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Executive Summary

This report describes the wind turbine scaled model built to perform wind tunnel tests on the offshore floating machine at Politenico di Milano Wind Tunnel. The wind turbine 1/75 scale model is based on the DTU 10MW reference wind turbine.

The report contains a detailed description of the model. All the machine parameters are given, covering the aerodynamic data as well as the structural and functional aspects of the mechanical design. In particular, the different chapters give the following information:

- The aerodynamic data of the blade: airfoil profile description and its aerodynamic coefficients, the blade twist angle, chord lengths and blade thickness as function of the blade station
- Tower and blades structural data
- Mechanics, mechatronic and functional description of nacelle and hub and all the actuators data

Contents

List of symbols

λ_L	Length scale factor
λ_V	Velocity scale factor
λ_f	Frequency scale factor
FOWT	Floating Offshore Wind Turbine
DTU	Technical University of Denmark
PoliMi	Politecnico di Milano
TSR	Tip Speed Ratio
IPC	Blade Individual Pitch Control
t/c	Blade Thickness Over Chord Ratio
Cl	Lift Coefficient
Cd	Drag Coefficient
Cm	Moment Coefficient
R	Rotor Radius
D	Rotor Diameter
r	Blade station
AoA	Angle Of Attack
Re	Reynolds Number
Ω	Rotor angular velocity
V*	Reduced velocity
SD70XX	Selig/Donovan Low Reynolds Airfoil Series
α	Angle of attack (AoA)
c_{FS}	Full scale chord
ρ	Air density
FEM	Finite Element Method
PoliMi 10MW WTM	PoliMi wind turbine model for Wind Tunnel
DTU 10MW RWT	DTU 10MW reference wind turbine

1   Introduction

Politecnico di Milano 10MW Wind Tunnel Model (PoliMi 10MW WTM) has been designed and built to perform wind tunnel tests on floating offshore wind turbines, see [1]. The model has been designed with DTU 10 MW reference wind turbine as target, in terms of aerodynamic and structural behaviour. The testing procedure is based on a Hardware-In-the-Loop approach: the motion due to the hydrodynamic interaction between the substructure and the sea will be provided by means of a mechanical system. This approach implies the capability for the turbine to bear the imposed accelerations in low and wave frequency ranges. To correctly simulate the aerodynamic forces, the model has its own motors and actuators to perform the control of the main shaft and to manage the Individual Pitch Control.

This document fully describes all the features of the wind tunnel model. The airfoil used to build the blade is given and the blades themselves are defined in terms of chord length, thickness and twist angle as function of the blade station. All the structural features of blades and tower are described. A complete explanation of nacelle and hub is reported, in terms of functional and mechanical design, including all the properties of motors and actuators.

The last chapter is devoted to present the differences, observed in terms of masses, between the target and the realized model and how to manage it during the hardware in the loop test sessions.

Figure 1-1 is a picture of the wind turbine model in the atmospheric boundary layer test section of the Polimi Wind Tunnel (GVPM). The facility is described in [1].

The wind tunnel model of the reference wind turbine has been finalized by the time of this deliverable, but the characterization in terms of aerodynamic behaviour and operating conditions qualification is ongoing: it is scheduled to measure the wake and to define the aeroelastic response in operational working condition. The scaling methodology is completely described in [1]

Figure 1-1 PoliMi 10 MW Wind Turbine Model in the Atmospheric Boundary Layer test section of PoliMi tunnel (GVPM)

2 Wind turbine model

The wind turbine model described in this deliverable is based on the DTU 10MW RWT design [2]. The PoliMi 10MW WTM scale factor is 1/75, hence the rotor diameter is 2.38 m. The scale factor has been selected considering the following constraints, see also [1]:

- the wind tunnel boundary layer test section dimensions set a physical limit to the length scale factor λ_L. This must be as large as possible, but it must ensure an acceptable solid blockage level and, on the other hand, a correct reproduction of the natural wind gradient;

- the highest possible scale factor for the velocities λ_V to reduce the Reynolds number difference between full-scale and model-scale and to have high wind speed while testing to optimize the noise to signal ratio of the acquired signals.

- the TSR equal at full scale and at model scale, implying a very high main shaft angular velocity and a very high bandwidth for the IPC controllers

For these reasons, the length scale factor λ_L was set to 75, whereas the velocity scale factors could be set to 2 or to 3, because the rotor is designed to work at PoliMi wind tunnel wind speed range (1-15 m/s).

The scaling procedure is based on the application of classical similarity rules.

The scale factor is defined as the ratio between a general DTU 10 MW turbine parameter and the corresponding PoliMi 10MW WTM parameter.

$$\lambda = \frac{p_{DTU\_10MW\_RWT}}{p_{PoliMi\_10MW\_WTM}} \tag{1.1}$$

The length factor λ_L is therefore defined from the DTU 10MW RWT diameter and the PoliMI 10MW WTM diameter.

$$\lambda_L = \frac{178.3(m)}{2.37(m)} = 75 \tag{1.2}$$

From the length scale the mass scale is defined as:

$$\lambda_M = \lambda_L^3 = 75^3 = 421875 \tag{1.3}$$

The second moment of inertia J scale is defined as:

$$\lambda_J = \lambda_L^5 = 75^5 = 2.373E9 \tag{1.4}$$

Table 1 reports the scaling factors for some quantities of interest.

Table 1 Scaling factors for some quantities of interest

		$\lambda_v = 2$ $\lambda_L = 75$	$\lambda_v = 3$ $\lambda_L = 75$
Length	**(m)**	75	75
Speed	**(m/s)**	2	3
Ω	**(rad/s)**	0.03	0.04
frequency	**(1/s)**	0.03	0.04
Acceleration	**(m/s^2)**	0.05	0.12
Mass	**(kg)**	4.22E5	4.22E5
Inertia	**(Kgm^2)**	2.37E9	2.37E9
F	**(N)**	22500	50625
Re	**(-)**	150	225

2.1 Model main Parameters

From the scale factor all the fundamentals model dimensions were defined by scaling the DTU 10MW RWT. Same dimensions are the perfect geometric scale of the DTU design, some were modified for technological reason mainly related to the excessive level of miniaturization requested by a perfect geometric downscale.

Table 2 Key parameters of the DTU 10MW RWT and direct downscale of the DTU 10MW RWT compared to the PoliMi 10MW WTM

		DTU 10MW RWT	DTU down-scaled	PoliMi 10MW WTM
Application		offshore	Same	Same
Rotor Orientation		Clockwise rotation - Upwind	Same	Same
Control		Variable speed- Collective Pitch	Same	Variable Speed – Collective Pitch- Individual Pitch
Number of blades		3	3	Same
Rotor Diameter	**(m)**	178.3	2.37	2.37
Hub Diameter	**(m)**	5.6	0.074	0.178
Hub Height	**(m)**	119	1.6	1.6
Drivetrain		Medium Speed, Multiple Stage Gearbox	Same	Transmission belt - epicycloidal gearbox
Gearbox ratio		50	Same	42
Hub Overhang	**(m)**	7.1	0.094	0.12
Shaft Tilt Angle	**(deg)**	5	5	5
Rotor Precone Angle	**(deg)**	-2.5	-2.5	0
Blade Prebend	**(m)**	3.33	0.044	0
Rotor Mass	**(kg)**	227962	0.540	1.255
Single Blade Mass	**(kg)**	41716	0.099	0.210
Nacelle Mass	**(kg)**	446036	1.057	1.788
Tower Mass	**(kg)**	628442	1.490	0.550
Total Mass	**(kg)**	1302440	3.087	6.25

3 Aerodynamic Characteristics

This chapter includes the information related to the aerodynamics of the PoliMi 10MW WTM rotor.

