GL Garrad Hassan

FATIGUE LOAD CALCULATIONS FOR ROMO WIND TO ASSESS SENSITIVITY TO CHANGES IN 10-MIN MEAN YAW ERROR

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REVISION HISTORY

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CONTENTS

1 INTRODUCTION

ROMO Wind AG has requested that GL Garrad Hassan (GH) perform a set of fatigue load calculations for a generic 2MW wind turbine according to the IEC 61400-1:2005 (edition 3) design standard [1]. The aim of this analysis is to quantify fatigue load sensitivity to changes in the ten-minute mean yaw error of the inflow. The ten-minute mean yaw errors considered vary from -20 to +20 degrees in 4 degree intervals. The load results presented in this report are therefore not indicative of load variations due to dynamic high-frequency yaw tracking during the operational life of the turbine. Rather they represent the variation in fatigue load over the lifetime of the turbine assuming a constant mean offset in yaw angle with a ten-minute averaging period.

The turbine model used for these load calculations has a rotor diameter of 75m and a hub height of 65m. Fatigue load calculations were performed for wind conditions with turbulence levels between class A and class B according to the definitions in [1]. The scope of the work was agreed in [2].

This report describes the load calculations that were carried out and presents the resulting fatigue loads for the main turbine components. In Section 2 the numerical model of the generic 2MW turbine is described while in Section 3 the analysis methods are presented. The design load cases are described in detail in Section 4 and the resulting fatigue loads are presented in Section 5.

2 TECHNICAL DESCRIPTION OF THE GENERIC 2MW WIND TURBINE

2.1 General description

The generic 2MW wind turbine used for these load calculations is a pitch-regulated variable speed turbine with a rated power of 2.0MW. The three-bladed rotor, featuring 36.25m blades, is orientated upwind of the tower and has a diameter of 75m.

The rotor nacelle assembly is supported on a tubular steel tower with a height of 63.125m, resulting in a hub height of 65m.

A complete description of the numerical model of the generic 2MW turbine is given in the Appendix.

2.2 Control systems

A basic power-production and supervisory controller has been designed by GH for this turbine, high-level details of which are presented in the Appendix. This section presents those aspects of the control systems that are relevant to the definitions of design load calculations.

2.2.1 Power-production controller

Power control is achieved by generator torque control and blade pitch control. The blades are pitched with independent actuators, following a collective pitch control strategy. The key steady-state controller parameters are summarised in Table 2.1.

Maximum steady state electrical power	2MW
Hub height	65m
Cut in wind speed	4m/s
Cut out wind speed	25m/s
Rated wind speed	12.8m/s
Minimum steady state generator speed	850rpm
Maximum steady state generator speed	1500rpm
Minimum operational pitch angle	-2°
Maximum pitch rate	$8^{\circ}/s$
Minimum pitch rate	$-8^{\circ}/s$

Table 2.1: Steady-state controller parameters

Figure 2.1 and Table 2.2 present power curve results calculated in accordance with the Normal Wind Profile (steady wind speeds including shear and upflow effects). These results confirm that the turbine has a rated wind speed of 12.8m/s.

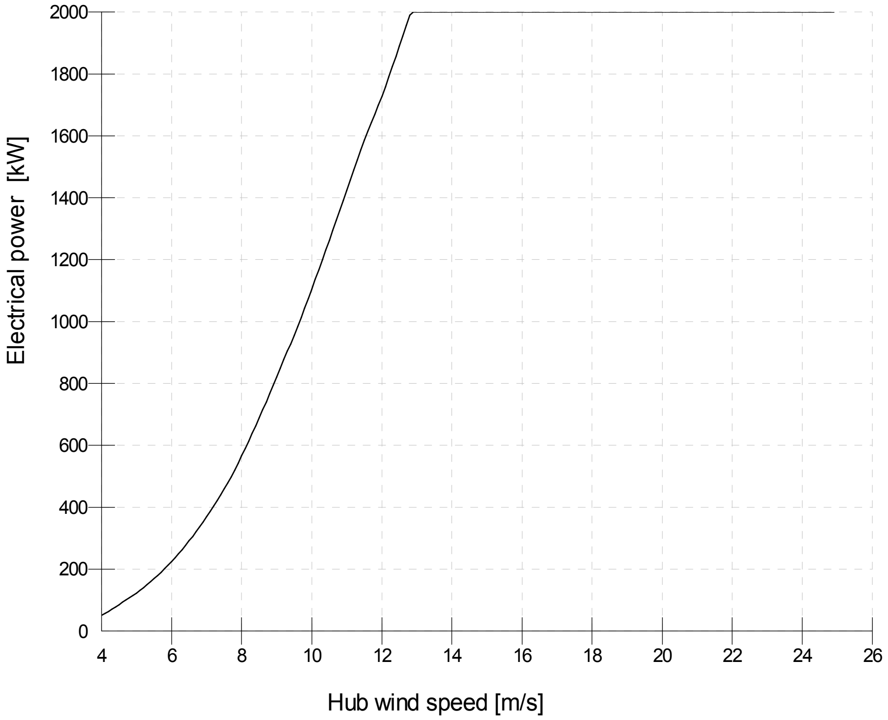


Figure 2.1: Normal Wind Profile power curve

Wind speed (m/s)	Power (kW)	Wind speed (m/s)	Power (kW)
4.0	51	12.8	1990
5.0	123	12.9	2000
6.0	225	13.0	2000
7.0	369	14.0	2000
8.0	566	15.0	2000
9.0	821	16.0	2000
10.0	1105	17.0	2000
11.0	1424	18.0	2000
12.0	1728	19.0	2000
12.1	1758	20.0	2000
12.2	1790	21.0	2000
12.3	1823	22.0	2000
12.4	1856	23.0	2000
12.5	1890	24.0	2000
12.6	1923	25.0	2000
12.7	1956		

Table 2.2: Normal Wind Profile power curve

2.3 Structural dynamics

Figure 2.2 presents a Campbell diagram for the generic 2MW wind turbine showing the frequencies of coupled modes of vibration as a function of rotor speed. In this figure the modes of vibration are labelled according to the dominant mode although the true modes in most cases are combinations of tower, rotor and drive-train displacements. The same information is presented numerically in Table 2.3.

