Identification of cumulative damage at the blade root of AB92 blade using Palmgren-Miner’s rule

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Abstract. This study presents the identification of cumulative damage at the blade root of AVANTIS AB92 wind turbine blade by evaluating the simulations generated output obtained from GH Bladed software. The blade length was 45.3 m and consisted of six (6) different airfoils. The blade material was made of GRP/Epoxy with a weight of 10.2 tons. At the blade root, the bolt hole circle diameter was 2.3 m with a 1.3 m distance from hub centre to rotor shaft flange. The fatigue loads at the blade connection of AB92 were performed according to Germanischer Lloyd guideline for a 2.5 MW horizontal axis wind turbine generator with wind class IEC IIA. The simulations were performed when the turbine operates during power production with and without occurrence of fault with wind condition satisfying the normal turbulence model. Design load cases such as during start-up and normal shutdown were also carried out with wind condition similar to normal wind profile model. The fatigue load cases at the blade connection were post-processed by determining the rainflow cycle counting and damage equivalent loads using GH Bladed software. Statistical estimation models such as graphical and exponential methods were also used to predict the Weibull parameters. The total fatigue damages due to bending moments and torsion at the blade connection were evaluated using the Palmgren-Miner’s rule at different expected behaviour of S-N curves. Calculation results indicate that the total fatigue damage due to torsion, flapwise and edgewise bending moments at the blade connection of AB92 when the slope parameter of S-N curve i.e., m = 3 are less than unity with values of 0.8702, 0.0354 and 0.0180, respectively.

Keywords: Rainflow cycle counting, Damage equivalent loads, Palmgren-Miner’s rule, Fatigue damage

1. Introduction

Typical examples of cyclic loads are fatigue loads which may lead to cumulative or total damage in the structural components of the material under test which may ultimately result in structural failure. Although these loads are below the load level that it may cause static failure, it requires many load cycles prior to fatigue failure takes place. There are two (2) possible scenarios to find the fatigue damage. First is to deal with cracks formation using fracture mechanics such as research works on stress intensity factor [1]. Second is to deal with relatively minor cracks by properly identifying the
fatigue life collectively which may include crack initiation with initial design flaw that needs an S-N curve model for characterization [2]. The term S and N in the acronym refer to stress and the number of loading cycles at fatigue failure, respectively.

In the present study however, a family of M-N curves (i.e., moment vs. cycles) generated from GH Bladed output was initially used and be converted to stresses versus allowable cycles or S-N curves. In rotor blade for instance, fatigue analysis shall be performed for all critical sections of the blade and at the blade root. The verification of fatigue strength shall be based on the characteristic S-N curves wherein the total damage is identified using the Palmgren-Miner’s rule [3]. The said method demands understanding of stress ranges distribution.

One of the commercial software that generates the M-N curves and can be subsequently converted to stress ranges distribution after performing simulations of horizontal axis wind turbine generator at different design load cases (DLC) is the GH Bladed [4]. Design load cases that require fatigue type of analysis are power production with and without occurrence of fault with wind conditions satisfying the normal turbulence model (NTM). In NTM, the wind turbulence is best described by energy transferred by the turbulence eddies. The distribution over frequencies can be regarded as coherence functions and power spectra over a period of approximately 10 minutes according to GL Wind 2003 guideline and IEC 61400-1 standard [5], [6]. Simulations were also performed when the turbine operates during start-up and normal shutdown with wind condition similar to normal wind profile model (NWP). In NWP, the wind distribution represents the mean wind speed in terms of elevation from the ground and with a power law exponent of 0.2. The said wind distribution is adopted to elucidate the mean wind shear in front of the rotor blade swept area.