The aerodynamic design procedure has to:

1. match the reference thrust coefficient
2. match the reference torque coefficient
3. match the first blade flap-wise frequency, correctly scaled
4. match the correct blade weight

Figure 3-1 gives an overview of the whole design I/O procedure. Starting from the full scale blade data and imposing the scaling parameter, there is the need to decide which air-foil to be used to obtain the same efficiency curve at very low Reynolds numbers. Moreover, a new structural design has to be carried out because of the smaller dimensions of the model scale blade.
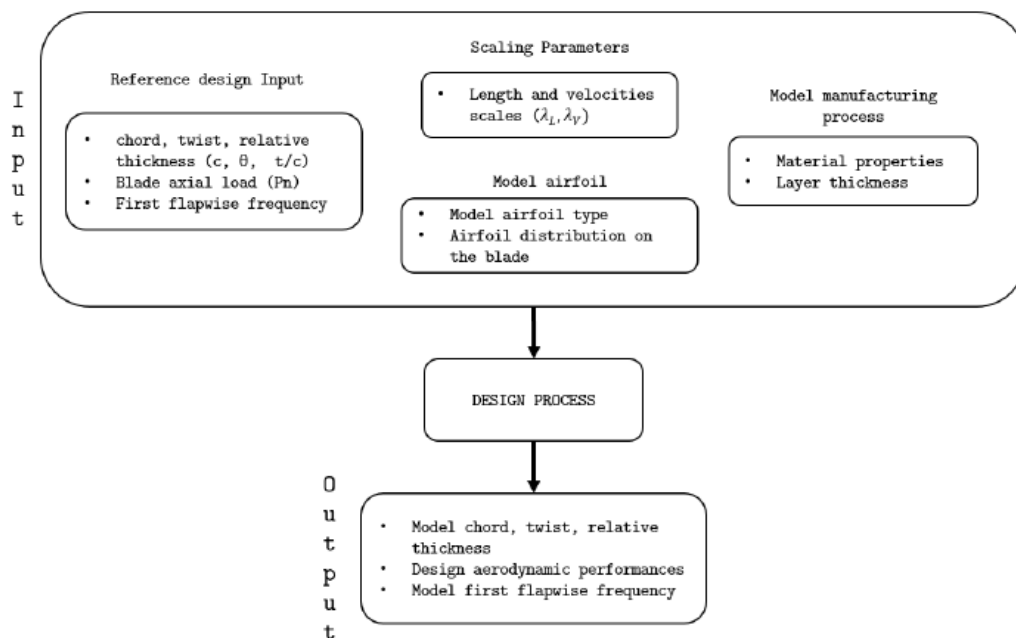

Figure 3-1 Aeroelastic blade design procedure Inputs and Outputs

As stated before, the idea is to use completely different airfoils and to correct the twist and the profile chord at each blade station in order to obtain thrust and torque coefficients as close as possible to the full scale one. The former is important to obtain a correct interaction with the dynamics of the floater, as well as to have a reliable wake downwind the wind turbine model, the latter to have good estimate of loads and power, due to effect of future control laws, upscaling from wind tunnel implementation.

3.1 Airfoil Geometry

A complete description of the aerodynamic design is in [1], however, a brief explanation is also herein reported. The selected airfoil differs from the ones applied for the DTU 10MW RWT in order to have the correct performances at the lower Reynolds numbers that characterize the airfoil aerodynamics for

the wind tunnel tests. Figure 3-2 reports a comparison among the Reynolds number at full scale and at model scale.
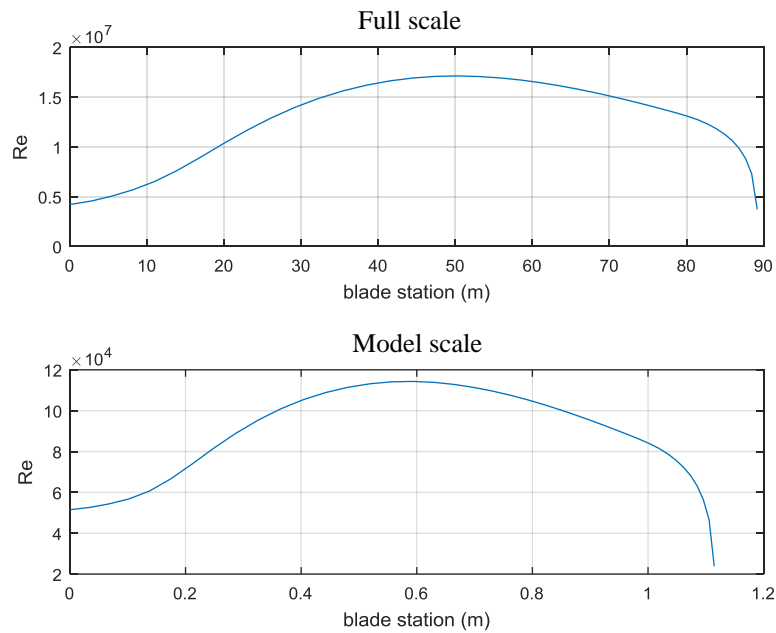
Figure 3-2 Reynolds number comparison fullScale (Real) vs model scale

The entire blade is designed using the SD7032 airfoil, only in the area near the blade root the blade section shape is interpolated with the circular section thus allowing a smooth transition to the circular section blade root, also due to structural strength and mechanical issue related to the assembly of the individual pitch control system.

3.2 Airfoil Aerodynamics performances

The aerodynamic coefficients for the SD7032 for Reynolds numbers equal to 100 000 and 300 000 are available in [3]. However, in order to obtain more refined Reynolds dependency data a new series of wind tunnel tests were performed on a 2D section model of the airfoil. Tests were carried out at the red wind tunnel facility located at the Lyngby DTU campus, as reported in [1].

The airfoil lift and drag coefficients were measured from surface taps and wake rake for Re = [50E3; 60E3; 75E3; 100E3; 125E3; 150E3; 200E3; 250E3].

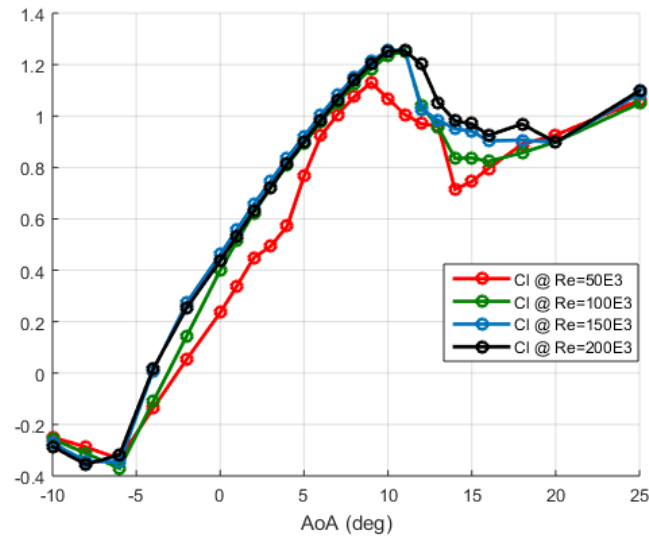Figure 3-3 to Figure 3-5 report the wind tunnel results for Reynolds number from 50E3 to 200E3.