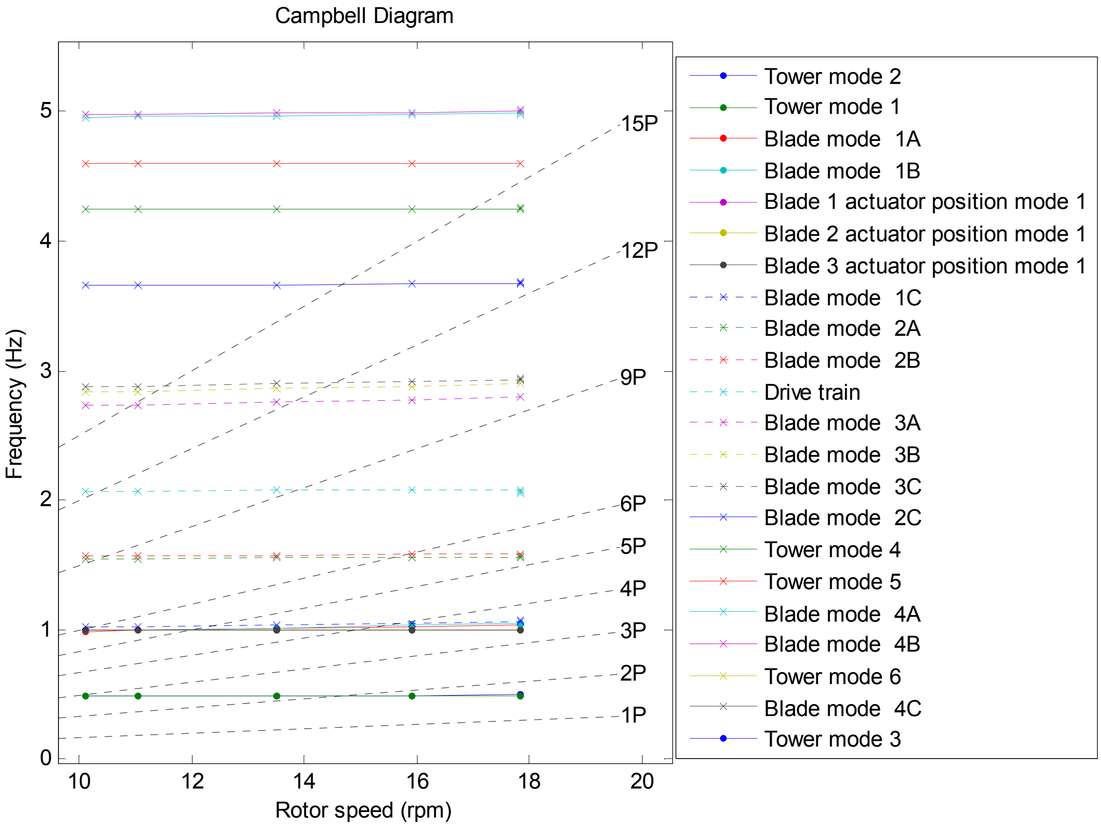


Figure 2.2: Campbell diagram for the generic 2MW wind turbine

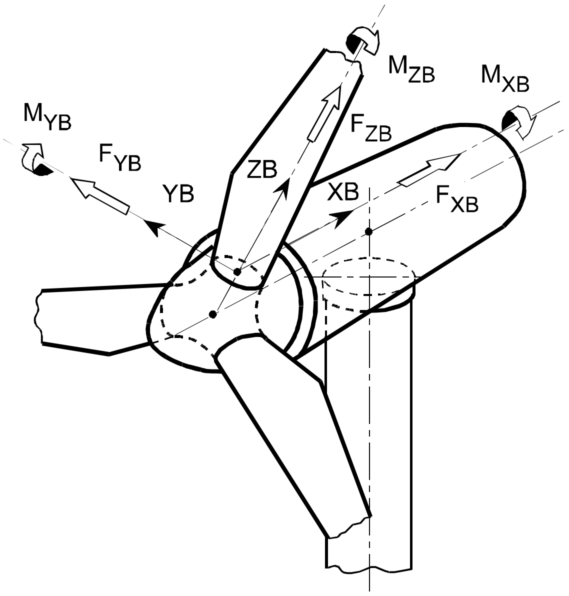
Rotor speed (1P)	rpm	**10.10**	**11.04**	**13.50**	**15.92**	**17.83**
1P	Hz	0.17	0.18	0.22	0.27	0.30
3P	Hz	0.51	0.55	0.67	0.80	0.89
6P	Hz	1.01	1.10	1.35	1.59	1.78
Tower mode 2	Hz	0.49	0.49	0.49	0.49	0.50
Tower mode 1	Hz	0.49	0.49	0.49	0.49	0.49
Blade mode 1A	Hz	0.99	0.99	1.01	1.02	1.04
Blade mode 1B	Hz	1.00	1.00	1.01	1.03	1.04
Blade 1 actuator position mode 1	Hz	1.00	1.00	1.00	1.00	1.00
Blade 2 actuator position mode 1	Hz	1.00	1.00	1.00	1.00	1.00
Blade 3 actuator position mode 1	Hz	1.00	1.00	1.00	1.00	1.00
Blade mode 1C	Hz	1.02	1.03	1.04	1.05	1.07
Blade mode 2A	Hz	1.55	1.55	1.55	1.56	1.56
Blade mode 2B	Hz	1.57	1.57	1.57	1.58	1.58
Drive train	Hz	2.07	2.07	2.08	2.08	2.08
Blade mode 3A	Hz	2.73	2.74	2.76	2.78	2.79
Blade mode 3B	Hz	2.84	2.84	2.86	2.88	2.90
Blade mode 3C	Hz	2.87	2.88	2.90	2.92	2.94
Blade mode 2C	Hz	3.66	3.66	3.67	3.67	3.68
Tower mode 4	Hz	4.25	4.25	4.25	4.25	4.25
Tower mode 5	Hz	4.60	4.61	4.61	4.61	4.61
Blade mode 4A	Hz	4.96	4.96	4.97	4.98	4.99
Blade mode 4B	Hz	4.98	4.98	4.99	5.00	5.01
Tower mode 6	Hz	10.94	10.95	10.95	10.96	10.97
Blade mode 4C	Hz	11.08	11.08	11.08	11.09	11.09
Tower mode 3	Hz	18.54	18.53	18.53	18.53	18.53

Table 2.3: Natural frequencies of the coupled modes of the generic 2MW wind turbine

3 ANALYTICAL BASIS

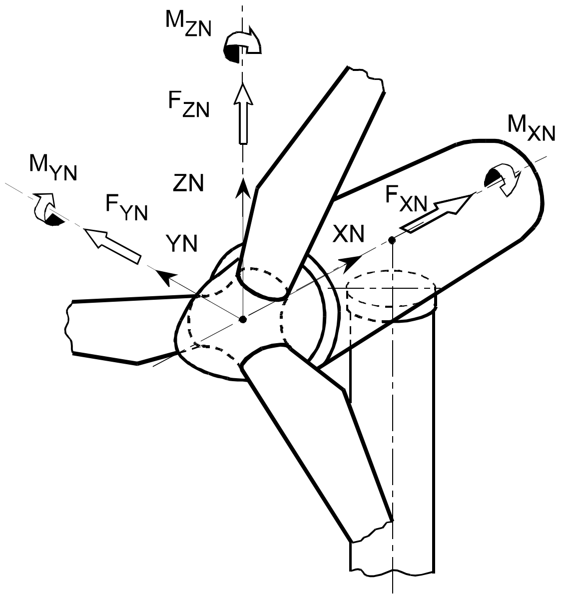
3.1 Coordinate Systems

The coordinate systems used in this report are defined by the GL regulation [3] and are shown in Figure 3.1 to Figure 3.4 below.