2. Materials and Methods

In this study, the AB92 blade was used and evaluated by performing fatigue load simulations at different design load cases using GH Bladed software. It was intended for a 2.5 MW permanent direct-drive wind turbine generator. The blade length was 45.3 m and consisted of six (6) different airfoils hereafter called AB92_40, AB92_35, AB92_30, AB92_25, AB92_21 and AB92_18 with airfoil section distributions of 21.52%, 3.31%, 9.93%, 13.25%, 19.87% and 32.12%, respectively. The blade material was made of GRP/Epoxy with a total weight of 10.2 tons. At the blade root, the bolt hole circle diameter was 2.3 m with a 1.3 m distance from hub centre to rotor shaft flange. The outer and inner diameters at the blade root were 2.39 m and 2.21 m, respectively. Figure 1 shows the chord length in terms of dimensionless blade length. The AB92 linear mass distribution as a function of dimensionless blade length is also shown in figure 2.

![Figure 1. AB92 chord profile as a function of dimensionless blade length.](image)

![Figure 2. AB92 linear mass distribution in terms of dimensionless blade length.](image)

2.1. Wind turbine classes

The fatigue loads at the blade connection of AB92 were performed according to International Electrotechnical Commission (IEC 61400-1 Edition 2) and Germanischer Lloyd (GL Wind 2003) guidelines for a 2.5 MW horizontal axis wind turbine generator with wind class IEC IIA. Table 1
shows the basic parameters for wind turbine generator (WTG) classes. The annual average wind speed for WTG class II is 8.5 m/s with subclass A. Subclass A classifies the category for larger turbulence characteristics wherein $I_{15}$ is the turbulence intensity characteristic value at 15 m/s and “a” is the slope parameter to be used in equation (1). The design lifetime of the turbine is at least 20 years.

| Wind Turbine Class | I | II | III | IV | S |
|--------------------|---|----|-----|----|---|
| $V_{ref}$ [m/s]    | 50| 42.5| 37.5| 30 |   |
| $V_{ave}$ [m/s]    | 10| 8.5 | 7.5 | 6  |   |
| $I_{15}$ A         | 0.18| 0.18 | 0.18| 0.18|   |
| $a$                | 2  | 2  | 2  | 2  |   |
| $I_{15}$ B         | 0.16| 0.16 | 0.16| 0.16|   |
| $a$                | 3  | 3  | 3  | 3  |   |

Values to be specified by the manufacturer.

2.2. Normal Turbulence Model (NTM)

The wind turbulence is described as the wind velocity stochastic variations from the 10 minute period. The turbulence model includes the effects of varying wind direction, wind speed and even rotational sampling. The characterization of natural wind turbulence by statistical parameters for short period of time in which the spectrum continues to be unchanged requires the following design variables: average wind speed, characteristic turbulence intensity and integral length scales.

Values of turbulence intensity at hub height should be taken into account. At different heights, the wind speed standard deviation may be assumed constant while the wind speed and turbulence intensity vary with height. The arbitrary change in wind speed across the blade swept area involving the determined wind speed changes creates together the blade rotation commonly known as the effect of rotational sampling. This effect may lead to a considerable influence on the blades fatigue strength.

The characteristic wind turbulence can be identified by calculating the standard deviation characteristic value of wind velocity component at hub height as shown in equation (1). Another option is to find the characteristic turbulence intensity by obtaining the ratio of standard deviation with the hub velocity. Both methods help to classify the characteristic wind turbulence for a particular site as shown in figures 3 and 4.

$$
\sigma_1 = I_{15} \frac{(15 \text{ m/s} + aV_{hub})}{(a+1)}
$$

Figure 3. Characteristic wind turbulence based on standard deviation.

Figure 4. Characteristic wind turbulence based on turbulence intensity.
2.3. Normal wind profile model (NWP)
The normal wind profile model refers to the mean wind speed in terms of elevation from the ground. For standard wind turbine classes, the NWP model can be expressed by the power law exponent of 0.2 as shown in equation (2).

\[ V(z) = V_{hub} \left( \frac{z}{z_{hub}} \right)^{\alpha} \]  

in which \( V(z) \) and \( V_{hub} \) are the wind speeds at the desired height and at the hub in m/s, respectively. \( z \) is the height above the ground, \( z_{hub} \) is the hub height above ground, and \( \alpha \) is the power law exponent.

