XROTOR

X-shaped Radical Offshore Wind Turbine for Overall Cost of Energy Reduction

D4.2

Preliminary design

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WP4 Design of Mechanical Structure and Analysis

T4.4 – Preliminary Design
D4.2 – Preliminary Design

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Executive Summary

This document provides an overview of a first, feasible design for the XROTOR wind turbine, with particular focus on the jacket support structure. Based on the existing aerodynamic model, load simulations were performed to assess the structural performance and safety of the jacket. The initial jacket design has been adapted from the OC4/Upwind jacket and choices made for the pre-project feasibility study. Some simplifications have been made, to make the design comparable to existing structures from these projects, and a first attempt at sizing optimization has been performed. The resulting preliminary design is documented in this report. The main conclusion from this work is that with the current large load cycles from the 2 bladed rotor the jacket will need to be somewhat stronger than for a corresponding horizontal axis wind turbine. Also a number of items have been highlighted that will merit more detailed study in the future, especially when more accurate aerodynamic loads become available.

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Contents

1 Introduction

This section introduces the preliminary design of the jacket structure design for the X-Rotor Wind turbine. The jacket is composed of tubular elements and joints and was initially based on the OC4 jacket, Vorphal et al (2013), on the preliminary study made by the X-Rotor consortium. It is composed of 4 legs, 4 bays and a rigid transition piece.

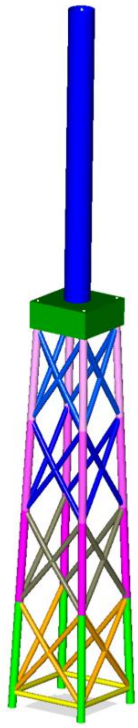

Figure 1 – Initial design inspired by OC4 jacket.

The assumed water depth for this phase is 40m. Cathodic protection is assumed for the member on the splash zone and below. Marine growth was considered on the submerged elements between the seabed and 2m below the MSL. The correspondent thickness and density were assumed to be 60mm and 1325 kg/m3 respectively.

The tower was assumed to have 43m height and a constant diameter and thickness of 3.79m and 35mm.

The yielding stress Young´s modulus and Poisson´s ratio adopted for the steel were 235MPa, 210 GPa and 0.3 respectively. A damping ratio of 1% was assumed for the structure.

1.1 Coordinate system

The coordinate system followed by this report respect the definition given by Ferreira (2021), where the horizontal plane is defined by the X and Z axes and the vertical axis is Y. The jacket is centred at the origin of the coordinate system. For a reference to the loads, the X axis defines the initial azimuthal position, Φ, that increase anti-clockwise, as per the rotational direction of the rotor. The normal force points to the inner side of the rotation, while the tangential force is positive following the anti-clockwise rotation. The pitching-moment is positive from the blade root to the blade tip.

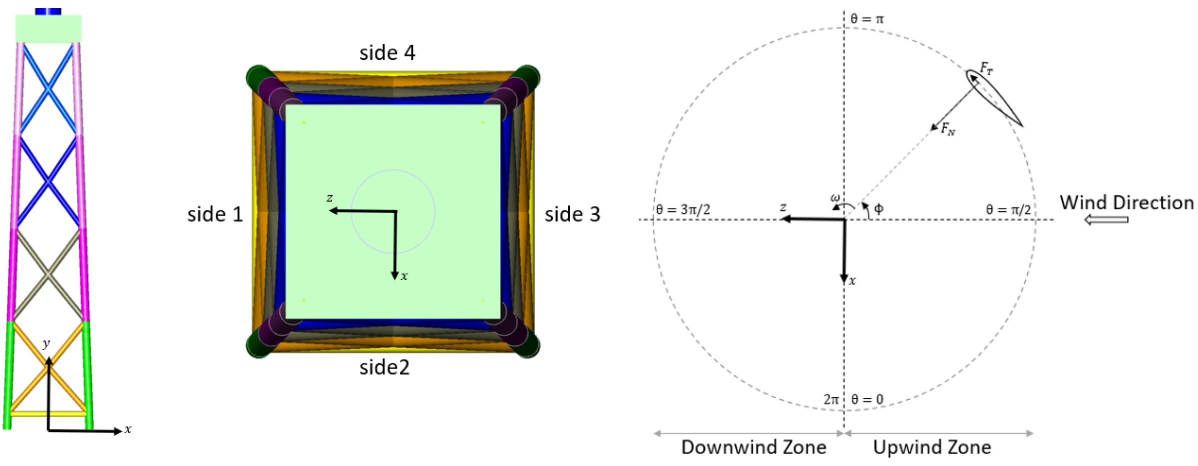

Figure 2 – Adopted coordinate system (a-b) Jacket, (c) Rotor – Adapted from Paraschivoiu (2002)

