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Development of a numerical model for floating Vertical Axis Wind Turbines

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Abstract. Vertical Axis Wind Turbines (VAWTs), which are primarily used in small-scale applications, such as in remote or urban areas, could be particularly promising for floating offshore wind projects, where they offer benefits like increased stability, lower maintenance costs, and the potential for closer spacing due to lesser aerodynamic wake effects. However, to be competitive with floating HAWTs, scaling up VAWTs size is an urgent necessity to facilitate large-scale industrialization. To achieve this goal, the development of tools capable of assessing VAWT performance in challenging offshore environments is crucial. This work aims to introduce a time domain model of a floating VAWT, developed within the Matlab-Simscape environment. The model comprises a floating platform, a wind turbine, and a mooring system. The aerodynamics is simulated using the Double Multiple Stream Tube method, which relies on Blade Element Momentum (BEM) theory. Hydrodynamics is modelled using WEC-Sim, a Simscape library developed by NREL and SANDIA. Among the main advantages of the model are the flexibility and low computational time. The article presents a case study involving a semi-sub foundation, the OC4-DeepCwind, supporting a Darrieus H-rotor VAWT. The results obtained are compared with those from QBlade Ocean, an open-source tool developed by TU Berlin, demonstrating a good agreement between the two codes.

1. Introduction

Among the main applications of VAWTs there are small-scale energy production: the sectors involved concern urban areas, for the installation of turbines on the roofs of buildings, and remote areas, not connected to the electricity grid, capable of satisfying small users, such as water pumping and desalination. However, over the last few years, a possible application concerns offshore wind generation [1]. Among the first to be studied in 2012, there is **DeepWind** technology: it is a 5MW ϕ-Darrieus turbine supported by a spar-buoy foundation. All the system is floating and the power is produced by a generator located at the bottom of the structure. The project involved experimental verification both in a test tank and in a wind tunnel; furthermore, a 1 kW prototype was tested at sea, in Roskilde fjord, near Risø campus (Denmark).

A pre-commercial scale attempt involved the Savonius Keel and Wind Turbine Darrieus (**Skwid**), developed by Modec, a hybrid wind-currents platform made of an 500 kW H-Darrieus turbine, supported by a floater on which a 60 kW Savonius turbine is arranged, to exploit the currents.

However, the installation of the demonstrator conducted in 2014 failed due to problems with the structure's buoyancy.

Among the most recent technologies is **SeaTwirl**, where a Darrieus H-shape turbine supports a spar-buoy foundation. The floater, which rotates together with the turbine, is anchored to the seabed with several catenary moorings while a static and non-rotating generator is enclosed on the substructure, just above sea level. Among the main advantages of this device is the scalability for higher powers and the reduced maintenance. A 30 kW prototype was installed in 2015 in Norway while by the end of 2023 while a 1 MW device will be installed at the Metcentre site, in Norway.

To study and analyze floating VAWTs, it is essential to use numerical models that allow evaluating their performance, with different levels of accuracy and computational time required. However, many state-of-the-art software, only allow to simulate HAWTs.

Among the first tools to be developed is **FloVAWT** (Floating Vertical Axis Wind Turbine), by Cranfield and Strathclyde Universities [2]. The aero-hydro-servo-elastic coupled model is based on Paraschivoiu's Double Multiple Stream Tube (DMST) model [3] for the aerodynamics while hydrodynamics is simulated using a time-domain model, which relies on hydrodynamic coefficients determined through a frequency-based potential analysis method [4]. Moorings are considered through a user defined force-displacement relationship.

HAWC2, developed by DTU, is a time-domain programme to simulate the structural response of a wind turbine due to wind, waves and currents. The tool formulation is based on multibody implementation of beam finite elements subjected to aerodynamic loads and connected by use of algebraic constraint equations [5]. HAWC2 aerodynamics is based on the BEM, including wake expansion and swirl, while the hydrodynamic loads are based on Morrison's equation, and could be calculated by an hydrodynamic software likes Wamit or Nemoh [6]. HAWC2 could be used for both floating and bottom fixed offshore wind turbines.

QBlade, developed by TU Berlin, is an open-source code for the simulation and design of wind turbines [7]. Users can design blades starting from airfoils, thanks to coupling with XFOIL, up to simulating the entire turbine. Furthermore, the latest version, QBlade Ocean, allows to simulate a complete system of floating offshore wind turbines, with both horizontal and vertical axis. Qblade models the structural dynamics using a multi-body formulation, with both rigid and flexible Euler-Bernoulli beam elements [8]. Aerodynamics is based on Lifting Line Free Vortex Wake method (LLFVW) while hydrodynamic loads could be calculated with potential flow theory, from Nemoh, Wamit, Orcawave, etc.

OpenFast, developed by National Renewable Energy Laboratory (NREL), is the state-of-the-art software for the simulation of floating offshore wind turbines. It is an open-source multi-physics tool able to model a FOWT system considering the full-system dynamic response, including the wind turbine, the foundation, the moorings, as well as the environmental loads from wind, waves and currents, under both operational and extreme conditions [9]. Despite OpenFast is not able to simulate a floating VAWT, an attempt was made to include it. In [10], OpenFast was coupled with the Offshore Wind ENergy Simulator (**OWENS**) [11] to include the simulation of floating VAWTs. In particular, the OpenFast modules HydroDyn and MoorDyn were coupled with OWENS to improve the coupled aero-hydro-servo-elastic modeling of floating offshore VAWTs [10].

In Table 1 a comparison of the main numerical codes developed for floating VAWT simulations are reported.

Among the numerical models previously presented, nearly all have been developed by research groups for academic and/or commercial purposes. The motivation behind developing a numerical model lies in the desire to have a flexible, computationally efficient, and entirely open-source model suitable for preliminary assessments and optimization purposes.