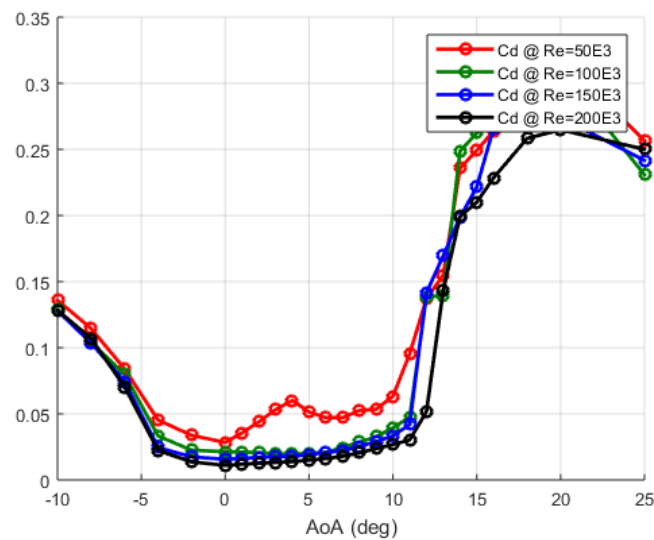**Figure 3-3 Lift coefficient for Re=50-200E3**
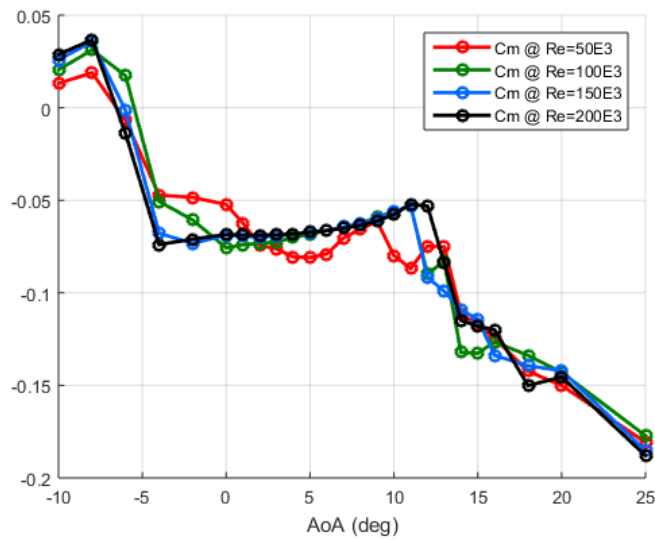

Figure 3-4 Drag coefficient for Re=50-200E3

Figure 3-5 Moment coefficient for Re=50-200E3

3.3   Rotor blade shape

The twist of the model blade also differs from full-scale, because the SD7032 model airfoil and the DTU ones have different zero lift values. The chord has been tuned to match the scaled rotor thrust.

Figure 3-6 reports the final model chord and twist compared to the geometric scaled design as a function of the blade station.
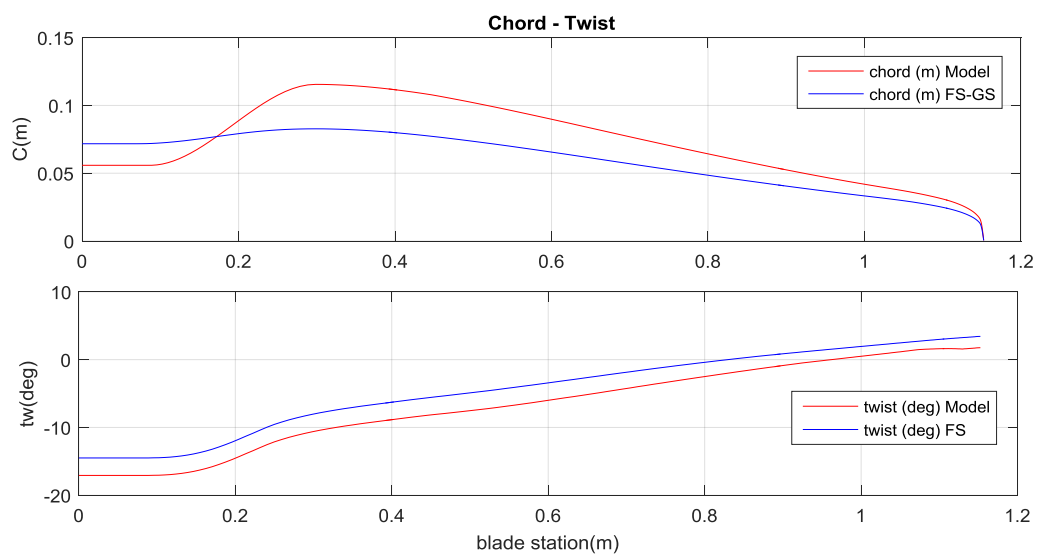

Figure 3-6 Chord and twist of the actual model (red line) and the geometric scaled one (blue line)

The rotor blade is defined by:

1. The chord, c, distribution
2. The twist angle, tw, distribution
3. The relative thickness, t/c, distribution
4. The distance, normalized to the chord length, between the pitch axis and the section leading edge, pitchX/c
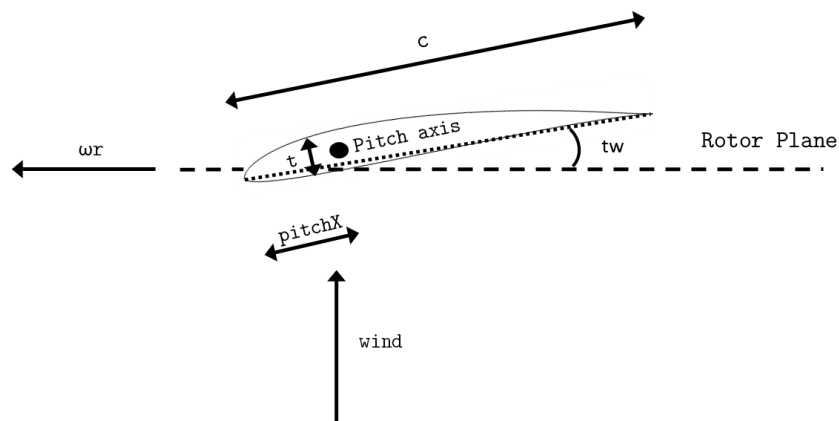

Figure 3-7 Blade Section dimensions definition

Table 3 reports the blade parameters at 40 different blade sections, where r is the distance of the section from the blade root.

Table 3 Distributed Blade Aerodynamic Properties

r (m)	c (m)	tw (deg)	t/c (-)	pitchX/c (-)
0.000	0.056	17.07	1.00	0.50
0.020	0.056	17.08	1.00	0.50
0.057	0.056	17.08	1.00	0.50
0.094	0.058	17.01	0.84	0.49
0.133	0.068	16.45	0.36	0.44
0.172	0.084	15.10	0.19	0.37
0.213	0.100	13.16	0.14	0.32
0.254	0.112	11.45	0.11	0.29
0.295	0.115	10.37	0.10	0.29
0.337	0.114	9.60	0.10	0.29
0.378	0.112	8.95	0.10	0.29
0.420	0.109	8.35	0.10	0.29
0.461	0.105	7.83	0.10	0.29
0.502	0.100	7.30	0.10	0.29
0.542	0.095	6.71	0.10	0.29
0.581	0.090	6.06	0.10	0.29
0.620	0.085	5.41	0.10	0.29
0.657	0.080	4.75	0.10	0.29
0.693	0.076	4.10	0.10	0.29
0.728	0.071	3.48	0.10	0.29
0.762	0.067	2.89	0.10	0.29
0.794	0.063	2.34	0.10	0.29
0.824	0.059	1.83	0.10	0.29
0.854	0.056	1.35	0.10	0.29
0.881	0.053	0.92	0.10	0.29
0.908	0.050	0.52	0.10	0.29
0.932	0.047	0.19	0.10	0.29
0.955	0.045	-0.11	0.10	0.29
0.977	0.043	-0.40	0.10	0.29
0.998	0.041	-0.67	0.10	0.29
1.017	0.039	-0.92	0.10	0.29
1.035	0.037	-1.15	0.10	0.29
1.051	0.035	-1.39	0.10	0.29
1.067	0.033	-1.54	0.10	0.29
1.081	0.032	-1.60	0.10	0.29
1.094	0.029	-1.62	0.10	0.29
1.106	0.027	-1.61	0.10	0.29
1.118	0.024	-1.61	0.10	0.29
1.128	0.019	-1.69	0.10	0.29
1.138	0.001	-1.76	0.10	0.29

3.4   Rotor Operational parameters

The operational parameters to the PoliMi 10MW WTM are the same of the DTU 10MW RWT without prebend, cone and structural deflections, [2] . The model and the reference wind turbine share the same TSR operational range, for each TSR an operational pitch angle is defined, see Table 4.

