D1.4

Loads and stresses cycles definition novel for test rigs

Lead Beneficiary	Technion
Delivery date	2021-03-29
Dissemination level	Public
Status	Public
Version	1.1
Keywords	Loads and stresses cycles

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815278.

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Document Information

Grant Agreement Number	**815278**
Project Acronym	NEMMO
Work Package	1
Task(s)	1.4
Deliverable	D1.4
Title	Loads and stresses cycles definition novel for test rigs
Author(s)	Steven H. Frankel
File Name	draft_NEMMO_D1.4_Technion_v2

Change Record

Revision	Date	Description	Reviewer
1.0	2021-03-22	Initial draft	Pablo Benguria
1.1	2021-03-29	Reviwed by Tecnalia	Pablo Benguria

1.0 Executive Summary

This report (Deliverable 1.4) summarizes our effort towards the Magallanes tidal turbine performance assessment against load and stress cycles. These tasks are identified in the Grant Agreement as Task 1.4. This work package uses a widely used open-source tool Qblade.

In this work, the Magallanes blade/turbine is considered for the load/stress analysis. Firstly, using the Xfoil module inside the Qblade, the coefficient of lift and drag are calculated for the range of -180^o to 180^o (not shown in the report, please refer to previous deliverables D1.2 and D1.3 for a complete description, as been provided by the Magallanes Renovables). Then, using the Qblade-Turbine BEM simulation module, the Magallanes turbine's performance is assessed by varying the range of tidal velocity in the range of 1.45-10.5 m/s. By performance of the Magallanes turbine, we refer to the tidal turbine's performance characteristics, viz. coefficient of power (C_P), coefficient of thrust (C_T), etc. With this tidal velocity range, the Magallanes tidal turbine's structural performance is assessed using the module Q-FEM of the Qblade. The modal analysis for structural dynamics is done to predict the most influencing frequency range of vibrations during the turbine operation. Finally, using the NREL-FAST module of the Qblade, the time series for different turbulent intensities is obtained, which acts as an input parameter to assess the Magallanes tidal turbine's life span.

Primarily, we have assessed the Magallanes tidal turbine's performance characteristics using the extreme events of tidal velocities and using the extremes of the turbulence intensities. In addition to that, we have proposed (from the previous literature) a methodology to calculate the lifetime of the Magallanes tidal turbine using the guidelines of DNV-GL-SE-0163 (DNVGL-SE-0163, October, 2015) and DNV-GL-SE-0164 (DNVGL-ST-0164, October, 2015).

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2.0 Introduction

Tidal turbines are subjected to different kinds of loads. These loading could be broadly classified as normal loading: edgewise bending, flapwise bending, axial loading, and extreme loading: flapwise bending (spinning rotor), and bending stress (spinning rotor). Furthermore, these loadings are primarily the governing factors to determine the lifetime of the turbines. Thus, load calculation and analysis of tidal turbine is an essential and integral part of the tidal turbine technology. Figure 1 shows the illustration of the overall setup of different kinds of loads and inputs that the tidal turbine encounters. In the present work, using the open-source software Qblade, we study the various loadings and their impact on the turbines' structural behavior. In Qblade, there are different modules for different physical phenomena and for different scientific interests. In fact, Qblade consists of all the necessary modules for aerodynamic design. Thus, the present work focuses on the Qblade simulations (Jonkrman, 2005) of the Magallanes blade/turbine.