2.4. Generation of turbulent wind fields
Prior to turbine simulation, a suitable wind field must first be generated. To generate a new wind field, the turbulence characteristics must be defined first. In GH Bladed, the simulation method used is based on that explained by Veers wherein, the rotor plane is covered by rectangular grid points. For each of these points, a separate time history of wind speed is generated such that the time history has the correct wind turbulence spectral characteristics [7]. Calculations using the turbulent wind field are crucially essential in rotor load eddy slicing transfer from lower frequencies to those related with the rotating blades slicing through the wind turbulent structure. The eddy slicing is an important source of blade fatigue loading.

3. Discussion of Results
3.1. Rainflow cycle counting
The fatigue load cases at the blade connection were post-processed by determining the rainflow cycle counting and damage equivalent loads using GH Bladed software. The GH Bladed measures the stress time history rainflow cycle counting and ensuing fatigue analysis from cycle count data. It is the most accepted method used for fatigue analysis of structures. The rainflow cycle count is binned in accordance with cycle mean and range values. The output from rainflow cycle counting analysis comprised of two-dimensional profile of the number of cycles binned on the means and ranges of the cycles. Figure 5 illustrates the rainflow cycle counting of stress history due to torsion at the blade root of AB92. The computation can be expanded to produce the damage equivalent loads. The blade coordinate system used is based on GL Wind 2003 guideline as shown in figure 6.

On the other hand, the rainflow cycle counting due to flapwise and edgewise bending moments are shown in figure 7 and figure 9, respectively. Blade root design is determined by the long-term profile of the bending moment range. The ranges of bending moment are presumed to comply with the exponential distribution as shown in equation (3). The Weibull parameters using graphical method
were also determined for comparison wherein the cumulative distribution function is presented in equation (4). The Weibull parameters such as shape and scale factors are summarized in table 2. The respective cumulative distribution function due to flapwise and edgewise bending moments are also shown in figure 8 and figure 10. In these figures, the cumulative distribution function using graphical and exponential methods were plotted for comparison with the actual cumulative distribution. The results indicate that both methods may be used to represent the actual cumulative distribution function. Student t-test from Kaleidagraph was used to determine the statistical details as shown in table 3.

\[
F(x) = 1 - e^{\left(\frac{x}{\alpha}\right)}
\]  
(3)

\[
F(x) = 1 - e^{\left(\frac{\sqrt{x}}{\alpha}\right)^k}
\]  
(4)

Figure 7. Rainflow cycle counting of stress history due to flapwise bending moment (i.e., \(M_y\)) at the blade root of AB92.

Figure 8. Cumulative distribution function due to flapwise bending moment at the blade root of AB92.

Figure 9. Rainflow cycle counting of stress history due to edgewise bending moment (i.e., \(M_x\)) at the blade root of AB92.

Figure 10. Cumulative distribution function due to edgewise bending moment at the blade root of AB92.
Table 2. Weibull parameters for graphical (GM) and exponential (EM) methods.

| Description | Torsion [M_{ZB}] | Flapwise Bending Moment [M_{YB}] | Edgewise Bending Moment [M_{XB}] |
|-------------|-------------------|----------------------------------|----------------------------------|
|             | GM                | EM                               | GM                               | EM                               |
| Shape factor [k] | 0.786             | 1.00                             | 0.896                            | 1.00                             |
| Scale factor [A]    | 22.74              | 26.33                            | 1,817.71                        | 1,433.08                         |

Table 3. Statistical details using Student t-test to compare the graphical and exponential methods with the actual cumulative distribution function.