ZB	Radially along blade axis.
XB	Perpendicular to ZB, and pointing towards the tower for an upwind turbine, or away from the tower for a downwind turbine (the picture shows an upwind turbine).
YB	Perpendicular to blade axis and shaft axis, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.
Origin	At each blade station.

Figure 3.1: Co-ordinate system for blade root loads and deflections



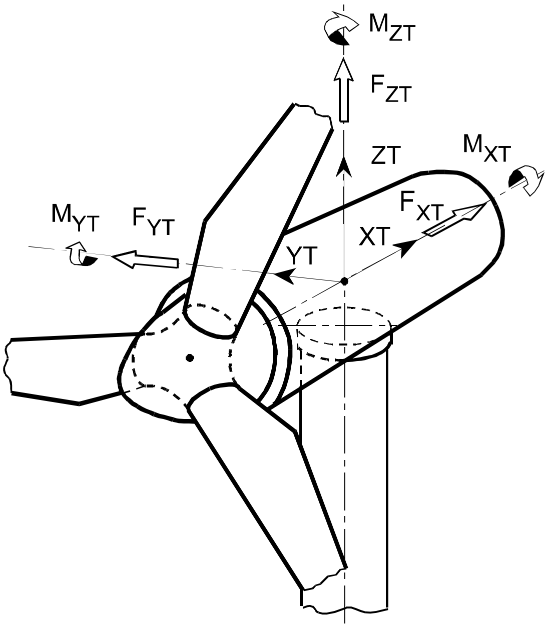
Hub loads in fixed frame of reference:

XN	Along shaft axis, and pointing towards the tower for an upwind turbine.
ZN	Perpendicular to XN, such that ZN would be vertically upwards if the tilt angle were zero.
YN	Horizontal, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.

Hub loads in rotating frame of reference:

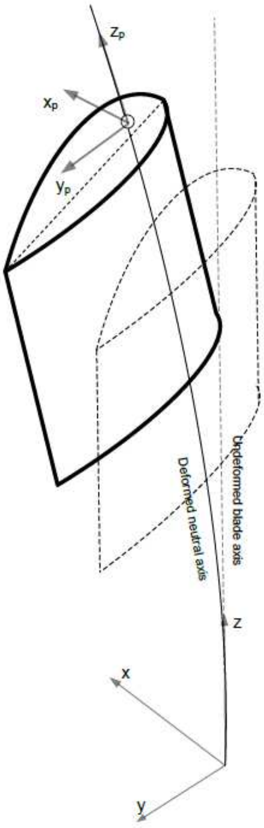
XN	Along shaft axis, and pointing towards the tower for an upwind turbine.
ZN	Perpendicular to XN, such that ZN would be aligned with blade 1 axis if the cone angle were zero.
YN	Perpendicular to XN and ZN, to give a right-handed co-ordinate system independent of direction of rotation and rotor location upwind or downwind of the tower.
Origin	At hub centre (intersection of blade and shaft axes).

Figure 3.2: Co-ordinate system for hub loads



XT	Pointing South.
ZT	Vertically upwards.
YT	Pointing East.
Origin	At each tower station.

Figure 3.3: Co-ordinate system for tower loads and deflections



XP	Orthogonal to YP and Zp to follow the right hand rule.
YP	Determined by the principle axis orientation
ZP	Radially along the deflected neutral axis
Origin	At each blade station.

Figure 3.4 Local blade co-ordinate system for loads and deflections

3.2 Numerical modelling

The numerical simulations described in this report were carried out using the *Bladed* software. *Bladed* is the industry standard software for wind turbine design calculations and has been extensively validated against measured data from a wide range of turbines and against analytical results [4].

GH Bladed provides an integrated numerical model which accounts for the following effects:
- Applied aerodynamic (& hydrodynamic) loading,
- Functional loads resulting from control system actions,
- Dynamic response of the structure.

The dynamic response of the turbine and the influence of the controller were considered for all load cases.

The theoretical methods that comprise the numerical modelling are described in detail in [5]. Table 3.1 summarises those aspects of the modelling that are specific to the results presented in this report.

Bladed interface version	4.3
DTBLADED version	4.3.0.42
Wake model	Dynamic wake model for all cases
Momentum theory	Glauert momentum theory with correction for skewed inflow
Stall model	Stall hysteresis model used, starting at 25% radius
Modal model	4 individual blade modes 6 tower modes
Rotor mass imbalance	134.4 kgm
Rotor pitch imbalance	Set angles of +0.3°, 0.0° and -0.3° on blades 1, 2 and 3 respectively
Wind shear exponent	0.2, except where otherwise stated
Vertical flow inclination	0°
Tower shadow model	Potential flow model

Table 3.1: Summary of analytical basis

3.3 Outputs

In this report loads are reported at:
- The blade root (at 1.25m radius)
- Blade station at 18.26m
- The rotor centre (in rotating and stationary coordinates)
- Yaw bearing
- Tower heights of 0m and 63.125m.

3.4 General notes on turbulent wind model

The turbulent variation in wind speed has been modelled using the Kaimal spectrum with the exponential coherence model according to the IEC 61400-1 edition 3 standard [1] with Λ_1 of 42m. The turbulence spectral parameters, which were used in generating turbulent wind fields, are given in Table 3.2.

Scale parameter Λ_1	Integral scale			Coherence scale parameter Lc	Coherence decay constant H
	longitudinal	lateral	vertical		
42	340.2	113.4	27.72	340.2	12

Table 3.2 - Turbulence spectral parameters for Kaimal model

4 LOAD CASES

4.1 Input Parameters

Parameters related to the wind class and turbine which contribute to the definitions of the design load cases are presented in Table 4.1.