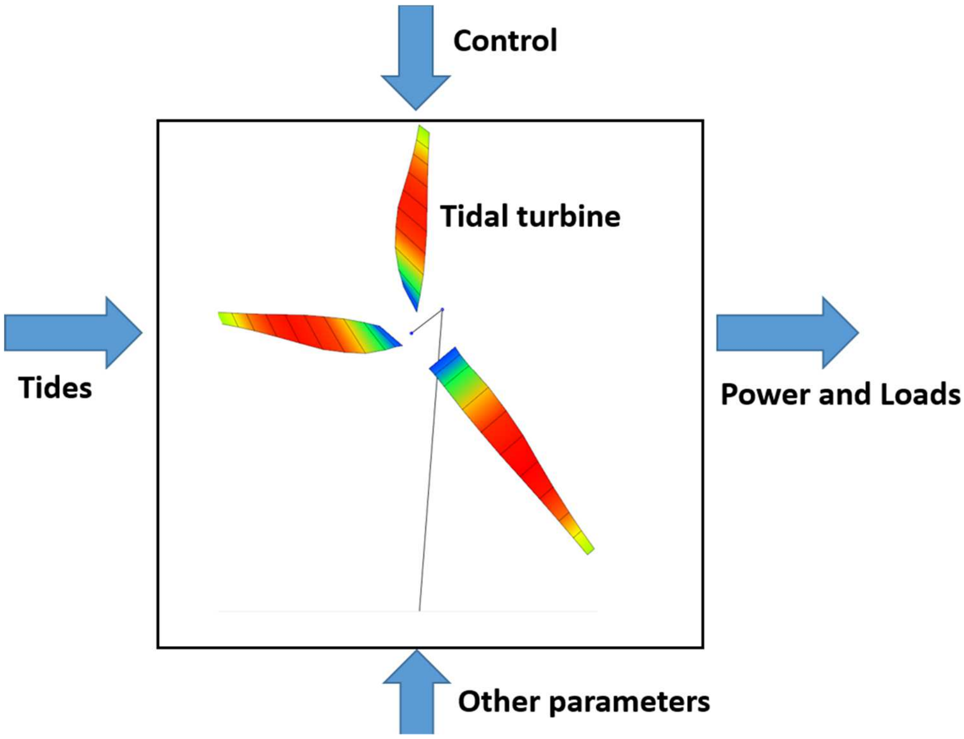

Figure 1: Illustrative figure to demonstrate the loads in tidal turbine (adapted from Madsen and Thomsen (Madsen, 2011))

The Qblade is extensively used in design efforts for wind turbines ((Batu, 2020), (Mazon, 2015), (Stewart, 2013), (Loza, 2019)). Recently in 2020, Sebestian et al. (Perez-Becker, 2020) has extensively studied and compared the lifetime of wind turbines using two independent software. The first software, known as OpenFAST, uses BEM (Blade Element Method) while the other is known as Qblade, which uses higher-order LLFVW (Lifting Line Free Vortex Wake) method. They found that there is indeed a major shift in the fatigue and extreme loads while using a higher-order LLFVW scheme.

In the present work, we used the Magallanes blade for our Qblade analysis. The Magallanes blade/turbine is shown in Figure 2, and the corresponding details of the slices/stations are explained in Table 1.