1.2 Members numbering

The geometry file was created in a script containing a parametrical model whose inputs are the jacket height, number of bays and bottom and base width. The nodes and beams numbering are described in Figure 3 and Figure 4 – Beam numbers available in Appendix A. They follow the sequence that the elements were created, spirally anti-clockwise from bottom to top and starting at side 1. First, the legs components are numbered, then the mud-braces and X-braces, whose braces numbering started from the lower-left-connection of the X-joint, following the spiral logic, and then upper-right, lower-right, and upper-left.

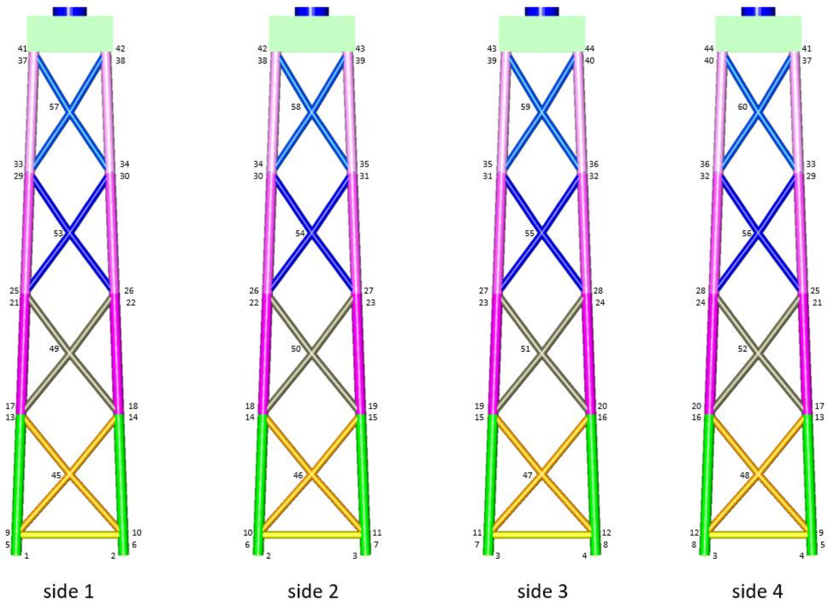

Figure 3 – Node numbers

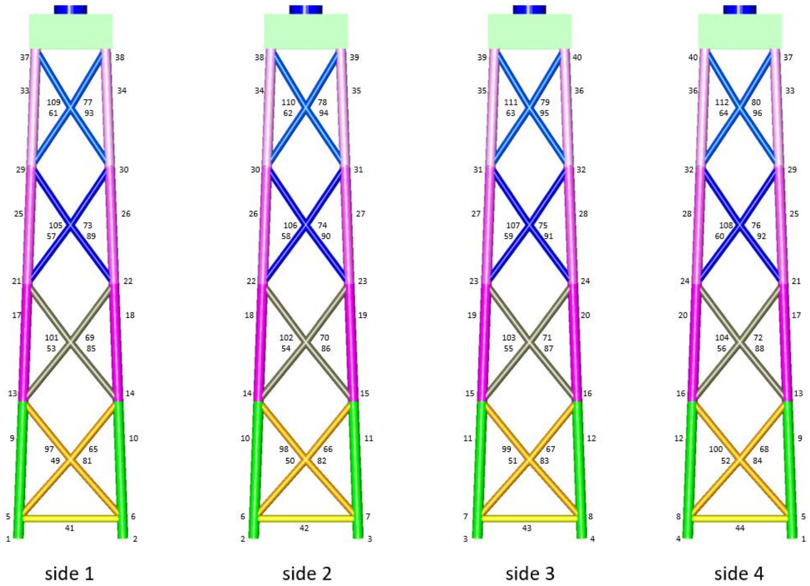

Figure 4 – Beam numbers

As can be seen in Figure 4, a short beam element was introduced between the main leg elements to model the K joints gap.

1 Initial set of loads

Due to the X-Rotor's unconventional shape configuration, it is worthwhile to start this report highlighting its loads. This report refers to the two bladed X-Rotor concept.

For simplicity, the load cases for the operational condition were lumped. They are described in Table 1, together with the angular velocity of the rotor, $\boldsymbol{\omega}$.