Turbulence Class	Between A and B	
Wind Class	AWMS at 6, 7, 8m/s	
Air density	1.225	kg/m^3
Expected value of turbulence intensity at 15 m/s, I_{ref}	0.15	-
Hub height	65	m
Rated Power, P_{rated}	2000	kW
Cut-in wind speed, V_{in}	4	m/s
Rated hub-height wind speed, V_r	12.8	m/s
Cut-out wind speed, V_{out}	25	m/s
Annual average wind speed at hub height, V_{ave}	6, 7, 8	m/s

Table 4.1 Design load case parameters

4.2 Load case descriptions

The cases considered are presented below. The tables in this section give the case name, the initial turbine state, the initial conditions (wind speed, yaw error and pitch angle) and the details of any transient events or model of turbulence.

The fatigue design load cases DLC1.2 and DLC6.4 have been considered according to the IEC 61400-1 edition 3 design standard [1]. No transient fatigue load cases have been considered as they are not deemed relevant to the investigation.

For wind turbine fatigue load calculations it is common practice to account for a yaw error of +/- 8 degrees over the turbine lifetime. This is achieved by running the simulations at 3 yaw angles of -8, 0 and +8 degrees, with equal weighting given to each yaw angle in the fatigue post-processing. The calculations presented in this report do not account for +/- 8 degree yaw error over the turbine lifetime. Instead, 11 full sets of fatigue load cases have been simulated, each with a constant yaw error assumed for the entire turbine lifetime. The yaw errors considered vary from -20 to +20 degrees in 4 degree intervals.

4.2.1 Fatigue load cases

Design load case (DLC): 1.2

Operating condition: Power production

Wind conditions: Normal turbulence model, $V_{in} < V_{hub} < V_{out}$

Type of analysis: Fatigue

Partial safety factors: Partial safety factor for fatigue

Description of simulations:

Load case ID	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw angle	Hours per year, AMWS (m/s)		
				6	7	8
1.2ax1-6	5	28.05	-20 to 20 deg in 4 deg intervals	2122.46	1716.59	1399.35
1.2bx1-6	7	23.25		2071.00	1875.08	1645.49
1.2cx1-6	9	20.58		1512.37	1603.70	1560.36
1.2dx1-6	11	18.89		871.74	1132.65	1258.44
1.2ex1-6	13	17.71		406.11	676.45	883.94
1.2fx1-6	15	16.85		154.85	345.96	547.62
1.2gx1-6	17	16.19		48.69	152.67	301.50
1.2hx1-6	19	15.67		12.69	58.41	148.24
1.2ix1-6	21	15.25		2.75	19.44	65.30
1.2jx1-6	23	14.90		0.50	5.64	25.84
1.2kx1-6	25	14.61		0.07	1.43	9.20

Comments:

Three-dimensional three-component Kaimal turbulent wind field (10 min sample).

Six turbulent wind fields used for each wind speed bin, each using a different random number seed (indexed 1-6).

Wind gradient exponent (exponential model), $\alpha = 0.2$
The second character x in the load case ID indicates 11 yaw angles: a = -20deg, b = -16deg, c = -12deg, d = -8deg, e = -4deg, f = 0deg, g = 4deg, h = 8deg, i = 12deg, j = 16deg, k = 20deg

Design load case (DLC):	6.4
Operating condition:	Parked (stand still or idling)
Wind conditions:	Normal turbulence model, $V_{hub} < 0.7\ V_{ref}$
Type of analysis:	Fatigue
Partial safety factors:	Partial safety factor for fatigue

Description of simulations:

Load case ID	Mean wind speed (m/s)	Longitudinal turbulence intensity (%)	Yaw angle	Hours per year AMWS (m/s)		
				6	7	8
1.2ax1-6	3	39.25	-20 to 20 deg in 4 deg intervals	1562.76	1177.58	916.62
1.2bx1-6	30	14.05		0.01	0.39	4.09

Comments:	Three-dimensional three-component Kaimal turbulent wind field (10 min sample). Six turbulent wind fields used for each wind speed bin, each using a different random number seed (indexed 1-6). All blades at idling pitch angle of 90 deg Wind gradient exponent (exponential model), $\alpha = 0.2$ The second character x in the load case ID indicates 11 yaw angles: a = -20deg, b = -16deg, c = -12deg, d = -8deg, e = -4deg, f = 0deg, g = 4deg, h = 8deg, i = 12deg, j = 16deg, k = 20deg

5 FATIGUE LOADS

5.1 Safety factors

The partial safety factor for fatigue loads required by the IEC 61400-1 Edition 3 standard is 1.0.

5.2 Integration of fatigue results

A total of 11 full sets of fatigue load cases have been simulated, each with a constant yaw error assumed for the entire turbine lifetime. The ten-minute mean yaw errors considered vary from -20 to +20 degrees in 4 degree intervals. The load results presented in this Section are therefore not indicative of load variations due to dynamic high-frequency yaw tracking during the operational life of the turbine. Rather they represent the variation in fatigue load over the lifetime of the turbine assuming a constant mean offset in yaw angle with a ten-minute averaging period.

A Weibull wind speed distribution is assumed for the integration of fatigue results. 3 sets of lifetime fatigue loads are calculated for each yaw angle with annual mean wind speeds of 6, 7 and 8 m/s respectively.

5.3 Damage equivalent load calculation

Damage equivalent loads are used to equate the fatigue damage represented by RFCC data to that caused by a single stress range repeating at a single frequency. The method is based on the Miner's rule. The damage equivalent stress is given by the following formula:

$$L_N = \sqrt[m]{\frac{\sum L_i^m n_i}{N}}$$

where	L_N	is the equivalent stress for N cycles
	L_i	is the stress range bin i.
	n_i	is the number of rain flow cycles at stress range bin i.
	m	is the negative inverse of the slope on the material's Wöhler curve (m is also referred to as the S-N curve slope).
	N	is the number of cycle repetitions in the turbine lifetime.

The S-N curve slopes (m) used here are 4 and 10, where 4 represents steel and 10 represents glass reinforced plastic (GRP).

The stress, L_i, depends upon the geometry of the structure under consideration. It is assumed that stress is proportional to load, therefore it is quite acceptable to use load instead of stress in the above equation.

For simplicity, L_i and n_i have been derived from the one-dimensional table with no correction to account for the fatigue damage due to mean stresses.

5.4 Interpretation of fatigue load results

The loads presented in this report have been calculated for a generic 2MW turbine model. The geometry, mass and stiffness properties of this model are not based on an actual wind turbine designed for a particular set of conditions. Rather, they are representative of typical turbine properties at the 2MW scale.

