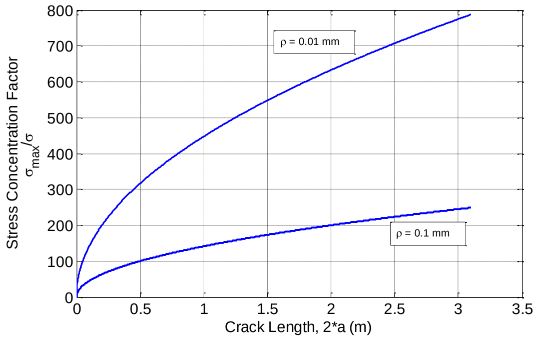

Figure 9 Stress concentration factors, K_t, as a function of crack length; shown for two different crack tip radii, rho.

4.2.2. Fatigue Life Considerations

An important blade design driver is fatigue life. The fatigue life of wind blade materials can be estimated using Miner's Rule which has the form:

$$Damage=\sum_i \frac{n_i}{N_F(\gamma_f \gamma_m S_i)} \le 1.0 \qquad (2)$$

where γ_f and γ_m are partial factors of safety for loads and materials, respectively; specified by design standards, n_i are the number of cycles at cyclic stress level S_i, and N_F are the number of cycles to failure at the given stress level. The material is said to have failed when the Damage summation exceeds unity.

The number of cycles to failure, N_F, depends on material properties derived from fatigue testing such that, in terms of cyclic stress amplitude,

$$N_F=\left(\frac{1}{C}S\right)^{-b} \qquad (3)$$

Equation (3) represents a simple two-parameter model for fatigue damage. More elegant, multi-parameter fatigue life models may be easily inserted for N_F at this point in the analysis process.

The damage computed using Miner's Rule can be linearly extrapolated to unity in order to arrive at an estimated fatigue life span of a material. Similarly, the damage for two different stress states can be compared in order to arrive at an estimate of the relative change in fatigue life. Consider the simple example of a 0.5m crack with 0.1mm crack tip radius. Equation (1) and Figure 9 would indicate a stress amplitude increase by a factor of 100 in the material nearest the crack. Computing the ratio of fatigue damage for two scenarios is an indicator of the expected change in fatigue lifetime.

$$\frac{Damage_{cracked}}{Damage_{healthy}}=\left(\frac{S_{cracked}}{S_{healthy}}\right)^b \qquad (4)$$

$$=K_t^{\,b}\approx 100^{12}=1\cdot 10^{24}$$

This magnitude of increase in fatigue damage would equate to an enormous decrease in fatigue lifetime for the material near the crack. In reality, this causes failure of the material and thus growth of the crack. An important question is whether the crack growth accelerates toward complete failure or slows toward a steady state. The hope is that the SHPM system will be able to understand damage and either prevent a catastrophic failure or mitigate damage growth.

4.2.3. Structural Impacts of Turbine De-Rating

If the structural loads in the blade can be reduced in the presence of damage, then the propagation of damage can be slowed. One means to reduce loads in the blade is to reduce the energy capture of the turbine, i.e. to derate the turbine. With derating, the turbine experiences lower aerodynamic and structural loads. The result is a decrease in production, but it may be more advantageous to sacrifice some production capacity in the near term in favor of greater benefits in the long term as explained in the next section.

Figure 10 shows a simulated distribution of fatigue damage for the 5-MW turbine. Each data point on the curve is computed using Eqn. (2) above. Stress cycles are found using rainflow counting of time waveform simulation data using Crunch [25] on data generated from aeroelastic simulations that were performed using FAST. The fatigue damage was calculated based on a Rayleigh wind distribution with average wind speed of 10 m/s, representative of an IEC Class I site. The data clearly show that maximum fatigue damage occurs as the turbine is operating in windspeeds that are slightly above 12m/s, the rated wind speed for this machine.