Table 1 Lumped operational load cases

Load case	U at 10 m (10min)	Hs	Tp	p	ω
1	< 3.5 m/s	-	-	0.084	0.233 rad/s
2	4 m/s	0.9 m	7.6 s	0.063	0.267 rad/s
3	5 m/s	1.0 m	7.5 s	0.077	0.333 rad/s
4	6 m/s	1.2 m	7.4 s	0.088	0.4 rad/s
5	7 m/s	1.4 m	7.3 s	0.094	0.467 rad/s
6	8 m/s	1.5 m	7.3 s	0.095	0.553 rad/s
7	9 m/s	1.7 m	7.3 s	0.092	0.6 rad/s
8	10 m/s	2.0 m	7.3 s	0.084	0.667 rad/s
9	11 m/s	2.2 m	7.3 s	0.074	0.733 rad/s
10	12 m/s	2.4 m	7.3 s	0.063	0.8 rad/s
11	13 m/s	2.6 m	7.4 s	0.051	0.833 rad/s
12	14 m/s	2.9 m	7.5 s	0.040	0.833 rad/s
13	15 m/s	3.2 m	7.5 s	0.030	0.833 rad/s
14	16 m/s	3.4 m	7.6 s	0.021	0.833 rad/s
15	17 m/s	3.7 m	7.7 s	0.015	0.833 rad/s
16	18 m/s	4.0 m	7.9 s	0.010	0.833 rad/s
17	19 m/s	4.3 m	8.0 s	0.006	0.833 rad/s
18	> 19.5 m/s	-	-	0.006	0.833 rad/s

The initial aerodynamic loads were obtained from Ferreira (2021), using the actuator cylinder theory, and considering the blades as rigid elements. The results provide the average normal and tangential force and pitching moment as a function of the blade span and rotor azimuthal position. At this stage, as the blades are still considered rigid elements, the uncoupled simulation between rotor and support structure is performed. The resultant components of the aerodynamic forces were defined on the blade root and are illustrated in Figure 5.