Table 4 Operational parameters

TSR	RPM (λ_V=2)	RPM (λ_V=3)	Pitch (deg.)
14.01	225	150	2.751
11.20	225	150	1.966
9.34	225	150	0.896
8.00	225	150	0.000
7.50	241	161	0.000
7.47	271	181	4.502
6.90	301	201	7.266
6.40	331	221	9.292
5.98	360	240	10.958
5.60	360	240	12.499
5.27	360	240	13.896
4.98	360	240	15.200
4.72	360	240	16.432
4.48	360	240	17.618
4.27	360	240	18.758
4.07	360	240	19.860
3.90	360	240	20.927
3.73	360	240	21.963
3.59	360	240	22.975

3.5   Wind tunnel results

The rotor aerodynamic performances have been evaluated using PoliMi wind tunnel (GVPM), tests were conducted considering two different rated wind speeds for the PoliMi 10MW WTM.

Defining the velocity scale λ_V as the ratio between the PoliMi 10MW WTM and the DTU 10MW RWT rated wind speed, tests results are reported for λ_V equal to 2 and 3. Table 5 reports the operational conditions tested during the wind tunnel tests done for model validation for the two selected velocity scale factors.

Table 5 Operational conditions for different velocity scale factors.

|		DTU 10MW RWT	PoliMi 10MW WTM λ_V=2	PoliMi 10MW WTM λ_V=3
Cut in wind speed	**(m/s)**	4	2	1.3
Rated wind speed	**(m/s)**	11.4	5.7	3.8
Minimum Rotor speed	**(RPM)**	6	240	150
Minimum Rotor speed	**(RPM)**	9.6	360	240

3.5.1 Wind tunnel results for $\lambda_V = 2$

The wind turbine model performances, in terms of thrust and torque as function of the incoming wind speed, has been evaluated for two different velocity scale factors. Table 6 reports a summary of the main findings for λ_V=2, including the test conditions in terms of wind speed, rotor angular velocity and pitch. Here only results for below rated operational condition are shown.

Table 6 Results for λ_V=2

Wind speed (m/s)	Rotational Speed (rpm)	Tip Speed Ratio	Pitch (deg)	Thrust (N)	Torque (Nm)
3.48	225	8.01	0	26.876	1.891
4.05	240	7.35	0	35.276	3.209
4.56	271	7.38	0	44.908	4.152
5.09	300	7.32	0	55.744	5.282
5.53	330	7.40	0	68.631	6.232

Figure 3-8 and Figure 3-9 show the wind tunnel results against the reference values, scaled, in terms of thrust and torque, respectively, as function of the incoming wind speed.
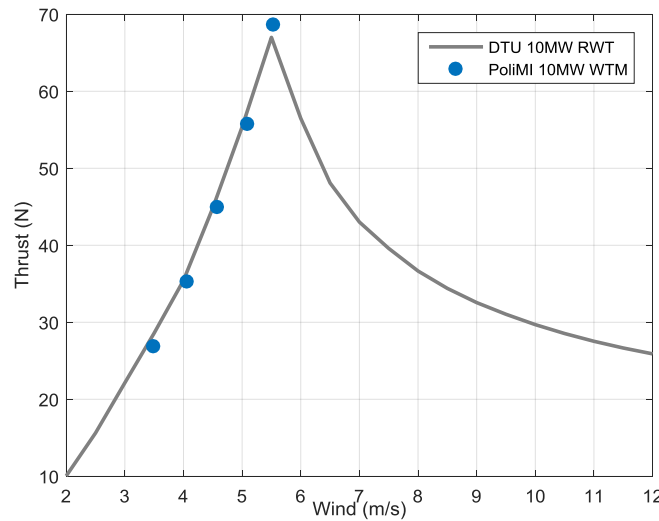
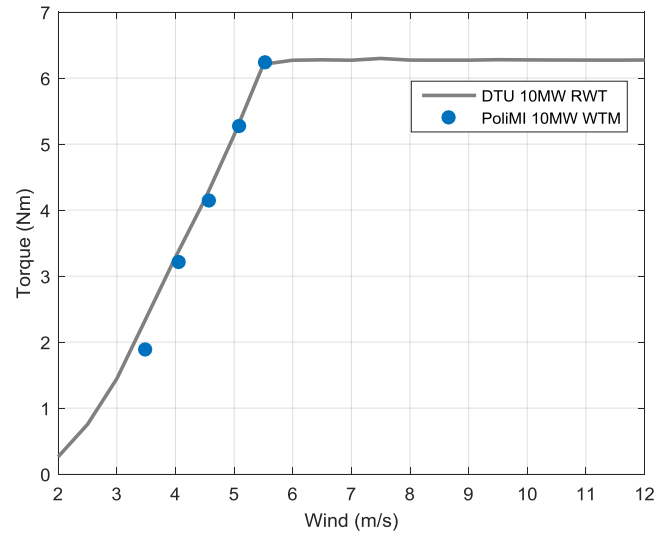**Figure 3-8 Thrust as function of the wind velocity λ_V=2**

Figure 3-9 Torque as function of the wind velocity λV=2

3.5.2 Wind tunnel results for $\lambda_V = 3$

Table 5 reports a summary of the main findings for λV=3, including the test conditions in terms of wind speed, rotor angular velocity and pitch.

Table 7 Results for λV=3

Wind speed (m/s)	Rotational Speed (rpm)	Tip Speed Ratio	Pitch (deg)	Thrust (N)	Torque (Nm)
2.33	150	8.00	0	10.778	0.500
2.70	161	7.39	0	13.792	0.863
2.98	181	7.54	0	17.629	1.161
3.83	240	7.77	0	33.550	2.676

Figure 3-10 and Figure 3-11 show the wind tunnel results against the reference values, scaled, in terms of thrust and torque, respectively, as function of the incoming wind speed. More specifically in Figure 3-12, the effect of pitch adjustment, for the perfect tuning of the aerodynamic performance, is visible on the machine reference curve.
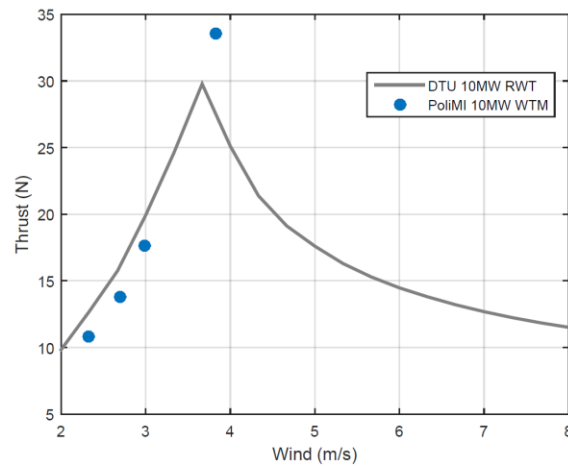
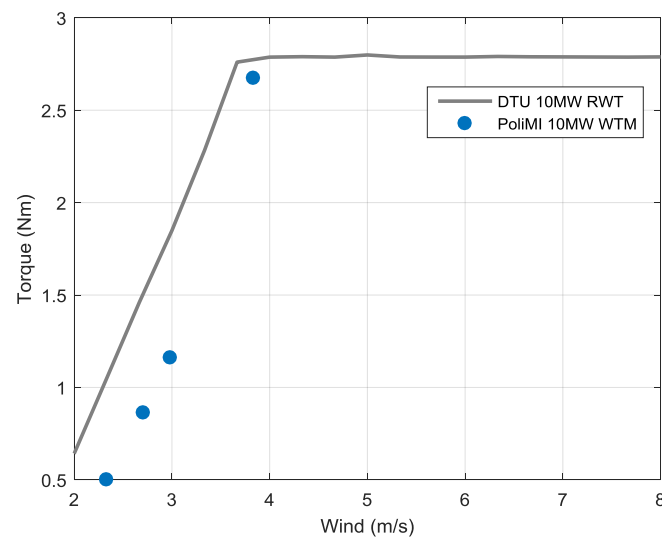**Figure 3-10 Thrust as function of the wind velocity λ$_V$=3**