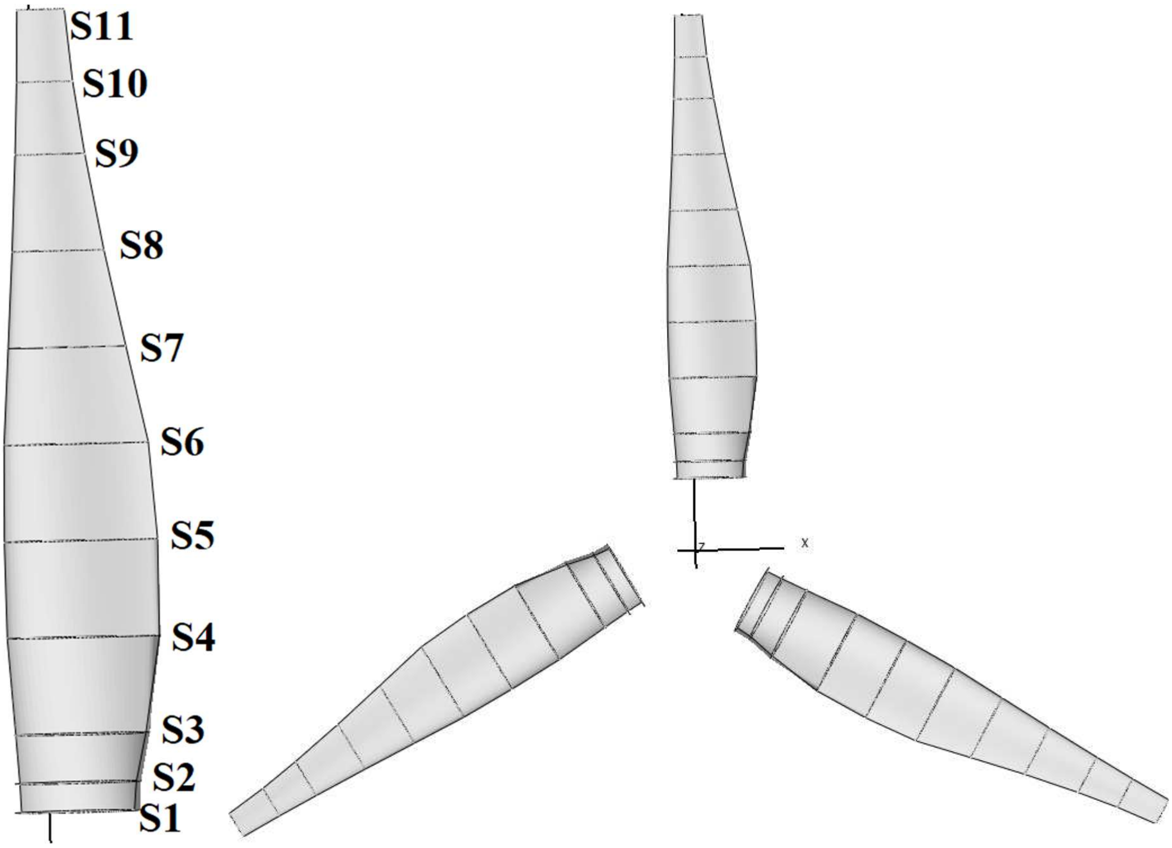

Figure 2: Illustrative figure of Magallanes blade and 3-blade turbine

Table 1: Details of stations of Magallanes blades

Slice/station name	Reynolds number	Radial distance (m)	Relative maximum speed (m/s)	Speed angle	Chord (m)
S2	3.67×10^6	1.02	3.3	40.2	1.3
S3	5.22×10^6	2.0	4.3	54.6	1.4
S4	8.08×10^6	3.0	5.9	64.7	1.6
S5	1.03×10^7	4.0	7.5	70.4	1.6
S6	1.19×10^7	5.0	9.2	74.2	1.5
S7	1.14×10^7	6.0	10.9	76.7	1.22
S8	1.03×10^7	7.0	12.6	78.5	0.95
S9	8.90×10^6	8.0	14.3	79.9	0.72
S10	7.82×10^6	8.75	15.6	80.8	0.58
S11	7.16×10^6	9.5	16.9	81.5	0.49

2.1 Outline of the report

This deliverable report describes the Qblade load simulations of Magallanes tidal turbine in the Grant Agreement for Task 1.4. The report is outlined in the following way:

- Section 1: Executive Summary
- Section 2: Introduction
- Section 3: Effect of tidal speed on the performance of Magallanes turbine
- Section 4: Effect of turbulent (intensity) on the performance of Magallanes turbine
- Section 5: Fatigue load analysis of Magallanes blade/turbine
- Section 6: Closure
- Section 7: References

3.0 Effect of tidal speed on load/performance of Magallanes turbine

The tidal speed range typically has a maximum velocity of 3.5 m/s and an average velocity of 2.5 m/s, as per the report "Hydrodynamic Design report" circulated by the Magallanes renovables (shown in Figure 3).

Given Design Parameters	
Nominal Speed, Vnom (m/s)	*2,5*
Maximum Speed Vmax (m/s)	*3,5*
TSR	*6,7*
Maximum Blade Radius R (m)	*9,5*
Max water Tª (ºC)	*16,0*
Sea water Density (kg/m3)	*1026*
Hub centreline depth	*14,5*
Root radius, root	*0,60*
Mechanical efficiency, η	*0,85*
Nominal Power, P nom (kW)	*850*
Rotor rotation speed (RPM)	*16,84*
Generator optimum rotation speed (RPM)	*1650*
Gear box ratio	*1:98*

Figure 3: Parameters in designing the Magallanes blade/turbine (credit to report "Hydrodynamic Design report" by Magallanes)

Thus, we tried to vary the inlet tidal speed in the range of 0.1 to 10.5 m/s for the constant rotational speed of 16.84 rpm and simulate the cases using the Qblade-Turbine BEM simulation module in Qblade. Notably, we used the power regulation method as "stall regulation," in which the pitch angle is fixed as zero. This power regulation method ensures a reliable operation of the turbine (Loza, 2019). But, as shown in Figure 4 that below the tidal speed of 1.4 m/s, the coefficient of power becomes negative. Thus we took the variation of mean tidal velocity in the range of 1.45 m/s to 10.5 m/s. The complete set of parameters/variables used in the present work are explained in Table 2. The variation of coefficient of power, thrust force, tip speed ratio, and power against the tidal speed is shown in Figure 5.

Table 2: Parameter/variables used in the present work

Sr No	Parameter/variable	Value/range
1	Tidal velocity range (m/s)	1.45-10.5
2	Average tidal velocity (m/s)	2.5
3	Turbulent Intensity (%)	0.5-5
4	Density of fluid (Kg/m^3)	1026
5	Dynamic viscosity of fluid (Pa-s)	1.19 x 10^{-3}
6	Rotor rotational speed (RPM)	16.84
7	Turbine radius (m)	9.5
8	Tip Speed Ratio or TSR	6.7
9	Shell/Internal material Young's Modulus or E (GPa)	73
10	Shell/Internal material density (Kg/m^3)	2900