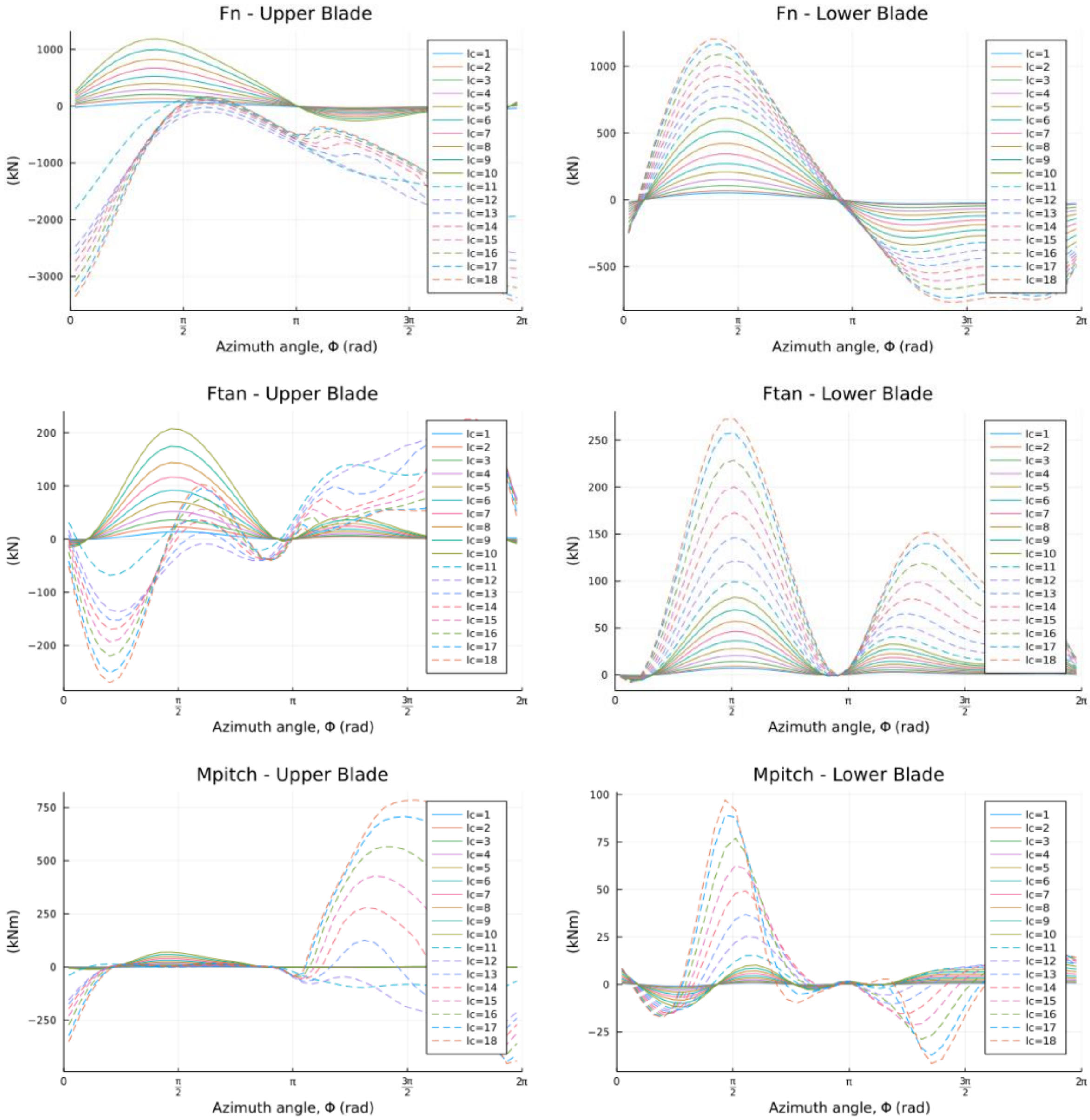

Figure 5 – Aerodynamic resultant loads at blade root

An increase in the loads value is observed on the load cases 11 to 18, which correspond to the wind speed velocities above the rated wind speed of 12,5 m/s. At these range, the upper blade pitch control is used to maintain the rotational speed and power production above 7MW, according to initial studies, Ferreira (2021).

Using the blade span position, cone angles and azimuth angle, the blade loads of the two bladed X-Rotor were transferred to the tower top as per the example given in Figure 6, where the horizontal component of the normal force for the load case 18 is transformed to the X and Z- global coordinates.

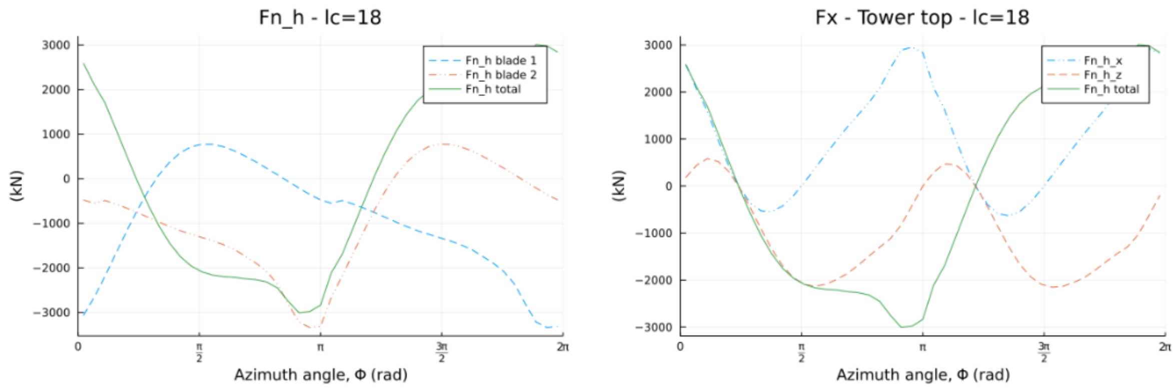

Figure 6 – Example load transformation

Similarly, all the forces and moments resultant on the tower top on the X, Z, and Y global coordinates were defined from the normal and tangential force, as well as the pitching moments provided by Ferreira (2021). In Figure 7, it is illustrated the predominance of the normal force component over the others loads for the horizontal and vertical forces and overturning moments. Only the vertical moment component, My, (torque) has it main partition from the tangential force.