Figure 3-11 Torque as function of the wind velocity λ$_V$=3

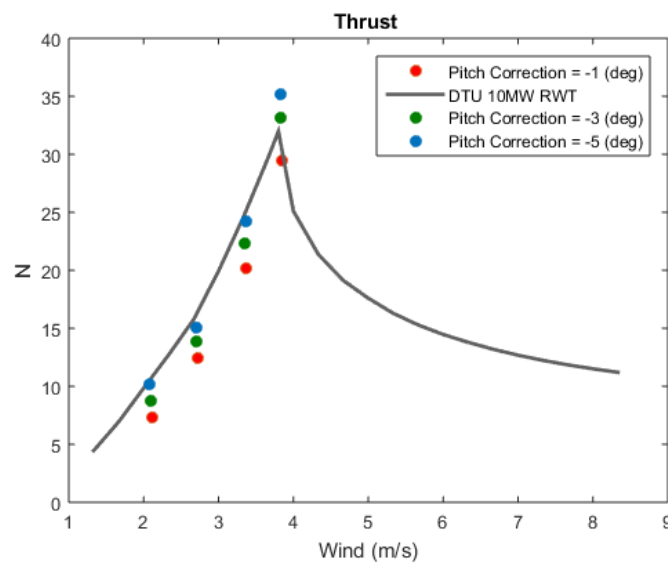**Figure 3-12 Thrust as function of the wind velocity λ$_V$=3, with collective pitch correction**

4   Structural Characteristics

The PoliMi 10MW WTM was designed as an aeroelastic model of the DTU 10MW RWT, therefore beside the aerodynamics of the rotor, also the correct structural design of the turbine was taken into consideration.

Three parts for the PoliMi 10MW WTM were designed considering the structural dynamics: the rotor, the nacelle-hub and the tower. They have been designed to satisfy functional criteria and having as a target the structural integrity of these parts, when subjected to the aerodynamic and inertial loads.

4.1   Rotor

The PoliMi 10MW WTM is a three bladed turbine with a clockwise upwind rotation direction, the blade shape comes from the aerodynamic design of the rotor.

The structural design was possible thanks to a beam FEM model for the estimation of the blade structural frequency, integrated with the aerodynamic optimizer. The blade FEM model is discretized in a total of 193 beam elements. The elements principal axes of inertia are aligned with the blade flapwise and edge-wise directions.
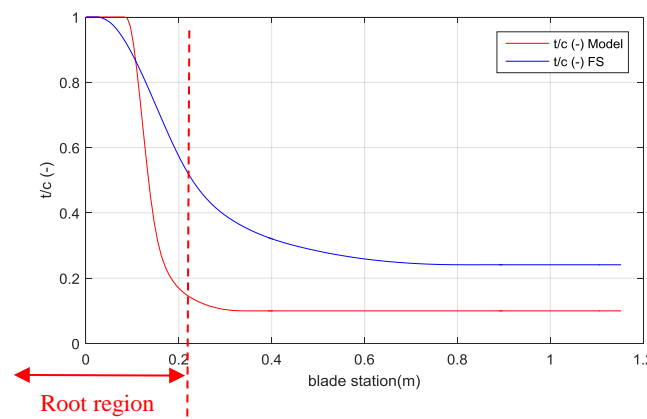

Figure 4-1 Blade thickness on chord ratio distribution; model versus full scale

A B-Spline based spanwise envelope of the blade profiles was adopted to define the 3D geometry for the manufacturing process.

From the so obtained blade design a file for machining a CNC mould has been delivered and processed, therefore the blades have been made using pre-preg carbon fibres and autoclave manufacturing approach. Figure 4-2 shows the blade aluminium mould, CNC machined from solid, and the final carbon fibre blade. This technology lets match the low weight target of the downscaled DTU turbine, approximately 100 grams for each blade (see Table 2).
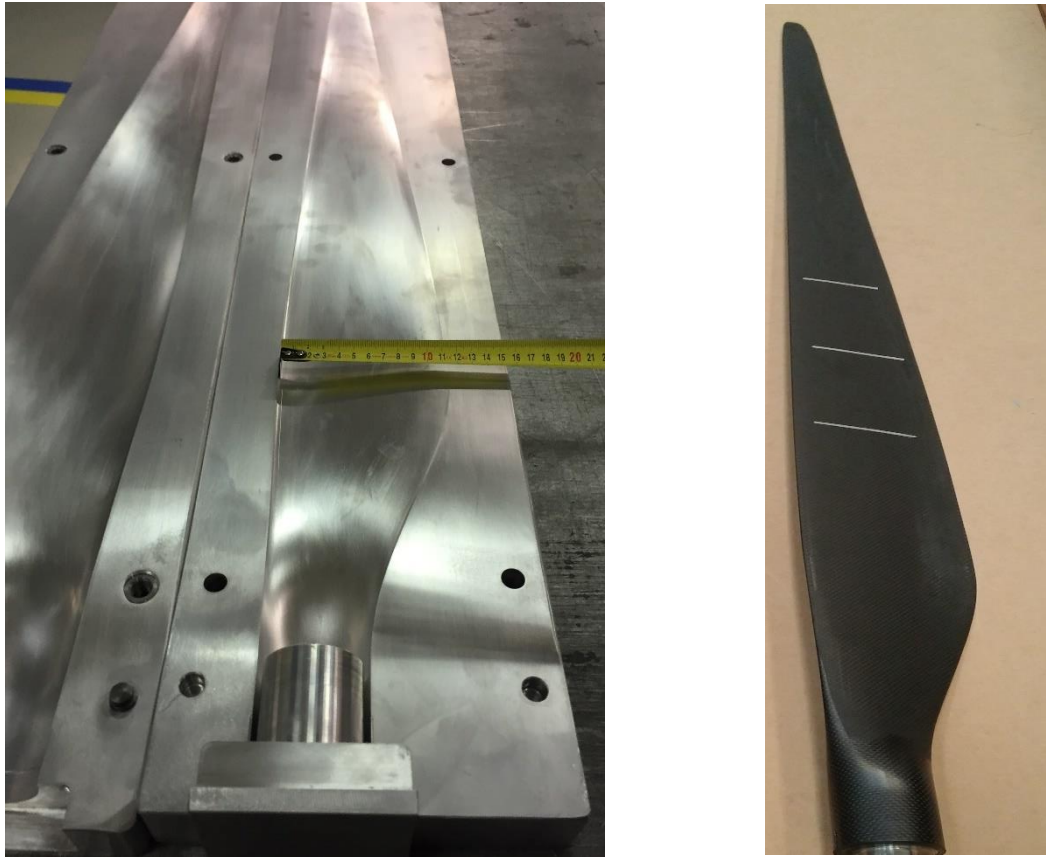
Figure 4-2 Blade manufacturing: aluminium mould (left) and carbon fibre layup

Table 8 reports the main data of the blade lay-up.

Table 8 Blade material definition

Material	High modulus unidirectional pre-preg layer
Number of layer	1
Orientation	Fiber aligned with the blade spanwise direction
Thickness	0.3 mm
Total Mass	0.200 kg

The blade structural verification and the dynamic analysis have been done by FEM computations (using the commercial software Abaqus) highlighted how a single layer of high modulus carbon fibre appeared to be the best solution in order to match the mass target preserving the high stiffness requirement. The blade estimated mass is slightly higher than the target and the first flap-wise frequency is around 15 Hz, with a target of 22.875 Hz and 15.25 Hz respectively for $\lambda_V=2$ and $\lambda_V=3$.