| Description | Torsion [M_{ZB}] | Flapwise Bending Moment [M_{YB}] | Edgewise Bending Moment [M_{XB}] |
|-------------|-------------------|----------------------------------|----------------------------------|
|             | Actual vs. GM     | Actual vs. EM                    | Actual vs. GM                    | Actual vs. EM                    |
| Mean Difference | 0.0100             | 0.0175                           | 0.0050                           | -0.0205                         |
| t Value     | 1.2743             | 2.0926                           | 0.5116                           | -1.9074                         |
| Correlation | 0.9899             | 0.9925                           | 0.9895                           | 0.9814                          |

3.2. Damage equivalent loads

The fatigue limit states are based on Rayleigh wind speed distribution with average wind speed of 8.5 m/s and turbine lifetime of 20 years. The load cases used were weighted at different wind speed ranges and frequency of occurrences. Apart from the rainflow cycle counting, one of the generated outputs from GH Bladed is the damage equivalent loads at the blade connection of AB92 as shown in table 4. Values of damage equivalent loads represent the empirical material constant identifying the S-N curve level. The empirical material constant is denoted as \( \ln K \) in equation (5).

\[
\ln N = \ln K - m \ln S \tag{5}
\]

where, \( S \) indicates the pairs of stress range and \( N \) defines the number of stress cycles to failure at the given stress range.

Table 4. Damage equivalent loads at the blade-hub connection of AB92.

| Slope of S-N Curve | Torsion [M_{ZB}] | Flapwise Bending Moment [M_{YB}] | Edgewise Bending Moment [M_{XB}] |
|--------------------|------------------|----------------------------------|----------------------------------|
| 3                  | 46.4             | 1,528.7                          | 3,182.2                          |
| 4                  | 47.5             | 1,693.7                          | 3,140.3                          |
| 5                  | 48.7             | 1,879.1                          | 3,121.3                          |
| 6                  | 49.8             | 2,061.7                          | 3,113.5                          |
| 7                  | 51.0             | 2,235.9                          | 3,112.3                          |
| 8                  | 52.1             | 2,400.3                          | 3,115.3                          |
| 10                 | 54.3             | 2,700.7                          | 3,129.5                          |
3.3. Palmgren-Miner’s Rule

The cumulative damage or the fatigue life of a particular structure at different or varying loads can be determined according to S-N curve approach considering a linear total damage by Palmgren-Miner’s rule. Total fatigue damage can be determined by getting the sum of the partial damage from individual load cycle at different stress levels, linearly independent in which the stress cycles occur. The accumulated damage can be predicted as

\[ D = \sum \frac{\Delta n(S_i)}{N(S_i)} \]  

in which \( \Delta n \) defines the number of stress cycles at a given stress range \( S \) in the life span of structure and \( N \) represents the cycles number at this particular stress range to failure. The total fatigue damage at the blade connection of AB92 due to torsion, flapwise and edgewise bending moments with different S-N curves are shown in table 5.

| Slope of S-N Curve | Torsion [M_{ZB}] | Flapwise Bending Moment [M_{VH}] | Edgewise Bending Moment [M_{XB}] |
|-------------------|------------------|-------------------------------|-------------------------------|
| 3                 | 0.8702           | 0.0354                        | 0.0180                        |
| 4                 | 0.8095           | 0.0320                        | 0.0183                        |
| 5                 | 0.7554           | 0.0289                        | 0.0184                        |
| 6                 | 0.7082           | 0.0263                        | 0.0185                        |
| 7                 | 0.6669           | 0.0243                        | 0.0185                        |
| 8                 | 0.6305           | 0.0226                        | 0.0185                        |
| 10                | 0.5690           | 0.0201                        | 0.0184                        |

4. Conclusions

The calculation results indicate that the total fatigue damage at the blade root of AB92 due to torsion, flapwise and edgewise bending moments when the Wohler exponent i.e., \( m = 3 \) are less than unity with values of 0.8702, 0.0354, and 0.0180, respectively. Overall, the cumulative damage due to torsion, flapwise and edgewise bending moments at different S-N curves are less than one.

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