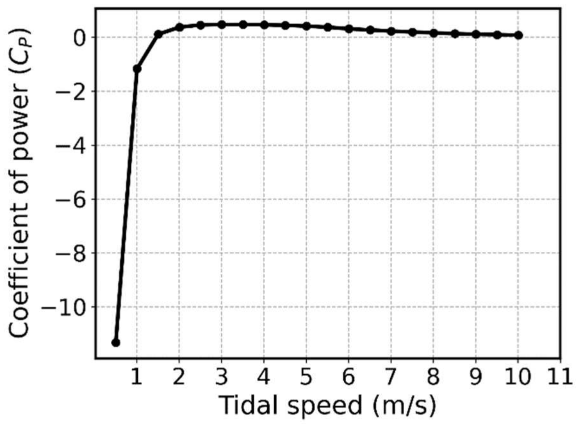

Figure 4: Varitation of coefficient of power against tidal speed

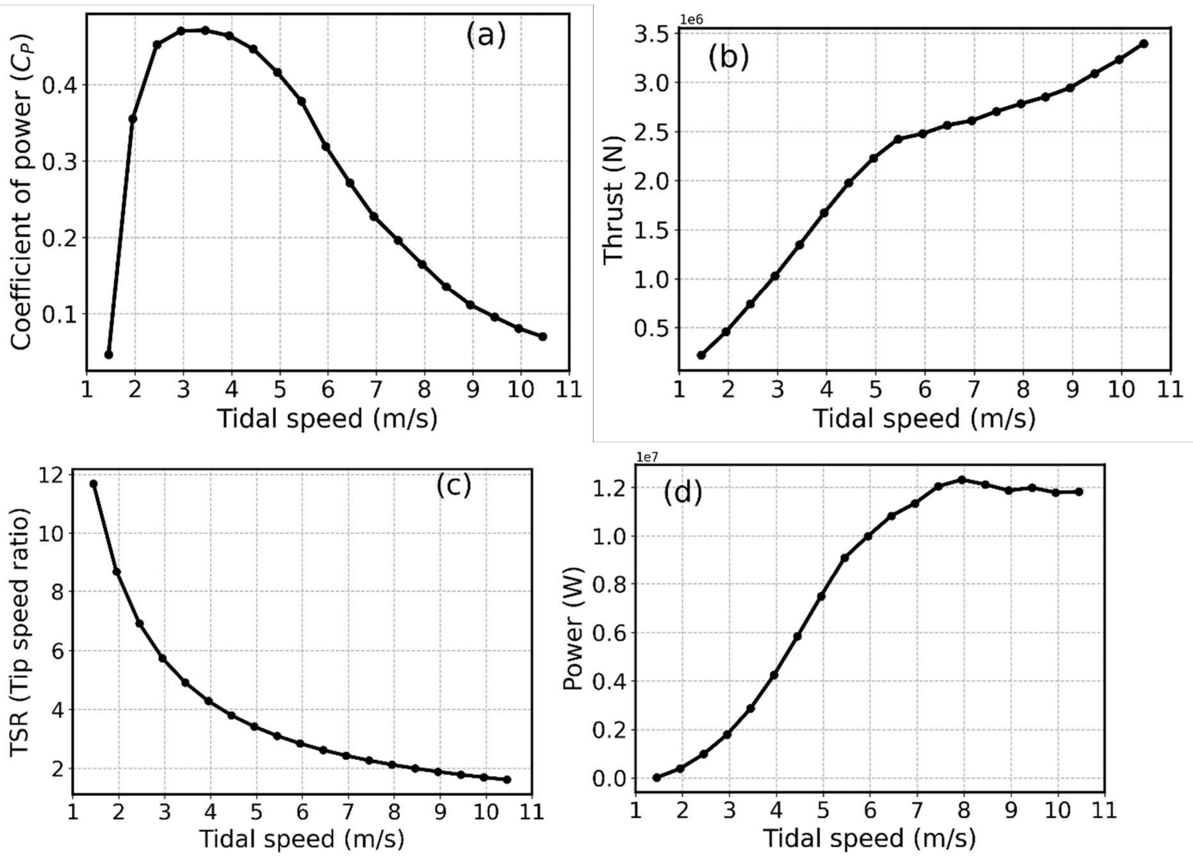

Figure 5: Varation with mean tidal speed of (a) coefficient of power, (b) thrust, (c) TSR (d) power