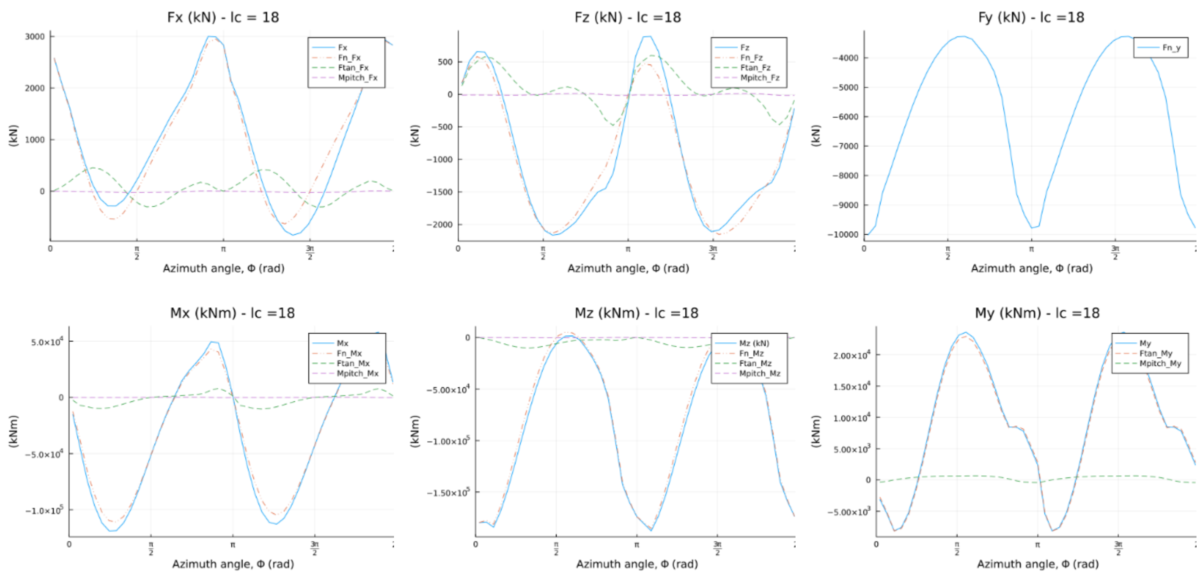

Figure 7 – Components of aerodynamic forces on tower top (global coordinates)

For simplification, at this stage it will be assumed that the thrust generated by the secondary rotors compensates the torque generated by the tangential force. In addition, due to the still uncertain nature of the loads, only the parcel correspondent to the normal force was be considered on the preliminary design, but for illustration, the summary of the extreme design loads is shown in Table 3 – Extreme values of aerodynamic loads correspondent to the wind speed of 41m/s. The contribution from the centripetal and gravitational forces are considered to be balanced between the two blades at this stage.

Table 2 – Extreme values of the lumped operational load cases - aerodynamic loads

Fx (N)	Fz (N)	Fy (N)	Mx (Nm)	Mz (Nm)	My(Nm)
2.95e6	-2,15 e6	-1.0e7	5.0e7	-1.85e8	2.36e7

It is observed from the decomposition of the loads that the two blade X-Rotor generates a high cyclical load on the substructure. The initial X-Rotor concept study indicates that the loads from the three bladed X-rotor are better balanced, significantly reducing the intensity of the load cycles.

In addition, this report checked the structure for one extreme load case, here defined when the rotor is in parked condition with a wind speed of 41m/s. The loads are still applied azimuthally, so that the turbine can be parked in any position. For this check, all the load components on the global coordinates where considered, Figure 8, as the secondary rotors will not be in operation.