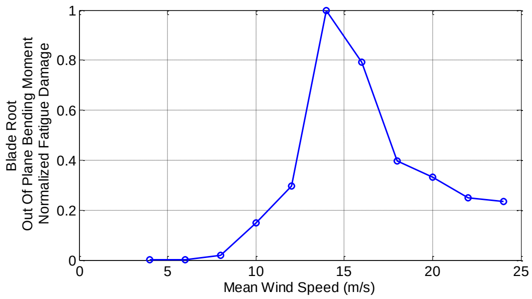

Figure 10 Fatigue damage distribution at operational wind speeds; blade root bending moment.

In the presence of damage, it could be beneficial to reduce the turbine loads in the vicinity of the peak in Figure 10 to slow the growth of the damage. This may be done through derating the turbine. Derating the turbine can be achieved through multiple prognostic control strategies, as shown in Figure 11. Mode 1 represents a decrease in the allowable rotor torque for control in Region 3 (when wind speeds are above the rated wind speed) and unmodified operation in Region 2. Mode 2 represents a decrease in allowable rotor torque in Region 3 as well as a decrease in rotor torque in Region 2, which may be achieved through feathering the blades in Region 2. Mode 3 represents an entirely new approach where low and high wind speed operation and energy capture remain unaffected. In Mode 3 the turbine is derated only in the vicinity of the Region 2.5 transition, thus affecting only the highest operational fatigue loads. Design and implementation of these prognostic control actions is an area for future research.

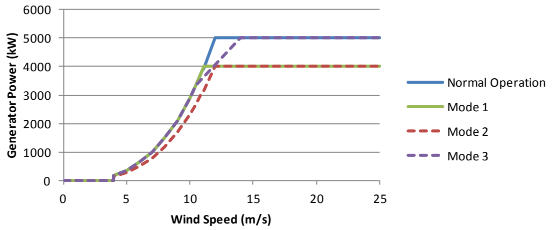

Figure 11 Illustration of various turbine derating schemes; curves for Modes 1, 2 and 3 illustrate 80% turbine rating.

It is helpful to analyze the effect of derating a turbine on the cyclic fatigue loads that are encountered on the blade. Figure 12 (a) shows the change in equivalent cyclic load experienced by the blade as a function of turbine rating. Figure 12 (b) shows the change in actual fatigue damage (inversely related to fatigue life) as a function of turbine rating. Again, the data points in these simulations were generated by FAST and Crunch, using the fatigue analysis process described previously in this report. Derating to 95% leads to a reduction in cyclic loads to levels that are 90% of the rated levels. In addition, it leads to fatigue damage that is 30% of what was incurred at the rated level. Such a decrease in fatigue damage is equivalent to an increase in the fatigue life of the blade by a factor of more than three. The decrease in blade stress resulting from derating will help offset the stress concentrations that arise due to the presence of damage as shown in Figure 9. More significant derating leads to more impressive extension of expected fatigue life. Clearly, an optimization of turbine energy capture versus maintenance costs is required and will provide more understanding regarding an appropriate level of turbine load reductions in place of immediate blade maintenance.