The variation of mean tidal speed has an immense effect on the structural behavior of the blade/turbine. With the increase in the tidal speed, the stresses developed on the blade/turbine also increases; figure 6 shows this effect. Particularly, Figure 6 (a), (b), (c), and (d) demonstrate the variation of von-Mises stress corresponding to the tidal velocities of 1.45, 2.45, 3.45, and 10.45 m/s, respectively. It is evident that the maximum von Mises stress for the tidal velocity of 10.45 m/s increases to 356.45 MPa as compared to 26.46 MPa, corresponding to the tidal velocity of 1.45 m/s. The detailed results of von Mises stress and deformation corresponding to the tidal velocities in the range of 1.45 to 10.45 m/s are listed in Table 3. In addition to that, the natural shapes and frequencies of the blade structure are obtained using the modal analysis, similar to the work of Batu et al. (Batu, 2020). Table 4 describes all the considered mode types (flap-wise, edgewise, torsional and longitudinal) and the frequency value associated with them.

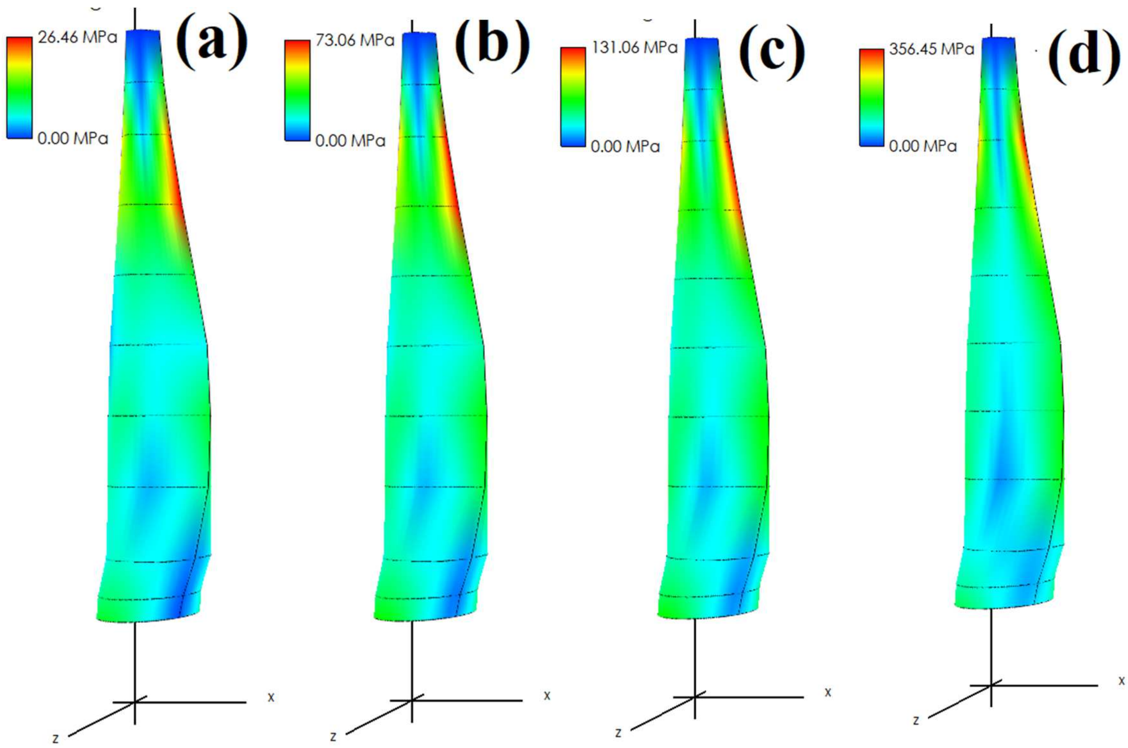

Figure 6: Von-Mises stress distribution in the turbine/rotor for tidal velocities of (a) 1.45, (b) 2.45, (c) 3.45, (d) 10.45 (velocities in m/s)

Table 3: Equivalent (von-Mises) stress, deformation for different mean tidal velocity

Sr. Number	Tidal speed (m/s)	Maximum von Mises stress (MPa)	Deflection in x direction (m)	Deflection in z direction (m)
1	1.45	26.46	0.002974	0.01718
2	1.95	47.09	0.006426	0.03123
3	2.45	73.06	0.112188	0.04808
4	2.95	100.67	0.016818	0.06499
5	3.45	131.06	0.023617	0.08264
6	3.95	163.67	0.031475	0.10020
7	4.45	197.37	0.040086	0.11687
8	4.95	229.62	0.048832	0.13135
9	5.45	256.8	0.05683	0.14254
10	5.95	279.73	0.062664	0.14852
11	6.45	302.22	0.068212	0.15399
12	6.95	319.33	0.072599	0.15782
13	7.45	337.26	0.07763	0.16292
14	7.95	355.31	0.081537	0.16664
15	8.45	361.25	0.082162	0.16682
16	8.95	370.65	0.082123	0.167556