For a real wind turbine the components are designed on the basis of a set of loads calculated with wind conditions appropriate to the design level (type class or site specific). The designer must ensure that sufficient strength is built in to the components to resist the cyclic stress experienced over the lifetime of the turbine. The utilisation factors for each component will be different according to the characteristics of the loading at that location and whether the component design is driven by fatigue or extreme loading. In order to quantify the impact of changes in loading in terms of the fatigue life of the components, a knowledge of these utilisation factors and the resulting safety margins inherent in the design is essential.

For the turbine model used in this work the component parameters are generic and have not been designed or optimised with respect to a specific set of loads, as would be the case for a real turbine design. As a result there is no information about any safety margins in the design. It is therefore not possible to give any sensible analysis of the load variations presented in this report in terms of changes in component lifetime.

GL GH could offer a more detailed analysis of expected performance improvement and the effects of load variations on component lifetime for a specific turbine on a specific site. The information that would be required to perform this analysis includes, among other things:

- Turbine design documentation including reserve strength margins, utilisation factors etc for all components to be analysed
- Design driving load cases for all components to be analysed
- Site environmental data

A more detailed proposal for this kind of work could be provided by GL GH on request.

5.5 Damage equivalent loads

Lifetime-integrated damage equivalent fatigue loads are presented in Tables 5.1 to 5.21 below. These loads have been calculated for a reference frequency of 0.0158 Hz, corresponding to 1E+07 cycles in a 20-year turbine lifetime.

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	1874.48	2160.10	21.90	109.17	145.72	181.89
-16	1864.47	2105.95	20.99	107.40	145.32	180.98
-12	1852.77	2070.39	20.49	105.57	144.78	180.39
-8	1843.14	2040.53	20.13	104.46	144.30	180.16
-4	1832.99	2026.97	19.48	104.39	143.78	179.53
0	1823.42	2024.39	19.21	103.31	143.32	178.90
4	1812.51	2046.56	19.23	103.51	142.78	179.25
8	1801.46	2074.26	19.25	103.79	142.26	179.34
12	1794.64	2103.04	18.99	104.28	141.84	180.29
16	1786.25	2141.22	19.14	104.91	141.42	180.14
20	1785.76	2194.01	19.08	106.30	141.28	180.89

Table 5.1 – Lifetime weighted equivalent loads: blade root (AMWS=8m/s), m=10

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	1843.65	2034.88	21.13	102.64	144.19	184.22
-16	1836.35	1987.18	20.35	100.86	143.93	183.35
-12	1826.47	1949.86	19.89	98.73	143.49	182.77
-8	1818.53	1914.56	19.56	97.32	143.11	182.55
-4	1809.34	1891.75	18.96	96.27	142.67	181.92
0	1800.48	1876.34	18.71	95.07	142.25	181.27
4	1789.92	1882.91	18.69	94.62	141.75	181.63
8	1778.96	1892.90	18.67	94.23	141.25	181.72
12	1771.33	1903.54	18.38	94.04	140.82	182.66
16	1762.51	1929.95	18.33	93.83	140.39	182.50
20	1760.44	1974.07	18.35	94.60	140.22	183.23

Table 5.2 – Lifetime weighted equivalent loads: blade root (AMWS=7m/s) , m=10

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	1797.41	1882.79	19.91	95.29	141.83	186.23
-16	1793.42	1842.39	19.28	93.58	141.72	185.45
-12	1785.83	1802.16	18.89	91.06	141.40	184.90
-8	1780.24	1763.10	18.61	89.40	141.13	184.70
-4	1772.48	1734.51	18.08	87.83	140.78	184.09
0	1764.71	1706.44	17.85	86.06	140.43	183.43
4	1755.06	1696.23	17.82	84.94	139.99	183.80
8	1744.85	1687.72	17.72	83.96	139.55	183.89
12	1736.79	1681.34	17.40	83.04	139.13	184.78
16	1728.04	1691.95	17.26	82.15	138.71	184.60
20	1724.59	1721.34	17.23	82.40	138.52	185.28

Table 5.3 – Lifetime weighted equivalent loads: blade root (AMWS=6m/s) , m=10

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	368.44	553.26	10.77	63.59	46.85	74.86
-16	363.70	543.19	10.38	62.17	46.34	74.46
-12	359.35	539.56	10.11	61.30	45.85	74.30
-8	355.29	536.88	9.88	60.96	45.39	73.99
-4	351.13	538.64	9.60	61.16	44.95	73.43
0	347.50	542.15	9.44	61.72	44.47	73.35
4	343.76	554.09	9.38	63.00	43.99	73.43
8	338.86	561.91	9.59	64.23	43.50	73.74
12	338.25	572.20	9.30	65.64	43.24	74.12
16	334.62	588.26	9.13	67.28	42.87	74.14
20	335.23	602.56	9.23	68.85	42.86	74.70

Table 5.4 – Lifetime weighted equivalent loads: blade section 18.261m (AMWS=8m/s) , m=10

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	359.31	516.75	10.40	59.44	45.83	75.94
-16	355.36	508.41	10.08	58.28	45.41	75.57
-12	351.49	504.98	9.83	57.40	44.98	75.42
-8	347.77	501.07	9.62	56.88	44.55	75.12
-4	343.70	500.61	9.36	56.78	44.12	74.57
0	340.08	501.41	9.22	56.93	43.66	74.49
4	336.10	508.56	9.15	57.66	43.16	74.55
8	330.87	512.44	9.29	58.32	42.64	74.87
12	329.31	518.12	9.01	59.16	42.31	75.25
16	325.35	531.02	8.83	60.49	41.91	75.25
20	325.13	542.12	8.87	61.77	41.81	75.80

Table 5.5 – Lifetime weighted equivalent loads: blade section 18.261m (AMWS=7m/s) , m=10

Yaw angle [deg]	Edge BM [kNm]	Flap BM [kNm]	Mz [kNm]	Flap SF [kN]	Edge SF [kN]	Fz [kN]
-20	345.35	470.43	9.82	54.35	44.28	76.88
-16	342.40	463.70	9.57	53.45	43.98	76.54
-12	339.21	459.94	9.36	52.52	43.61	76.43
-8	336.08	454.98	9.18	51.86	43.25	76.14
-4	332.22	452.48	8.96	51.49	42.85	75.61
0	328.70	450.73	8.83	51.25	42.40	75.53
4	324.62	452.59	8.75	51.37	41.92	75.58
8	319.28	452.94	8.81	51.45	41.40	75.88
12	316.67	454.58	8.54	51.78	41.00	76.26
16	312.57	462.75	8.36	52.66	40.60	76.23
20	311.40	469.65	8.34	53.54	40.42	76.76