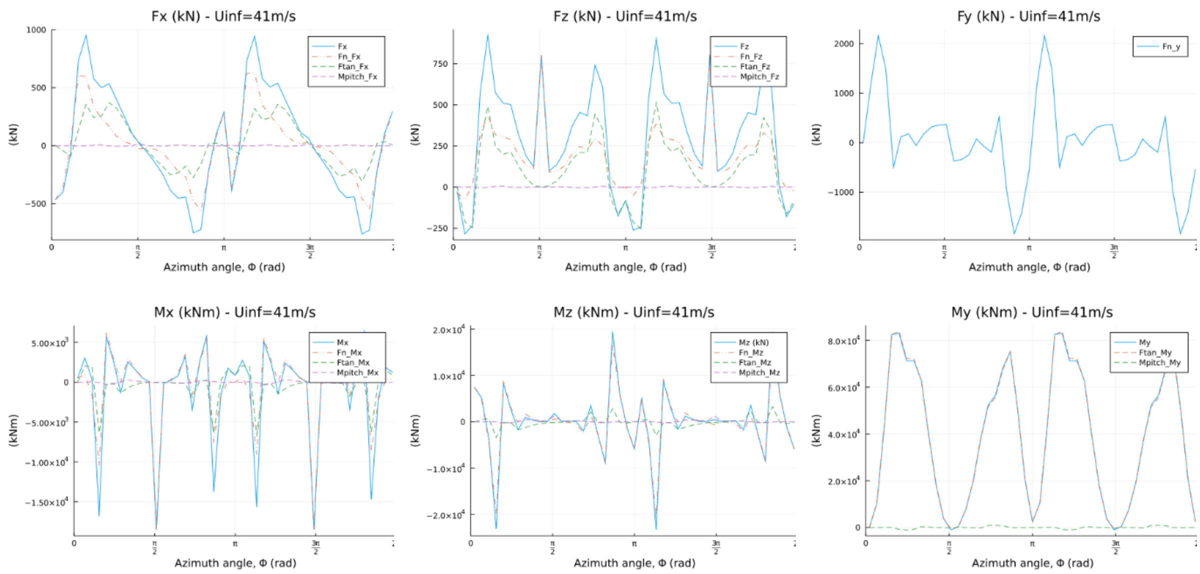

Figure 8 – Components of extreme aerodynamic forces on tower top (global coordinates)

The Table 3 brings the summary of the extreme load values for a wind speed of 41m/s.

Table 3 – Extreme values of aerodynamic loads correspondent to the wind speed of 41m/s

Fx (N)	Fz (N)	Fy (N)	Mx (Nm)	Mz (Nm)	My(Nm)
9.51e5	9.22 e5	2.17e6	-1.85e7	-2.33e7	8.29e7

2 Initial geometry and assumptions

As it was introduced, the OC4 jacket was adopted as a starting point of the external geometric parameters, such as bottom and upper jacket width and elements dimensions. However, due to the higher loads generated by the two-bladed X-Rotor, it was demonstrated that this initial jacket dimensions are not suitable. Thus, following a preliminary study carried out by the X-Rotor consortium, Amiri (2021), the jacket bottom and upper width were assumed to be 2.5 bigger than the OC4 Jacket. The bottom width of 30m and upper width of 20 m were adopted as initial external dimensions of the jacket, Figure 9.

The jacket height is 56,11m and four bays are equally distributed on its height.

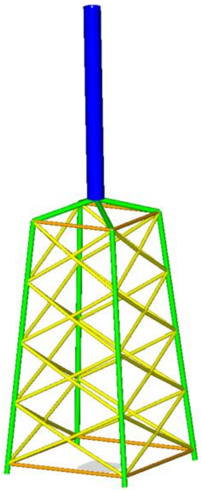

Figure 9 – Initial design a jacket suitable for the two-bladed X-Rotor

- Transition piece

With the increase in the jacket upper width, the assumption of adopting a block of concrete as a completely rigid structure may be discussed. Thus, the transition piece was further simplified by rigid beam elements connecting the tower bottom to the upper joints of the jacket.

- Equipment arrangement

The tower will comport the rotor shaft, two bearings and a rotary transformer that will transmit the power from the secondary rotors to the fixed structure. It was assumed that the rotary transformed will be positioned in between the two bearings that support the shaft, as demonstrated in Figure 10.

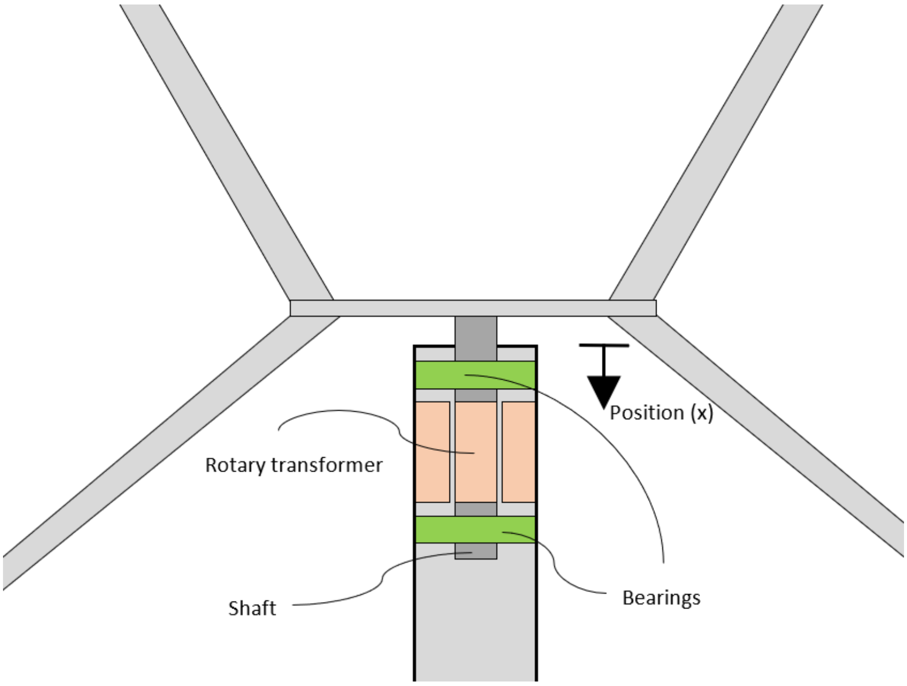

Figure 10 – Draft of components arrangement

The assumed masses and positions of these and other electrical and mechanical components follow in the Table 4

