A Preliminary Study of Reliability-based Controller Scheduling in Offshore Wind Turbines

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Introduction

In this work, a study of the long-term fatigue reduction effects in offshore wind turbines due to an active controller is conducted. Several approaches are tested, including possible life extension of a monopile foundation, compensation for reduced material consumption and the uncertainty of the long-term stress amplitude distribution. The physical model and environmental loads are represented with a Weibull stress distribution, and the controller is assumed to be modifying the distribution by scaling the distribution scale parameter. This first approach to fatigue reduction control is simple, but will give an indication of how well an advanced controller should be working to get financial benefits or increased lifetime reliability.

Basic Concepts

It is assumed that the long-term stress range at a specific location in the foundation can be expressed by a two-parameter Weibull distribution:

$$f_S(s) = \frac{b}{a}\left(\frac{s}{a}\right)^{b-1} e^{-\left(\frac{s}{a}\right)^b} \tag{1}$$

where the mean and variance of the stress amplitudes are given as:

$$\mu = a\Gamma(1+1/b) \tag{2a}$$

$$\sigma^2 = a^2\left[\Gamma(1+2/b) - \left(\Gamma(1+1/b)\right)^2\right] \tag{2b}$$

Further, the controller action r_c is taken as the fraction of reduced mean and standard deviation of the distribution, yielding a modification of the scale parameter, from a:

$$r_c = \frac{a_c}{a} = \frac{\mu_c}{\mu} = \frac{\sigma_c}{\sigma} \tag{3}$$

The above-mentioned load effect representation and controller model will form the basis of this study.

Models

The expected fatigue damage during N cycles can be found by integrating the stress amplitude distribution using the Palmgren-Miner summation and bi-linear SN-curves. A similar expression can be found in [1] and [2] for single-slope SN-curves.

$$\begin{aligned} D_N &= \sum_{i=1}^{N} \frac{s_i^{m_1}}{K_1}\mathcal{H}(s_i - s_0) \\ &\quad + \frac{s_i^{m_2}}{K_2}\left[1 - \mathcal{H}(s_i - s_0)\right] \\ &= N\left\{\frac{a^{m_1}}{K_1}\Gamma\left[1+\frac{m_1}{b}, \left(\frac{s_0}{a}\right)^b\right]\right. \\ &\quad \left. + \frac{a^{m_2}}{K_2}\gamma\left[1+\frac{m_2}{b}, \left(\frac{s_0}{a}\right)^b\right]\right\} \\ &= N\left\{D_1(a,b) + D_2(a,b)\right\} \end{aligned} \tag{4}$$

Here, $\Gamma[\cdot,\cdot]$, $\gamma[\cdot,\cdot]$ and $\mathcal{H}(\cdot)$ are the upper incomplete, incomplete gamma and Heaviside step functions, respectively. The remaining parameters are given in Table 1. As deduced, the fatigue damage is a closed-form, linear summation of contributions from the upper and lower part of the SN-curves. To evaluate the time-dependent reliability, the limit state equation for N load periods are given as:

$$g_N = \Delta - D_N \tag{5}$$

where Δ is log-normally distributed with a mean value of 1 and standard deviation of 0.3. The probability of failure

$$P_{f,N} = P[g_N \leq 0] \tag{6}$$

and corresponding reliability index

$$\beta_N = -\Phi^{-1}(P_{f,N}) \tag{7}$$

are then found by Monte Carlo Simulation or the first order reliability method (FORM).

Fatigue lifetime and Reliability

First, an overview of relevant stress distributions are obtained and plotted in Figure 1. By this figure, we can find the Weibull parameters giving an expected fatigue lifetime of 20 years by evaluating the time until the reliability limit is reached. The minimum reliability index is 3.1, which means a probability of failure of 10^{-3}. The remaining parameters are given in the table below, which is similar to what is presented in [3]. Figure 1 also shows the contributions from the two slopes in the SN-curve, meaning that the lighter area contains a larger contribution from the low-cycle slope. Next, a Monte Carlo simulation is performed to obtain a time-dependent reliability, where a controller action of $r_c = 0.95$ is introduced when the reliability is below 3.7, corresponding to a probability of failure of 10^{-4}. In Figure 2, an increase of the foundation lifetime of 2 years can be observed.