Table 5.6 – Lifetime weighted equivalent loads: blade section 18.261m (AMWS=6m/s) , m=10

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	541.37	2782.50	2764.69	121.53	1305.65	1301.57
-16	541.72	2678.99	2665.30	120.93	1304.23	1301.07
-12	543.00	2587.37	2580.92	120.25	1302.44	1300.04
-8	544.59	2512.06	2511.16	120.22	1300.24	1298.95
-4	545.90	2454.39	2461.36	120.58	1297.64	1297.41
0	544.34	2419.39	2427.24	120.81	1294.96	1295.53
4	542.89	2398.95	2409.97	120.88	1291.85	1293.69
8	543.18	2394.43	2406.51	121.05	1288.97	1291.29
12	542.47	2401.17	2410.49	121.29	1285.72	1288.90
16	542.56	2417.43	2417.80	121.83	1282.40	1286.45
20	544.23	2437.62	2429.54	122.51	1279.29	1283.65

Table 5.7 –Lifetime weighted equivalent loads: hub in rotating coordinates (AMWS=8m/s), m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	517.88	2613.11	2597.62	111.77	1283.82	1280.26
-16	519.12	2515.20	2503.49	111.71	1282.95	1280.22
-12	521.13	2423.11	2417.97	111.36	1281.60	1279.55
-8	523.12	2341.62	2341.17	111.61	1279.80	1278.79
-4	522.85	2270.99	2278.05	112.18	1277.52	1277.48
0	523.47	2217.46	2225.14	112.54	1275.12	1275.80
4	521.90	2174.89	2185.67	112.58	1272.28	1274.12
8	521.97	2146.34	2158.14	112.64	1269.63	1271.78
12	520.72	2132.13	2140.43	112.57	1266.52	1269.50
16	518.45	2132.28	2130.64	112.73	1263.30	1267.04
20	518.76	2144.51	2132.87	112.90	1260.25	1264.18

Table 5.8 –Lifetime weighted equivalent loads: hub in rotating coordinates (AMWS=7m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	480.99	2393.04	2380.58	101.42	1252.88	1249.92
-16	483.77	2307.11	2297.90	101.81	1252.66	1250.39
-12	486.97	2221.55	2218.26	101.75	1251.85	1250.15
-8	489.68	2141.93	2142.60	102.26	1250.55	1249.77
-4	489.84	2067.94	2074.95	102.96	1248.69	1248.74
0	491.04	2006.21	2013.05	103.46	1246.68	1247.28
4	489.35	1952.98	1962.48	103.50	1244.22	1245.82
8	488.95	1911.89	1922.27	103.48	1241.92	1243.58
12	486.84	1887.11	1893.17	103.16	1239.05	1241.47
16	482.84	1878.38	1874.37	103.06	1235.96	1239.05
20	481.12	1886.45	1871.87	102.83	1233.01	1236.14

Table 5.9 –Lifetime weighted equivalent loads: hub in rotating coordinates (AMWS=6m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	541.37	1780.29	1758.73	121.53	52.05	82.05
-16	541.72	1776.19	1759.80	120.93	52.28	82.24
-12	543.00	1777.84	1764.35	120.25	52.37	82.20
-8	544.59	1779.91	1768.45	120.22	52.61	82.33
-4	545.90	1784.02	1772.14	120.58	53.36	82.65
0	544.34	1791.18	1773.12	120.81	53.03	82.37
4	542.89	1797.00	1772.70	120.88	53.14	82.43
8	543.18	1807.70	1773.74	121.05	52.82	82.12
12	542.47	1821.87	1773.67	121.29	53.34	82.67
16	542.56	1848.75	1775.09	121.83	56.28	82.95
20	544.23	1884.94	1780.54	122.51	54.26	84.15

Table 5.20 –Lifetime weighted equivalent loads: hub in stationary coordinates (AMWS=8m/s), m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	517.88	1619.47	1611.26	111.77	47.03	75.05
-16	519.12	1620.22	1615.70	111.71	47.36	75.35
-12	521.13	1625.59	1623.35	111.36	47.50	75.36
-8	523.12	1630.00	1629.28	111.61	47.75	75.57
-4	522.85	1634.72	1634.20	112.18	48.02	75.66
0	523.47	1641.62	1636.15	112.54	48.14	75.66
4	521.90	1646.13	1636.22	112.58	48.24	75.72
8	521.97	1655.19	1636.66	112.64	47.92	75.33
12	520.72	1664.70	1636.27	112.57	48.39	75.73
16	518.45	1682.44	1634.98	112.73	48.79	75.74
20	518.76	1706.91	1636.55	112.90	48.75	76.66

Table 5.11 –Lifetime weighted equivalent loads: hub in stationary coordinates (AMWS=7m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	480.99	1453.89	1458.50	101.42	41.51	66.79
-16	483.77	1458.80	1465.48	101.81	41.93	67.23
-12	486.97	1467.66	1475.66	101.75	42.14	67.34
-8	489.68	1473.50	1482.71	102.26	42.44	67.66
-4	489.84	1478.37	1488.86	102.96	42.65	67.75
0	491.04	1484.78	1491.41	103.46	42.85	67.79
4	489.35	1488.04	1492.05	103.50	42.91	67.83
8	488.95	1495.31	1491.74	103.48	42.51	67.34
12	486.84	1499.48	1491.23	103.16	42.78	67.49
16	482.84	1507.12	1487.35	103.06	42.62	67.25
20	481.12	1519.12	1485.58	102.83	42.74	67.85

Table 5.12 –Lifetime weighted equivalent loads: hub in stationary coordinates (AMWS=6m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	4994.48	11740.80	1741.33	219.81	95.92	76.77
-16	4994.54	11518.50	1742.48	217.29	96.08	76.91
-12	4940.88	11271.60	1747.70	214.58	95.79	76.85
-8	4941.43	11199.50	1751.96	213.84	96.28	76.99
-4	5295.75	11161.40	1756.53	213.57	101.23	77.36
0	4956.14	11062.30	1757.21	212.38	96.95	77.00
4	4915.40	10949.70	1758.89	211.03	96.45	77.04
8	4822.42	10873.40	1759.33	210.25	95.08	76.70
12	4785.94	10811.70	1758.35	209.21	94.32	77.43
16	5975.85	10844.80	1760.02	209.90	109.05	77.65
20	5041.08	10857.90	1765.95	210.20	96.42	78.82