Table 4 – Components - assumptions

Item	Mass (t)	Position from tower top
two-bladed rotor	150 tons	0 m
Shaft	33 tons	0 – 10 m
Bearing 1	5 tons	3 m
Rotary transformer	26 tons	4 – 8 m
Bearing 2	5 tons	9 m
Switch gear	2 tons	10 – 13 m
Power electronic convertor	3 tons	13 – 16 m
Cables	2 tons	0 – 43 m

These components masses were lumped and distributed along the tower top nodes with correspondent height. In addition to the mass of these electrical and mechanical equipment, the total mass of the two-bladed X-Rotor (including secondary rotors) was added to the tower top.

3 Initial analysis dimensions

A jacket similar to the OC4 jacket, Figure 1, project was tested under the operational loads of the two bladed X-Rotor turbine. The elements were checked for yielding and fatigue considering the combination of stresses in and out of plane, together with the axial stress. The braces and legs were also checked for buckling to guarantee that, in extreme loads, yielding would occur on the element before it buckles.

The material safety factor adopted was 1.1. The fatigue safety factor is 1.25 for the considered design fatigue factor of 3.0 (no crack inspection during the lifetime of 20 years). This was adopted to all the components disregarding their position. The stress concentration factor on the joints were calculating from Efthymiou`s equations.

As this initial assumption was not compatible with the higher cyclic loads of the two bladed concept, the increased size jacket, Figure 9, has being tested investigated instead.

The preliminary cross-section parameters of these tubular elements are given in Table 5. These values do not correspond to the final design, where accurate joint details are also defined from the fatigue analysis. The stress on member were checked for both operational and extreme load cases. The node position and beam element correspondent to each type are described on Appendix A.

Table 5 – Cross section parameters

Element type	Diameter	Thickness
Legs	1.2 m	0,06 m
X-braces	0.8 m	0,03 m
horizontal braces	0.8 m	0,03 m

The first calculated natural frequency of the initial design of X-Rotor jacket structure is 0,759 Hz when the bottom legs are considered clamped at the seabed. This value is above of the 2P frequency of the two bladed X-Rotor.

4 Conclusion

The main outcome of this document is the observation that the two-bladed X-Rotor concept requires a non-conventional support structure due to its high cyclical loads. It could be experienced the difficulty in trying to maintain the external geometry similar to the OC4 concept for comparison, while still attending the standard fatigue requirements. Thus, based on an initial study, Amiri (2021), it was chosen to adopt a bigger jacket with widths 2.5 times the OC4 jacket, resulting on the bottom and top widths of 30m and 20m respectively.

The total mass of the jacket defined for the preliminary stage was of 100.8 tons. One should observe that the assumptions made at this stage are still simplistic, likewise adopting the average wind-speed loads, using constant wind speed along the height and even the non-adoption of joint cans, meaning that the thickness of the tubular elements where throughout dependent of the required thickness at the joint connection. The element dimensions presented are quite not feasible in fatigue without joint detailing.

It should also be observed that there is yet not consideration on the structural loads on the pitch control utilized above the wind speed ratio. Thus, the nature of the loads are still uncertain.

In addition, Amiri (2021) indicates that the loads generated by the three-bladed concept are better balances along one rotation and indicates that this concept requires a lighter structure, comparable with the ones for turbines with similar power production and then, it should be further accessed.