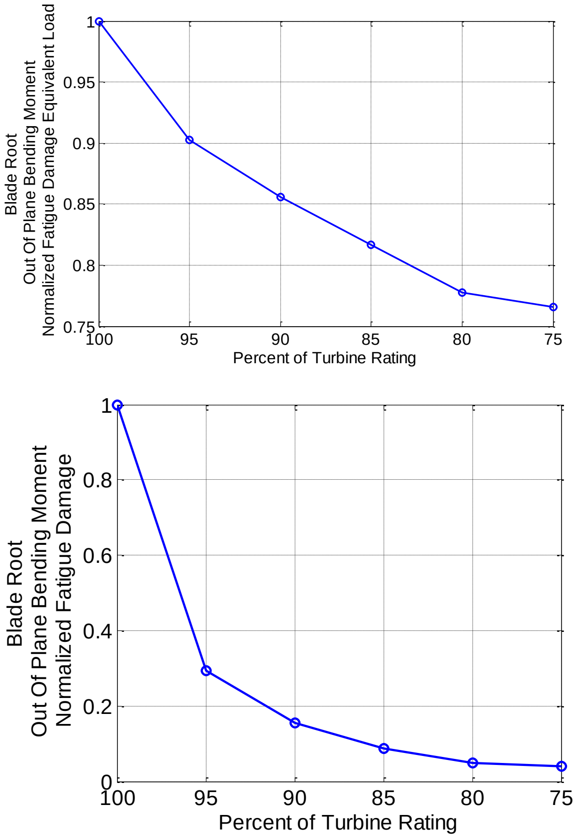

Figure 12 Decrease in (a) normalized cyclic load amplitude (top) and (b) normalized fatigue damage as a function of turbine rating (lower); simulations performed in 11 m/s average wind speed.

4.3. The Use of SHPM and Load Management for O&M

Many of the traditional analyses [6-11] of the benefits of SHPM systems into wind plant O&M take a passive view of the wind farm. This means that knowledge of the damage state of the turbine simply results in optimization of the maintenance of the turbines rather than changes in how the wind farm is operated. However, due to the difficulty of access associated with offshore wind turbines it may not always be possible or desired to repair a turbine as soon as a detectable amount of damage is present.

The decrease in loads and fatigue damage that can be achieved by derating a turbine (Section 4.2) demonstrates the feasibility of extending the life of a given turbine at the cost of a small percentage decrease in revenue. One of the benefits of this methodology is that for a single turbine even if maintenance cannot be performed when damage is detected, the turbine can be derated slightly so that it still generates revenue but does not accumulate large amounts of additional damage. This could potentially reduce the associated repair costs significantly if the transition between two different types of repairs can be avoided. A second benefit to the derating process that is especially relevant for offshore wind plants is that it this life extension methodology increases the possibility of servicing multiple turbines during a single visit to the offshore wind plant. Smart turbine load management, therefore enables the turbine operator to affect the progression of damage in a turbine so that the timing of operations and maintenance procedures can be optimized for the entire wind farm. Once quantitative damage size versus repair costs functions have been determined, further simulations of an entire offshore wind plant could be used to quantitatively evaluate the cost reductions possible with a SHPM system and load management methodology.

5. CONCLUSIONS

In addition to significant improvement in operations and maintenance costs of wind turbines, a structural health and prognostics monitoring system can be used as an integral component of health-driven wind turbine control. Consequently, damage mitigating control methodologies were investigated for smart turbine load management. These simulations demonstrated a promising result in that derating the turbine power production by as little as 5% resulted in a blade fatigue life extension of 300%, as well as a reduction in the equivalent loading by 10%. Therefore, if the health of a turbine is known, the power production of that turbine can be derated slightly to avoid growth of damage, avoid costly unscheduled repairs, and coordinate the lower-cost scheduled repair of multiple turbines. While further research into the optimal damage mitigating control methodologies is needed, it is evident that extensions of life along with increased turbine revenues may be achieved through small and simple changes in a turbine’s control methodology, which we refer to this as prognostic control. Furthermore, these load management strategies could prove especially beneficial for offshore turbines where execution of maintenance trips may be limited by weather events and the increased possibility of servicing multiple turbines during a single visit to the wind plant can result in reduced offshore O&M costs.

A multiscale simulation methodology has been developed for the investigation and development of SHPM methods for offshore wind turbine blades. By investigating the effects of damage on multiple scales, the developed methodology provides better understanding of the underlying physical consequences of damage on both a local and global level which leads to the identification of operational responses that are most sensitive to these physical changes with insight into effective sensing approaches.

For a representative damage feature in a blade, a trailing edge disbond, the blade pitching moment operational responses were most sensitive to the presence of the disbond. The hope is that other mechanisms of damage in blades or other turbine components or fault conditions will also have unique signatures in the operational response. The investigation of additional relevant features along with maturation of prognostic control strategies for improvement of O&M processes is the ongoing focus of this project.

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