Table 5.33 –Lifetime weighted equivalent loads: Tower station height 0m (AMWS=8m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	4235.44	10653.60	1592.14	198.47	82.87	70.30
-16	4232.92	10488.10	1596.50	196.58	82.95	70.56
-12	4168.86	10293.30	1604.72	194.47	82.56	70.57
-8	4195.32	10272.10	1611.10	194.34	83.31	70.78
-4	4285.80	10277.30	1616.96	194.65	84.86	70.85
0	4217.69	10216.40	1618.59	193.92	84.23	70.83
4	4178.93	10129.70	1620.73	192.84	83.83	70.87
8	4067.99	10074.90	1620.53	192.20	82.35	70.44
12	4022.44	10020.40	1619.39	191.10	81.53	70.99
16	4323.22	10067.50	1618.28	191.79	84.33	70.93
20	4106.05	10080.70	1620.25	191.92	81.16	71.76

Table 5.14 –Lifetime weighted equivalent loads: Tower station height 0m (AMWS=7m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	3763.93	9713.00	1439.24	178.73	72.50	62.52
-16	3751.02	9596.58	1445.94	177.31	72.46	62.96
-12	3667.24	9457.08	1456.37	175.79	71.81	63.08
-8	3697.94	9481.62	1464.17	176.14	72.55	63.41
-4	3741.88	9527.02	1471.18	176.99	73.61	63.46
0	3725.60	9502.85	1473.43	176.64	73.61	63.50
4	3683.82	9449.74	1476.06	175.97	73.21	63.51
8	3529.76	9428.70	1475.17	175.60	71.38	62.97
12	3458.64	9389.58	1474.21	174.49	70.36	63.24
16	3576.60	9473.79	1470.59	175.50	70.96	62.91
20	3625.37	9506.10	1469.13	175.73	70.60	63.41

Table 5.15 –Lifetime weighted equivalent loads: Tower station height 0m (AMWS=6m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	570.48	1803.89	1740.34	161.78	67.25	76.77
-16	570.21	1792.50	1741.61	159.05	67.32	76.91
-12	570.05	1787.57	1746.81	156.75	66.72	76.85
-8	569.04	1783.84	1751.01	156.23	66.92	76.98
-4	571.14	1783.43	1755.88	155.98	71.71	77.36
0	567.43	1784.54	1756.36	155.34	67.30	76.99
4	565.29	1785.03	1757.88	154.47	66.86	77.04
8	562.90	1789.85	1758.80	154.17	65.66	76.70
12	562.30	1797.08	1757.69	153.90	65.13	77.44
16	563.73	1815.26	1759.44	155.17	80.17	77.65
20	561.48	1840.91	1765.42	155.97	68.31	78.82

Table 5.46 –Lifetime weighted equivalent loads: Tower station height 63.125m (AMWS=8m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	543.87	1633.16	1591.27	146.84	57.19	70.30
-16	544.62	1627.31	1595.79	144.82	57.20	70.57
-12	545.32	1627.25	1603.94	143.18	56.43	70.56
-8	544.94	1626.28	1610.29	143.20	56.95	70.78
-4	545.20	1627.73	1616.39	143.43	58.28	70.85
0	544.29	1629.87	1617.84	143.19	57.42	70.83
4	542.09	1629.55	1619.80	142.53	57.04	70.87
8	539.53	1633.71	1620.08	142.35	55.64	70.44
12	538.52	1637.57	1618.79	141.89	54.98	71.00
16	536.11	1649.26	1617.79	143.13	58.63	70.93
20	533.48	1666.44	1619.79	143.53	55.83	71.76

Table 5.17 –Lifetime weighted equivalent loads: Tower station height 63.125m (AMWS=7m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	504.37	1459.17	1438.49	133.48	50.55	62.52
-16	506.75	1458.33	1445.42	132.08	50.44	62.96
-12	508.72	1463.00	1455.73	131.09	49.35	63.07
-8	509.36	1464.25	1463.52	131.50	49.91	63.40
-4	509.93	1466.92	1470.70	132.18	50.70	63.46
0	509.91	1470.18	1472.80	132.30	50.45	63.50
4	507.51	1469.07	1475.28	131.92	50.06	63.51
8	504.56	1472.78	1474.80	131.99	48.14	62.97
12	502.76	1472.82	1473.70	131.43	47.14	63.25
16	498.51	1477.47	1470.19	132.87	48.53	62.91
20	494.10	1485.76	1468.75	133.15	48.98	63.41

Table 5.18 –Lifetime weighted equivalent loads: Tower station height 63.125m (AMWS=6m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	567.94	1803.88	1741.34	166.04	69.08	76.86
-16	567.98	1792.67	1742.50	163.24	69.18	76.98
-12	567.54	1787.58	1747.72	160.76	68.55	76.93
-8	567.31	1783.75	1751.96	160.12	68.73	77.06
-4	569.10	1783.40	1756.53	159.82	73.64	77.47
0	565.39	1784.52	1757.22	159.20	69.08	77.08
4	563.66	1785.14	1758.93	158.14	68.63	77.13
8	561.58	1789.85	1759.35	157.80	67.42	76.80
12	560.94	1797.15	1758.36	157.50	66.85	77.55
16	562.61	1815.35	1760.02	158.59	82.40	77.76
20	560.48	1840.71	1765.95	159.51	70.16	78.93

Table 5.59 –Lifetime weighted equivalent loads: Yaw bearing (AMWS=8m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	541.50	1633.10	1592.14	150.70	58.73	70.38
-16	542.56	1627.48	1596.51	148.66	58.79	70.63
-12	542.94	1627.25	1604.73	146.87	57.97	70.64
-8	543.43	1626.21	1611.09	146.80	58.48	70.85
-4	543.30	1627.68	1616.97	147.00	59.77	70.95
0	542.36	1629.86	1618.60	146.81	58.92	70.90
4	540.63	1629.73	1620.78	145.98	58.53	70.96
8	538.40	1633.73	1620.55	145.76	57.10	70.52
12	537.34	1637.65	1619.39	145.32	56.43	71.09
16	535.17	1649.30	1618.29	146.34	60.20	71.02
20	532.64	1666.18	1620.25	146.92	57.31	71.86