5 References

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Appendix A

- **Nodes coordinates**

ID_node	X	Y	Z
1.0	-15.0	-15.0	0.0
2.0	15.0	-15.0	0.0
3.0	15.0	15.0	0.0
4.0	-15.0	15.0	0.0
5.0	-14.8	-14.8	2.25
6.0	14.8	-14.8	2.25
7.0	14.8	14.8	2.25
8.0	-14.8	14.8	2.25
9.0	-14.79	-14.79	2.35
10.0	14.79	-14.79	2.35
11.0	14.79	14.79	2.35
12.0	-14.79	14.79	2.35
13.0	-13.6	-13.6	15.69
14.0	13.6	-13.6	15.69
15.0	13.6	13.6	15.69
16.0	-13.6	13.6	15.69
17.0	-13.59	-13.59	15.79
18.0	13.59	-13.59	15.79
19.0	13.59	13.59	15.79
20.0	-13.59	13.59	15.79
21.0	-12.4	-12.4	29.13
22.0	12.4	-12.4	29.13
23.0	12.4	12.4	29.13
24.0	-12.4	12.4	29.13
25.0	-12.39	-12.39	29.23
26.0	12.39	-12.39	29.23
27.0	12.39	12.39	29.23
28.0	-12.39	12.39	29.23
29.0	-11.2	-11.2	42.57
30.0	11.2	-11.2	42.57
31.0	11.2	11.2	42.57
32.0	-11.2	11.2	42.57
33.0	-11.19	-11.19	42.67
34.0	11.19	-11.19	42.67
35.0	11.19	11.19	42.67
36.0	-11.19	11.19	42.67
37.0	-10.0	-10.0	56.01
38.0	10.0	-10.0	56.01
39.0	10.0	10.0	56.01
40.0	-10.0	10.0	56.01
41.0	-9.99	-9.99	56.11
42.0	9.99	-9.99	56.11
43.0	9.99	9.99	56.11
44.0	-9.99	9.99	56.11
45.0	0.0	-14.2	9.02
46.0	14.2	0.0	9.02
47.0	0.0	14.2	9.02
48.0	-14.2	0.0	9.02
49.0	0.0	-13.0	22.46
50.0	13.0	0.0	22.46
51.0	0.0	13.0	22.46
52.0	-13.0	0.0	22.46
53.0	0.0	-11.8	35.9
54.0	11.8	0.0	35.9
55.0	0.0	11.8	35.9
56.0	-11.8	0.0	35.9
57.0	0.0	-10.6	49.34
58.0	10.6	0.0	49.34
59.0	0.0	10.6	49.34
60.0	-10.6	0.0	49.34

- **Beam connections**

ID_beam	ID_node_start	ID_node_end	Type
1	1	5	leg
2	2	6	leg
3	3	7	leg
4	4	8	leg
5	5	9	leg
6	6	10	leg
7	7	11	leg
8	8	12	leg
9	9	13	leg
10	10	14	leg
11	11	15	leg
12	12	16	leg
13	13	17	leg
14	14	18	leg
15	15	19	leg
16	16	20	leg
17	17	21	leg
18	18	22	leg
19	19	23	leg
20	20	24	leg
21	21	25	leg
22	22	26	leg
23	23	27	leg
24	24	28	leg
25	25	29	leg
26	26	30	leg
27	27	31	leg
28	28	32	leg
29	29	33	leg
30	30	34	leg
31	31	35	leg
32	32	36	leg
33	33	37	leg
34	34	38	leg
35	35	39	leg
36	36	40	leg
37	37	41	leg
38	38	42	leg
39	39	43	leg
40	40	44	leg
41	5	6	horizontal
42	6	7	horizontal
43	7	8	horizontal
44	8	5	horizontal
49	9	45	x brace
50	10	46	x brace
51	11	47	x brace
52	12	48	x brace
53	17	49	x brace
54	18	50	x brace
55	19	51	x brace
56	20	52	x brace
57	25	53	x brace
58	26	54	x brace
59	27	55	x brace
60	28	56	x brace
61	33	57	x brace
62	34	58	x brace
63	35	59	x brace
64	36	60	x brace
65	45	14	x brace
66	46	15	x brace
67	47	16	x brace
68	48	13	x brace
69	49	22	x brace
70	50	23	x brace
71	51	24	x brace
72	52	21	x brace
73	53	30	x brace

74	54	31	x brace
75	55	32	x brace
76	56	29	x brace
77	57	38	x brace
78	58	39	x brace
79	59	40	x brace
80	60	37	x brace
81	10	45	x brace
82	11	46	x brace
83	12	47	x brace
84	9	48	x brace
85	18	49	x brace
86	19	50	x brace
87	20	51	x brace
88	17	52	x brace
89	26	53	x brace
90	27	54	x brace
91	28	55	x brace
92	25	56	x brace
93	34	57	x brace
94	35	58	x brace
95	36	59	x brace
96	33	60	x brace
97	45	13	x brace
98	46	14	x brace
99	47	15	x brace
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101	49	21	x brace
102	50	22	x brace
103	51	23	x brace
104	52	24	x brace
105	53	29	x brace
106	54	30	x brace
107	55	31	x brace
108	56	32	x brace
109	57	37	x brace
110	58	38	x brace
111	59	39	x brace
112	60	40	x brace