Table 1: Simulation parameters

Parameter	Distribution	Mean	Std.dev.
Δ	Log-normal	1	0.3
$\log K_1$	Normal	12.164	0.25
$\log K_2$	Normal	16.106	0.25
m_1	Fixed	3	-
m_2	Fixed	5	-
s_0	Fixed	52.63	-
N_y	Fixed	8e6	-
P [MW]	Fixed	10	-
D [m]	Fixed	9	-
t [m]	Fixed	0.11	-
H [m]	Fixed	80	-

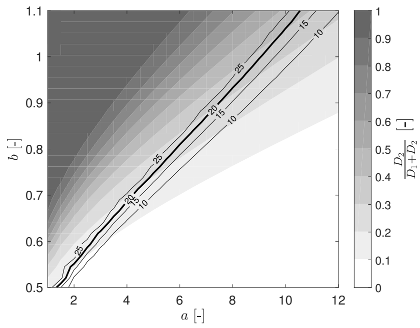

Figure 1: Structural lifetime and SN-curve contributions as a function of Weibull parameters

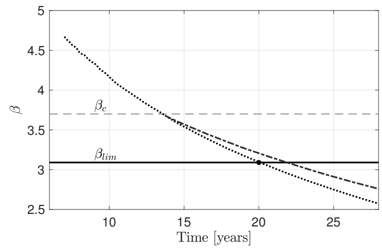

Figure 2: Time-varying reliability index

Results

Using the same simulation parameters as above, a test is performed on how much controller-induced fatigue reduction is required to compensate for some variance introduced to the Weibull parameters.

Figure 3 shows the required r_c for several COV values introduced to the parameters a and b, which are now considered to be normally distributed. Note that only a is given, since there is a one-to-one relationship between a and b in Figure 1 on the 20 year contour line. Also, the controller is assumed to be active during the whole lifetime.

Finally, an estimate of cost reductions and increased revenue due to lifetime extension is made, using the rated power, monopile diameter, thickness and height given in Table 1. The capacity factor is taken as 0.5, and the energy price is assumed to be constant at 0.1[€/kWh]. All incomes related to extended lifetime production are discounted with a rate of return of 9% and the combined steel and production price is 2€/kg. However, the load mitigating controller is not active until a reliability index of 3.7 is expected, which is approximately after 12 years. The vertical axis in Figure 4 shows the production loss factor, where 0.98 indicates a 2% power production loss when the controller is active. ΔC_E is the relative foundation cost change due to increased energy production, while ΔC_S is the capital saved on reducing the steel thickness while maintaining reliability and assuming only quasi-statically added load effects. To conclude, there is a potential in indirectly reducing the cost of energy with a different controller algorithm, but focus should be on extended production or reduced damage uncertainty.

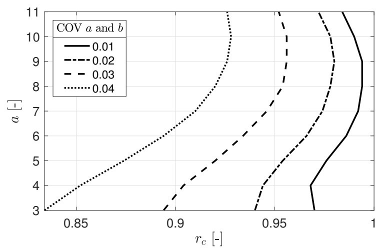

Figure 3: Control action to compensate for stress parameter variance

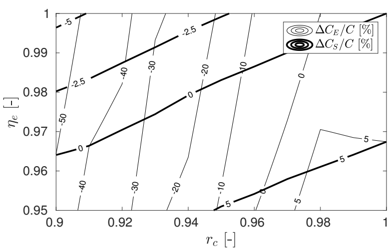

Figure 4: Foundation cost change in %

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