Table 5.20 –Lifetime weighted equivalent loads: Yaw bearing (AMWS=7m/s) , m=4

Yaw angle [deg]	Mx [kNm]	My [kNm]	Mz [kNm]	Fx [kN]	Fy [kN]	Fz [kN]
-20	502.24	1459.08	1439.24	137.00	51.93	62.60
-16	504.94	1458.47	1445.95	135.63	51.88	63.02
-12	506.55	1462.99	1456.39	134.53	50.74	63.14
-8	508.09	1464.20	1464.17	134.90	51.27	63.46
-4	508.25	1466.86	1471.19	135.54	51.93	63.54
0	508.15	1470.18	1473.44	135.74	51.79	63.56
4	506.25	1469.32	1476.12	135.23	51.39	63.59
8	503.65	1472.81	1475.18	135.25	49.40	63.04
12	501.80	1472.87	1474.21	134.77	48.43	63.33
16	497.78	1477.48	1470.59	135.99	49.78	62.99
20	493.47	1485.47	1469.13	136.49	50.27	63.49

Table 5.21 –Lifetime weighted equivalent loads: Yaw bearing (AMWS=6m/s) , m=4

6 REFERENCES

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2. “Proposal for a set of load calculations investigating the influence of yaw error on turbine loading”, GH proposal 111789-UKBR-P-01 issue B, 5th October 2012.

3. Germanischer Lloyd, Rules and regulations, IV - Non-marine Technology, Part 1 – Wind Energy, Regulation for the certification of the Wind Energy Conversion Systems. Chapter 1 - 10.

4. “Bladed Multibody Validation”, GH report 1042/BR/01 issue B, published 22 February 2011

5. *Bladed* Theory Manual, GH Report 282/BR/009, December 2009.

APPENDIX 1

Model Definition of Turbine

GENERAL CHARACTERISTICS OF ROTOR AND TURBINE

Rotor diameter	75	m
Number of blades	3	
Teeter hinge	No	
Hub height	65	m
Offset of hub to side of tower centre	0	m
Tower height	63.125	m
Tilt angle of rotor to horizontal	4	deg
Cone angle of rotor	0	deg
Blade set angle	0	deg
Rotor overhang	4.3	m
Rotational sense of rotor, viewed from upwind	Clockwise	
Position of rotor relative to tower	Upwind	
Transmission	Gearbox	
Aerodynamic control surfaces	Pitch	
Fixed / Variable speed	Variable	
Diameter of spinner	2.5	m
Radial position of root station	1.25	m
Extension piece diameter	1.9	m
Extension piece drag coefficient	1	
Cut in windspeed	4	m/s
Cut out windspeed	25	m/s

BLADE GEOMETRY

Blade length	36.251	m
Pre-bend at tip	3	m
Pitch control	Full span	

Blade Mass Integrals (No ice)

Blade Mass	5320	kg
First Mass Moment	63513	kgm
Second Mass Moment	1251713	kgm²
Blade inertia about shaft	1418803	kgm²

HUB MASS AND INERTIA

Mass of hub	17000	kg
Mass centre of hub	0	m
Hub inertia: about shaft	12000	kgm²
perpendicular to shaft	0	kgm²
Total Rotor Mass	32970	kg
Total Rotor Inertia	4270181	kgm²

TOWER DETAILS

Station Number	Height (m)	Diameter (m)	Mass/unit length (kg/m)	Stiffness (Nm^2)
1	0	4.5	3307.1	2.21E+11
2	2.5	4.42475	3251.43	2.1E+11
3	5	4.34951	2666.23	1.67E+11
4	10	4.19901	2061.21	1.2E+11
5	20	3.89802	1722.37	8.67E+10
6	30	3.59703	1588.76	6.81E+10
7	40	3.29604	1294.25	4.66E+10
8	50	2.99505	1029.24	3.06E+10
9	63.125	2.6	892.848	2E+10

Total Tower Mass	101534	kg
Total Turbine Mass	199504	kg

Drag coefficient for tower	0.6
Environment	Land

Movement of tower foundation

Tower base translational motion?	No
Tower base rotational motion?	No

NACELLE GEOMETRY

Nacelle width	6	m
Nacelle length	2.5	m
Nacelle height	2.5	m
Nacelle drag coefficient	1.6	

NACELLE MASS

Nacelle mass	65000	kg
Nacelle centre of mass lateral offset	0	m
Nacelle centre of mass above tower top	1.3	m
Nacelle centre of mass in front of tower axis	1.-0.6	m
Yaw inertia (about tower axis)	215000	kgm^2
Nodding inertia (about CoG)	0	kgm^2
Rolling inertia (about CoG)	0	kgm^2
Total Tower-head Mass	97970	kg
Total Yaw Inertia: 0° azimuth	2959713	kgm^2
Total Yaw Inertia: 90° azimuth	2959713	kgm^2

DRIVE TRAIN

Gearbox transmission		
Gearbox ratio	84.15	
Position of shaft brake	High speed shaft	
Generator inertia	130	kgm²
Low speed shaft	Flexible	
LSS stiffness	2.4e8	Nm/rad
LSS damping	0	Nms/rad

GENERATOR CHARACTERISTICS

Generator model	Variable Speed	
Power electronics time constant	0	s
Maximum generator torque	14400	Nm
Minimum generator torque	0	Nm
Phase Angle	0	deg

MECHANICAL LOSS TORQUE (kNm, referred to low speed shaft)

Low speed shaft torque (kNm)	Loss torque (kNm)
0	23
960	37
1280	49

ELECTRICAL LOSSES

No losses

POWER PRODUCTION CONTROL

Variable Speed Pitch Regulated Controller	Dynamic	
Minimum generator speed	850	rpm
Optimal mode quadratic speed-torque gain	0.14	Nms²/rad²

Optimal mode maximum generator speed	1500	rpm
Generator torque set point	13403	Nm
Above-rated generator speed set-point	1500	rpm
Minimum pitch angle	-2	deg
Maximum pitch angle	90	deg
Pitch direction	to Feather	
Speed transducer time constant	0	s
Power transducer time constant	0	s
Maximum negative pitch rate	-7	deg/s
Maximum positive pitch rate	7	deg/s
Torque controller	Discrete	
Pitch controller	Discrete	

Discrete Controller:

Communication interval	0.01	s
Power production control:	Pitch,	
Torque,		
Yaw		

PITCH ACTUATOR

Pitch actuator responds to	Position demand	
Pitch Rate response	Passive	
Second order response frequency	1	Hz
Second order response damping factor	0.8	
Lower pitch limit	-0.5	deg
Upper pitch limit	91.5	deg
Lower pitch rate limit	-8	deg/s
Upper pitch rate limit	8	deg/s
Pitch actuation	Individual	

IDLING SIMULATION

Pitch angle for idling	90	deg
External controller	No	