Figure 4-3 shows the deflected shape of the first flap-wise natural mode.
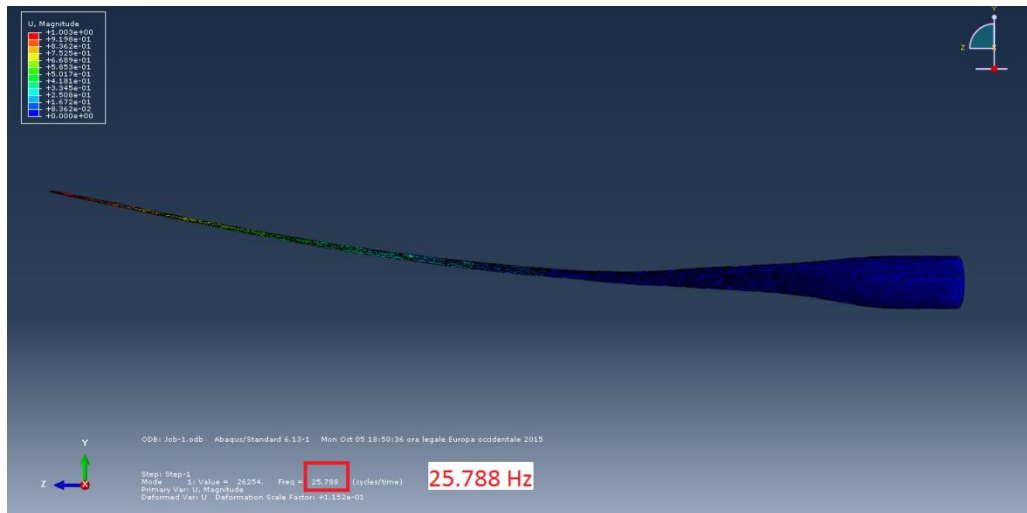
Figure 4-3 Fem analysis (Abaqus) of the blade, 1st flapwise mode frequency 25.78 Hz

4.2 Tower

The PoliMi 10MW WTM tower is made up by carbon fibre, whose structural design has been done by means of a beam FEM model for calculating the structural dynamic response.

To simplify the tower manufacturing the geometry has been reduced to a simple cylinder with circular cross section neglecting the tapered shape. The tower realization has been done on a male mould using an autoclave vacuum process.

Table 9 reports the material definition of the tower.

Table 9 Tower material definition

Material	Unidirectional and balanced pre-preg carbon fibre
Number of layer	4
Orientation	2 unidirectional vertical 2 balanced at 45 degree
Thickness	1.25 mm
External Diameter	62.5
Total Mass	0.550 kg

The so realized tower is very light, it is lighter than the target and it is also very stiff, being its first natural frequency equal to circa 11 Hz, with a target value of 9.37 Hz and 6.25 Hz respectively for $\lambda_V=2$ and $\lambda_V=3$.

5 Mechanical design and actuators

PoliMi 10MW WTM has very strict constraints regarding the mass, especially those of the nacelle and the rotor. The presence of three motors dedicated to the IPC control on the rotor as well as the need for the main shaft motor and the slip ring on the nacelle represent huge constraints on the overall mass.

In the overall mechatronic design three different functional groups have been identified, hereafter are described in terms of functions and most significant parts:

Nacelle: the nacelle represents the connection between the tower and the rotor; the characteristic elements of this group are the main shaft motor, which is misaligned with respect to the main shaft. The transmission is realized by means of a toothed belt. It is important to mention the presence of the slip ring which, guarantees the connection to the IPC motors, in terms of power supply and digital/analogy signals input/output.

Rotor: two subgroups can be identified, the hub and the blades. The pitch control mechanisms that have been designed are the core of this part.

Tower top: the functional element of the tower is a 6-axes balance which is placed between the nacelle and a connection flange on the top of the tower to measure the overall rotor forces.

5.1 Nacelle

The nacelle has been designed from scratch by PoliMi. The PoliMi 10MW WTM nacelle, Figure 5-1 and Figure 5-2, is made by a monolithic carbon fibre structure that supports the low and high-speed shaft with two THK cross roller bearing. The slip-ring *Princetel SR202G* is attached on the downwind side, this component allows the power and signal transmission from the ground to the rotating frame of the rotor. The nacelle also includes the main shaft motor that allows the control of the rotor speed (see sect. 5.3.1).
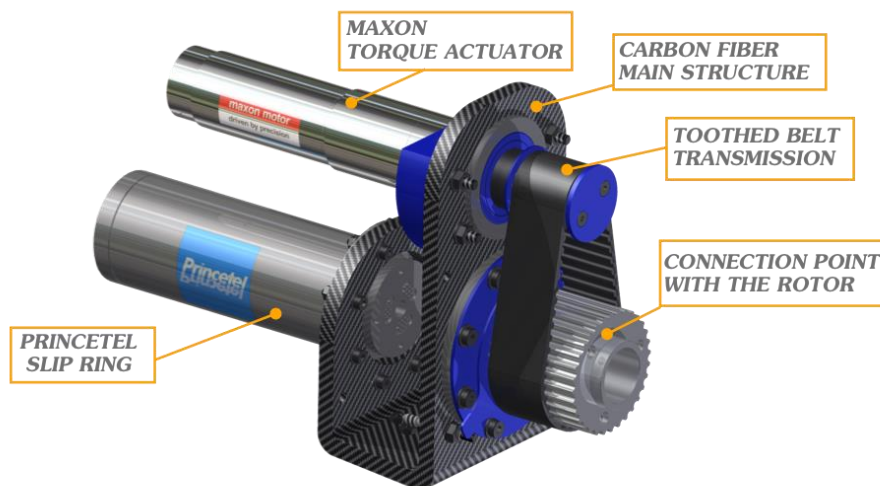

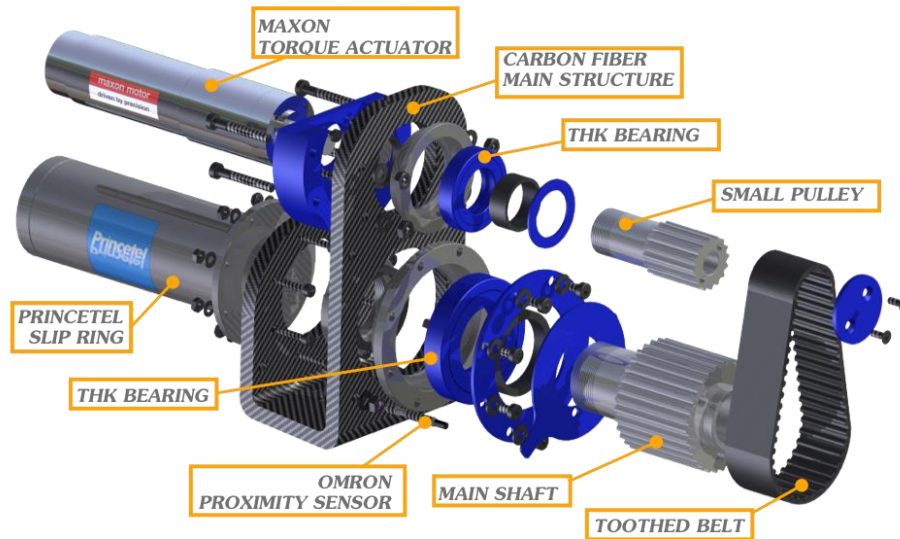**Figure 5-1 Nacelle of PoliMi 10MW WTM**
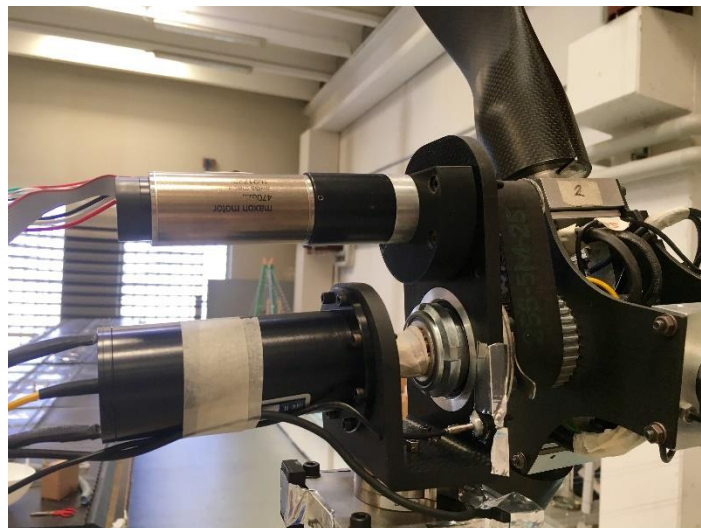
Figure 5-2 Exploded view of the nacelle

Figure 5-3 Side view of the nacelle

Figure 5-3 shows a side view of the nacelle assembled. Table 10 reports the mass of all the nacelle component excluding the motor, the two-shaft weight includes the bearing, the screw and flanges weight.