17	9.45	390.91	0.084612	0.172126
18	9.95	374.18	0.081325	0.141625
19	10.45	356.45	0.0790386	0.172618

Table 4: Modal analyis of Magallanes blade for rotation speed of 16.84 rpm

Sr no	Mode Type	Mode number	Natural frequency (Hz)
1	Flap wise	1	18.69
		2	46.42
		3	95.96
		4	168.92
2	Edge wise	1	33.95
		2	108.33
		3	234.9
		4	433.76
3	Torsional	1	195.14
		2	380.37
		3	534.72
		4	729.97
4	Longitudinal	1	517.18
		2	814.48
		3	1149.1
		4	1517.8

4.0 Effect of turbulent (intensity) on load/performance of Magallanes turbine

We considered four turbulence intensities (in %) as 0.5, 1, 2.5, and 5 for the same average tidal velocity of 2.45 m/s. NREL-FAST module is used to obtain the time series for different turbulence intensities. Figure 7 shows the effect of turbulent intensity on the various governing parameters of the Magallanes tidal turbine, viz. (a) mean tidal velocity at the hub (b) rotor power, (c) coefficient of power, and (d) coefficient of thrust. With the increase in the turbulent intensity, the fluctuations in these aforementioned parameters also increase drastically.

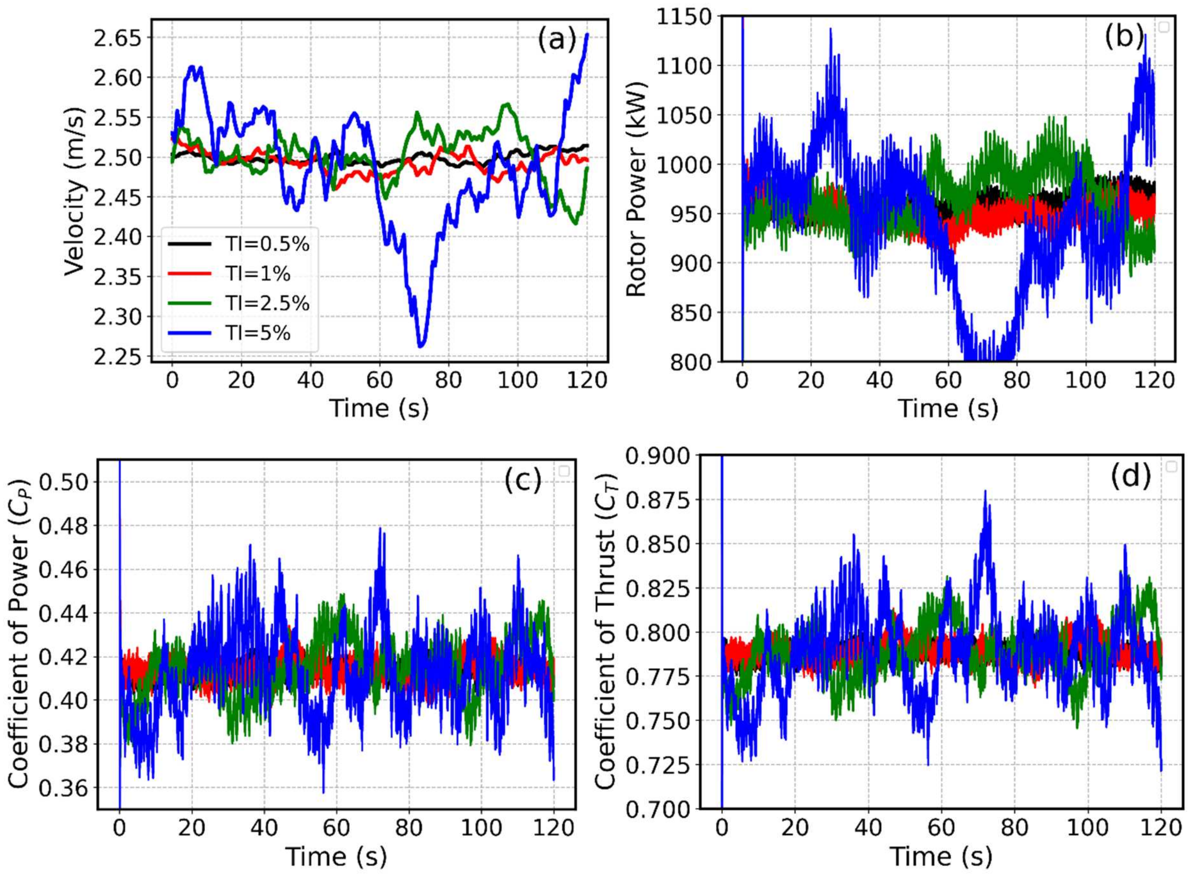

Figure 7: Effect of turbulent intensity corresponding to mean tidal velocity of 2.45 m/s for (a) velocity at the hub of turbine, (b) rotor power, (c) coefficient of power, and (d) coefficient of thrust.