Table 10 Nacelle components masses

|	
Low speed shaft (rotor)	381 g
High Speed Shaft (motor)	112 g
Support structure	100 g
Transmission belt	24 g
Slip Ring	270 g
Cables	100 g
Total	0.987 kg

5.2 Rotor

The hub is composed by two 3mm thick carbon fibre plates, three screw connect the hub to the nacelle low speed shaft. The screws have also a structural role in increasing the stiffness of the central part of the rotor.

An aluminium blade top is glued to the blade root permitting the mounting of a THK cross roller bearing which is supported by a CNC machined aluminium bearing housing. The bearing constraints the blade in all direction except along the blade pitch rotation axis, which is connected through an Oldham joint to a Harmonic Drive actuator (see sect.5.3.2).
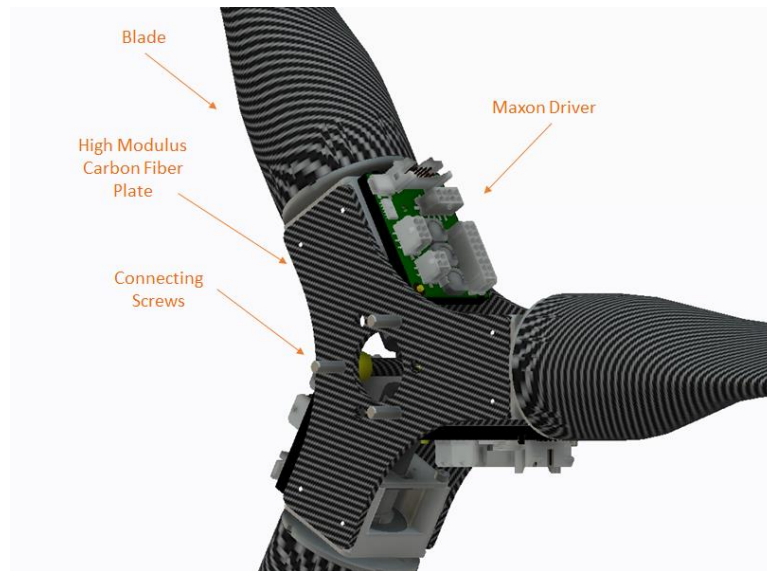
Figure 5-4 Hub of the PoliMi 10MW WTM
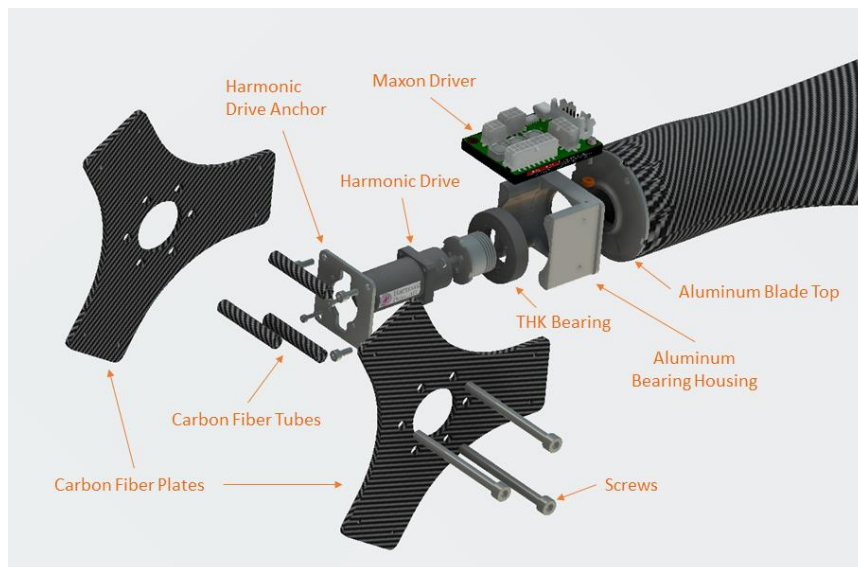
Figure 5-5 Exploded view of the hub

Figure 5-6 and Figure 5-7 are pictures of the hub once assembled, showing respectively a side and a front view of the rotor with the IPC control system and actuators.
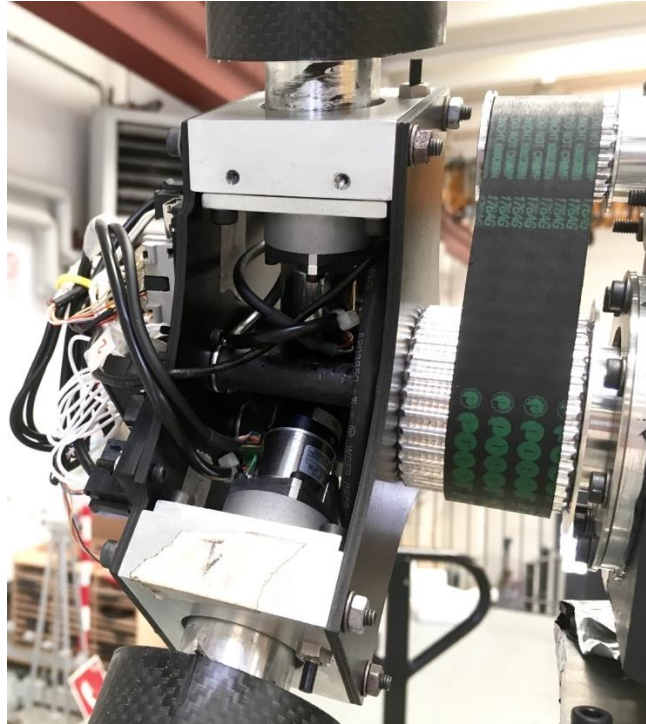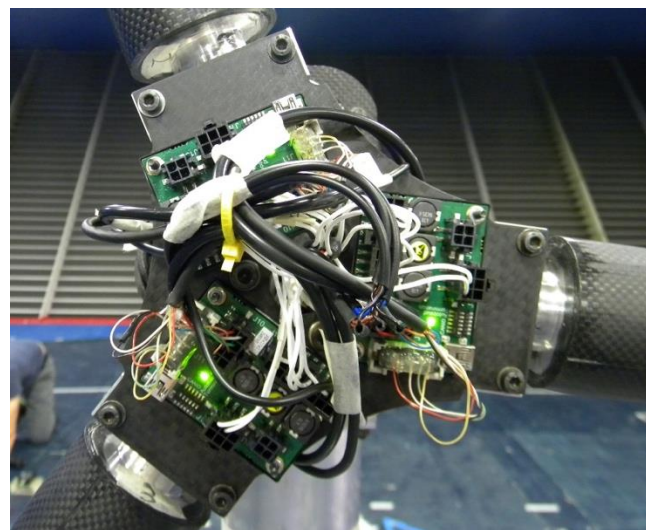
Figure 5-6 Side view of the IPC hub

Figure 5-7 Front view of the IPC hub

Table 11 reports the hub components weight excluding the Harmonic drive actuators

Table 11 Hub components masses

Carbon shell	33 g (x2)
Blade aluminium top	42 g (x3)
Blade Bearing	40 g (x3)
Bearing housing	57 g (x3)
Screw	41 g (total)
Total	0.483 kg

5.3 Model actuators

PoliMi 10MW WTM mounts different electronic devices that can be grouped according to the design task. An EC (electronically commuted) electrical motor is connected through a transmission system to the rotor, in order to control the machine rotational speed. A dedicated PWM (pulse-width modulation) servo-controller is used to drive the motor and collect data about its operational state.

Three AC servo actuators are embedded into the rotor to impose a pitch angle to the blades. Each motor is independently driven by a digital position controller that provides current commutation as well as different control functionalities.

5.3.1 Rotor

The rotor of the wind tunnel model is connected through a synchronous belt transmission system, to the drive unit, composed by a 200 Watt EC motor coupled with an incremental MR (magnetic rotary) encoder and a planetary gear.

The electrical motor mounted on the turbine is a brushless *Maxon EC-4pole 30,* which main characteristics are reported below.

Table 12 *Maxon EC-4pole 30* technical data

Nominal voltage	(V)	24
Nominal speed	(rpm)	16100
Nominal torque (max continuous)	(mNm)	94.6
Nominal current (max continuous)	(A)	7.58
Max efficiency	(%)	89.4
Phase to phase resistance	(Ω)	0.102
Phase to phase inductance	(mH)	0.0163
Torque constant	(mNm/A)	13.6
Speed constant	(rpm/V)	700
Number of pole pairs		2
Number of phases		3
Mass	(kg)	0.3
Rotor inertia	(gcm^2)	3.33

The motor module is directly coupled with a *Maxon Encoder MR Type ML* with 3 channels, 500 counts per turn and an integrated line drive.

The driving unit is finally connected to the smaller pulley of the belt transmission system by means of a *Maxon Planetary Gearhead GP 32 HP*.

Table 13 *Maxon Planetary Gearhead GP 32 HP* technical data

Gear type		Straight
Nominal reduction		21:1
Absolute reduction		299/14
Max continuous torque	(Nm)	4
Max continuous input speed	(rpm)	8000

Max efficiency	(%)	75
Mass	(kg)	0.178
Mass inertia	(gcm^2)	1.6

The EC motor is driven by a *Maxon ESCON 70/10* PWM servo controller. The device is featured by an embedded speed control (closed loop) and a subordinated current control. The speed reference can be set by an external analogy input and measurements of the main motor parameters (actual current, actual speed) are available as analogy output.

Table 14 *Maxon ESCON 70/10* technical data

Nominal voltage (+V$_{CC}$)	(V)	10 - 70
Max output voltage	(V)	0.95 (+V$_{CC}$)
Max output current	(A)	10 - 30
PWM frequency	(kHz)	53.6
Max efficiency	(%)	98 %
Max speed EC motors	(rpm)	150000
Analog input channels		2 (differential)
Analog output channels		2 (referenced to GND)
Hall sensor signals		H1, H2, H3
Encoder signals		A, A\, B, B\

5.3.2 Blade

PoliMi 10MW WTM has been designed to have the possibility of separately control the three blades pitch angle. Each blade is connected, on the pitch axis, to a dedicated *Harmonic Drive RSF - 5B - 30 - E050 - C* servo-actuator. Inside the actuator, an AC motor is combined with a Harmonic Drive gear unit (nominal reduction 30:1) and a 3 channels incremental encoder. In Table 15 the characteristics of the pitch actuators are summarized (reported values are referred to the actuator output shaft and are already comprehensive of the transmission ratio).

Table 16 *Harmonic Drive RSF – 5B – 30 – E050C* technical data

Nominal voltage	(V)	24
Nominal speed	(rpm)	333
Nominal torque (max continuous)	(mNm)	180
Nominal current (max continuous)	(A)	1.11
Phase to phase resistance	(Ω)	0.82
Phase to phase inductance	(mH)	0.27
Torque constant	(mNm/A)	300
Speed constant	(rpm/V)	25
Number of pole pairs		4
Number of phases		3
Mass	(kg)	0.086
Encoder pulses		15000

Each pitch actuator is driven by a *Maxon EPOS 24/2* motion controller. The device is responsible of current commutation and offers an integrated closed – loop position control with a subordinated closed – loop current control and additional feed – forward actions, design to compensate non – linear friction and high inertial loads. From *EPOS 24/2* it's possible to have, directly as analogy signals, or through the embedded RS232 and CAN open interfaces, the real – time value of the main parameters of the connected actuator.

6 Model masses and influence on the HIL tests

During the scaling procedure of the wind turbine we faced two main challenges, the first was to reach the target values of aerodynamic thrust and torque at low Reynolds Numbers and the second was to correctly scale the total mass of the machine.

The target model is very light and, in particular, the masses of the rotor hub and of the nacelle are quite difficult to be reached because most of their components are commercial, such as motors, gearboxes and actuators. The custom parts, as reported in Figure 6-1 and in Figure 6-2, are roughly equal to ¼ and one third of the total mass respectively for the nacelle and the rotor.
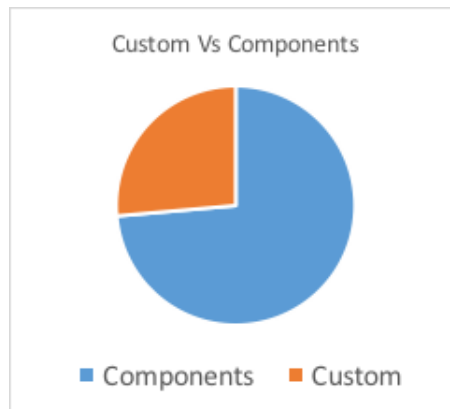

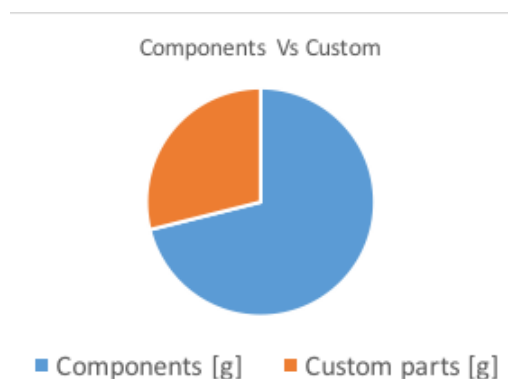Figure 6-1 Nacelle mass distribution in terms of custom parts and commercial components

Figure 6-2 Rotor mass distribution in terms of custom parts and commercial components

Table 17 and

Table 18 report the target mass and the mass as realized, respectively, of the nacelle and of the rotor. The same tables also highlight the mass fraction due to the custom parts and of the commercial components, it is pretty clear that the design of these parts of the model has a very light influence on the final masses.

Table 17 *Rotor mass: comparison among masses, target and as realized*

Total Mass	1255 g
Target Mass	540 g
Custom parts	367 g
Components	903 g

Table 18 *Nacelle mass: comparison among masses, target and as realized*

Total Mass	1788 g
Target Mass	1057.3 g
Custom parts	405 g
Components	1130 g

During the HIL tests the net aerodynamic force will be calculated during the real time integration procedure, as described in [1], keeping into account the real inertial forces acting on the model, i.e. the forces due to mass values higher that the target.

7 References

[1] H. Lifes50+, "Deliverable 3.1 http://lifes50plus.eu/results/," [Online].

[2] C. Bak, "The DTU 10-MW Reference Wind Turbine," Technical University of Denmark, DTU Wind Energy, Denmark, 2013.

[3] C. A. Lyon, A. P. Broeren, P. Giguere, A. Gopalarathnam and M. S. Selig, Summary of Low-Speed Airfoil Data – Volume 3, 1997.

[4] H. Bredmose, R. Mikkelsen, A. M. Hansen, R. Laugesen, N. Heilskov, B. Jensen and J. Kirkegaard, "Experimental study of the DTU 10 MW wind turbine on a TLP floater in waves and wind," in *EWEA Offshore 2015 Conference*, 2015.