5.0 Fatigue load analysis of Magallanes turbine

Again, using the NREL-FAST module in Qblade, the time series of the thrust force, edge-wise moment, and span-wise moment could be obtained for different turbulent intensities, shown in Figure 8.

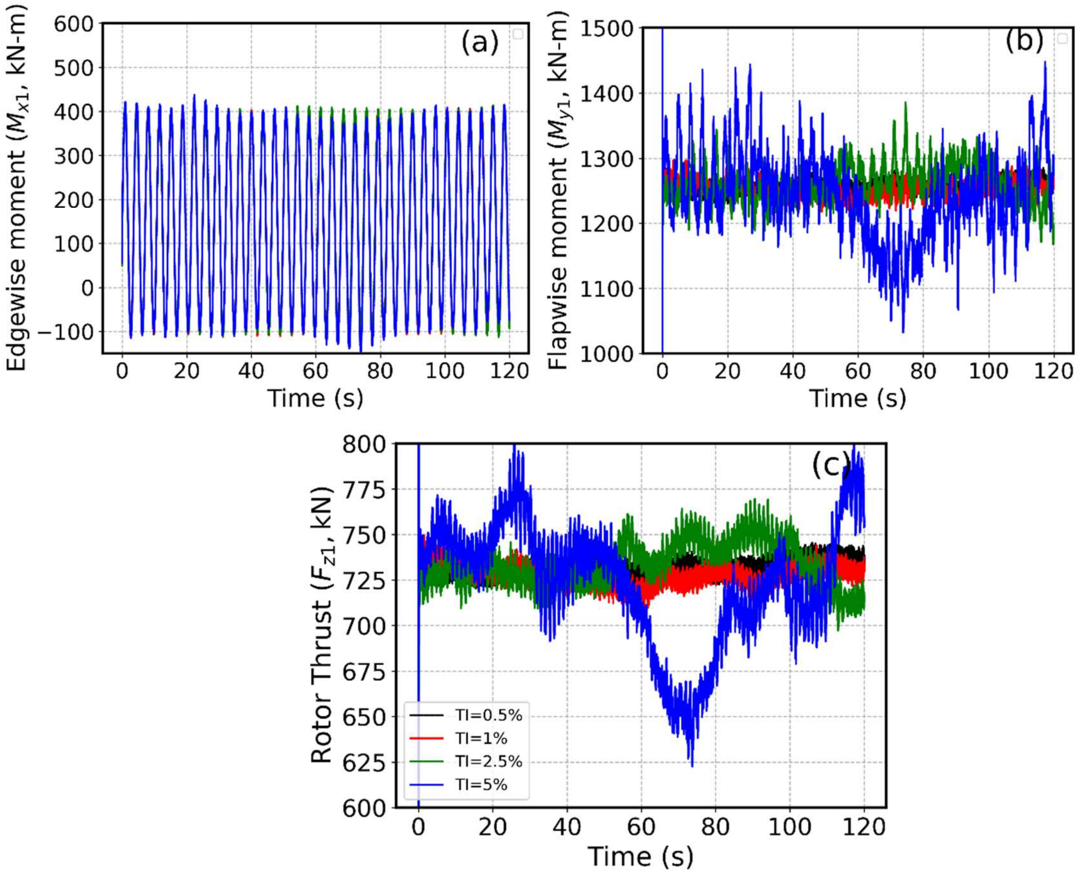

Figure 8: Time series of (a) in-plane (or edgewise) bending moment and (b) out-of-plane (flapwise) bending moment (c) rotor thrust force, for different turbulent intensities

Now, by using the time series data of thrust force, edge-wise moment, and span-wise moment (shown in Figure 8) the quivalent stress (σ_{eq}) at the root of the blade/turbine can be calculated using (Loza, 2019):

$$\sigma_{eq} = \frac{F_{z1}}{A_1} + \frac{\left(M_{x1}^2 + M_{y1}^2\right)^{0.5}}{W_1} \qquad (1)$$

Here, F_{z1} is thrust force, $M_{x1}$is edge-wise moment and M_{y1} is flapwise moment, $A_1$is cross-section area of root and W_1 is the root modulus given by:

$$W_1 = \frac{\frac{\pi}{4}\left(r_0^4 - r_i^4\right)}{r_0} \tag{2}$$

Here, r_0 and r_i are external and internal radii of the blade root respectively. After obtaining the time series of the quivalent stress (σ_{eq}), the characteristic cumulative damage is obtained using the standards of DNV-GL-SE-0163 (DNVGL-SE-0163, October, 2015) and DNV-GL-SE-0164 (DNVGL-ST-0164, October, 2015) given by:

$$\mathrm{D_c} = \sum_{i=0}^{I} \frac{n_{c,i}}{N_{c,i}} \tag{3}$$

Here, $\mathrm{D_c}$ is the characteristic cumulative damage, I is the number of stress range blocks, $n_{c,i}$ is the number of load cycles for a given stress amplitude (calculated using the rainflow method), $N_{c,i}$ is the number of permissible load cycles for a given stress amplitude (based on the Goodman method). The design cumulative damage ($\mathrm{D_D}$) is calculated using:

$$\mathrm{D_D} = DFF \times D_C \tag{4}$$

Here, DFF is the design fatigue factor which depends on the type of material. To be noted here that for the design criteria $\mathrm{D_D} \leq 1$, since $\mathrm{D_D} = 1$ refers to the fault. Finally, the life time of the blade/turbine is given by:

$$\mathrm{T\ (in\ years)} = \frac{T_{sims}(in\ mins\ )}{24 \times 60 \times 365 \times D_D} \tag{5}$$

6.0 Closure

The present work focused on the performance assessment of Magallanes blade using the Qblade simulations. In this work, we used different modules of the Qblade to obtain the different performance characteristics of the Magallanes turbine for varying tidal velocities and for varying turbulent intensities. In order to get the lifetime of the tidal turbine for the extreme loading and fatigue events, the data from the Qblade simulations need to fed up in the MATLAB simulations for getting the complete sense of the lifetime of the Magallanes turbine. The complete flow chart for the proposed work plan is detailed in Figure 9. This flow chart is a standard way to depict the lifetime of the wind turbines and has been adapted from the work of Loza et al. (Loza, 2019).

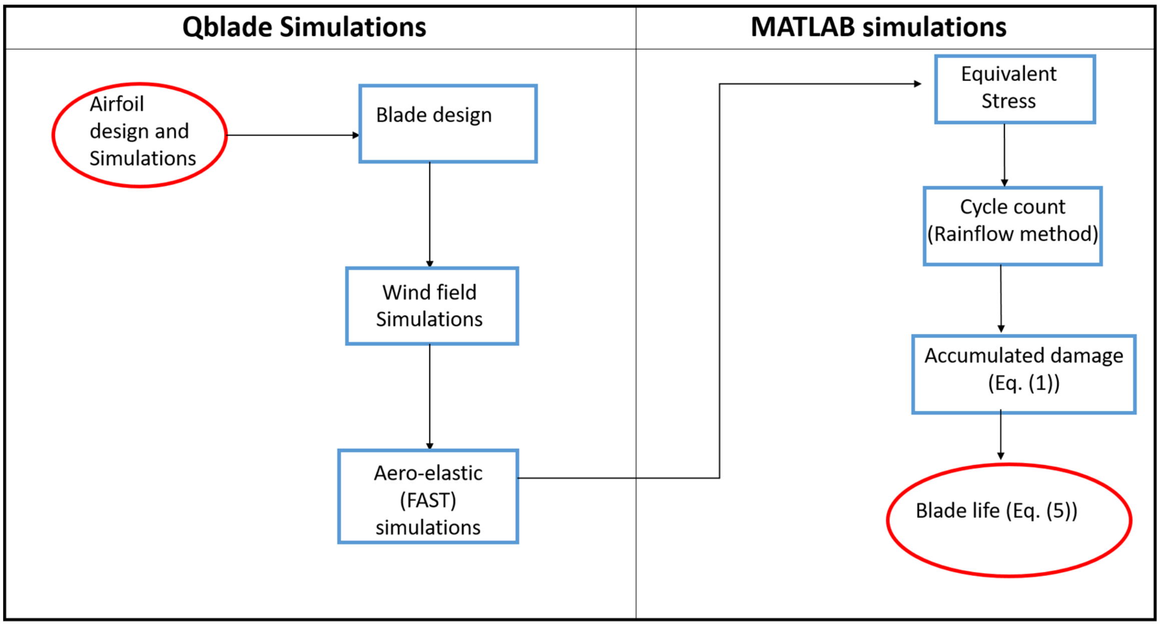

Figure 9: Work flow plan of the proposed work adapted from Loza et al. (Loza, 2019)

7.0 References

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