Table 1. Comparison between different numerical models for floating VAWTs, adapted from [12].

	Aerodynamics	**Hydrodynamics**	**Mooring**	**Control**	**Simulation**	**License**
FloVAWT	BEMT	PT, ME, CE	QS	VSTC	TD	RIG
HAWC2	BEMT+ DS+ DI	ME, CE + QD	SM, QS, FE	BPC, VSTC, UD	TD	RIG, CO
QBlade Ocean	(BEMT, GDW)+DS+DI, FWV	ME, CE	QS	VSTC, UD	TD	OS, CO
OpenFast + OWENS	(BEMT, GDW)+DS+DI	ME, CE+QD	QS, FE, LM	BPC, VSTC, YC, UD	TD	RIG, OS

Where:

- Aerodynamics: BEMT = blade element momentum theory; GDW = generalized dynamic wake; DS = dynamic stall; FWV = free-wake vortex; DI = dynamic inflow;
- Hydrodynamics: PT = potential theory; ME = Morrison equation; QD = quadratic drag; CE = Cummins equation;
- Mooring dynamics: QS = quasi-static; FE = finite element; LM = lumped mass; SM = stiffness matrix; DYN = dynamic
- Control: BPC = blade pitch control; VSTC = variable speed torque control; YC = yaw control; UD = user defined
- Simulation: FD = frequency-domain; TD = time-domain
- Development/License: RIG = research institute or group; OS = open-source; CO = commercial;

This work aims to introduce a numerical model of a floating vertical axis wind turbine: the model, developed in Matlab-Simscape, consists of a floating platform, a wind turbine and a moorings system. The aerodynamics is modelled with the DMST theory, while the hydrodynamics is modelled using WEC-Sim. The results obtained are compared with QBlade. A case study of a semi-sub foundation, the OC4-DeepCwind, supporting a Darrieus H-rotor VAWT is presented.

2. Material and methods

The model structure is based on Most tool, developed by MOREnergy Lab of Politecnico di Torino. Most is a wind-to-power model, developed for the design and analysis of FOWTs, including all the main components like the floating foundation and hydrodynamics, wind turbine and aerodynamics, electric generator and its control law [13]. Most has been compared with the state-of-the-art software OpenFast, providing a good agreement and resulting in a Root Mean Square Error (RMSE) on pitch position and output power lower than 2% [14]. To evaluate the performances of a VAWT, the following implementations have been made.

- *Aerodynamics*: The aerodynamics is simulated using the Double Multiple Stream Tube (DMST) method, which relies on the blade element momentum theory. Aerodynamic forces are computed using look-up tables previously calculated.
- *Hydrodynamics*: The hydrodynamics of the floating foundation is calculated using WEC-Sim, which employs a time-domain approach to solve the dynamics of floating bodies based on a frequency-domain boundary element method. The hydrodynamic characteristics, including linear hydrostatics, added mass, radiation damping, and wave excitation coefficients, can be assessed using external software tools such as Wamit, Ansys Aqwa, Nemoh, or Capytaine.

- *Moorings*: Two options have been integrated: quasi-static mooring lookup tables, obtained by solving catenary equations or Moordyn, a WEC-Sim module that considers the contributions of inertia and viscous friction of the chains.

Figure 1 shows a representation of the model.

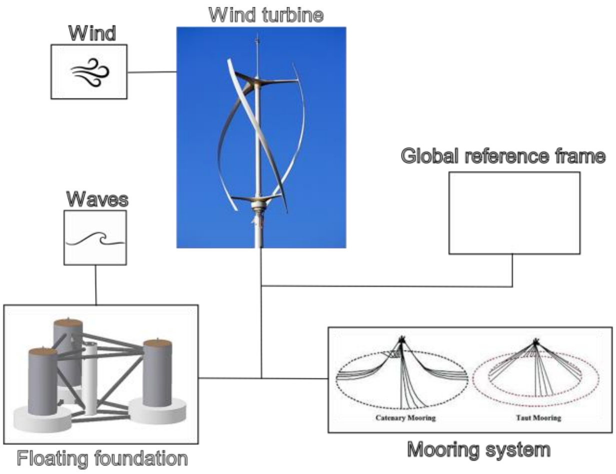

Figure 1. The numerical model representation.

The wind turbine used in this study is a Darrieus H-rotor VAWT with straight blades. The VAWT has been developed starting from the data available from two European projects, respectively the H2OCEAN (2012) [15] and S4VAWT (2016) [16] projects. The VAWT consists of a 3 bladed H-rotor, with a variable pitch mechanism and a nominal power of 6 MW.

Table 2. Wind turbine data.

Wind turbine	***VAWT***
Nominal power	6 MW
V_cut_in, V_rated, V_cut_off	3, 10, 25 m/s
Ω_min, Ω_rated	2.1, 6.6 rpm
Wind turbine radius	63 m
Wind turbine height	140 m

The floating foundation considered is a semi-submersible platform, the OC4 [17]. The platform has a triangular shape at whose vertices there are 3 columns plus a central column which supports the wind turbine. The columns are connected to each other via tubular elements. The OC4 main data are reported in Table 3.

Table 3. OC4 foundation data.

Floating foundation	***OC4***
Main column diameter	6.5 m
Offset column diameter	12 m
Draft	20 m
Column height	32 m
Mass including ballast	1.347E+7 kg
Roll, Pitch & Yaw moment of inertia	6.827E+7 kg · m^2 6.827E+7 kg · m^2 1.226E+10 kg · m^2

3. Aerodynamics

The approach used in this work for the estimation of aerodynamic forces acting on the wind turbine is based on the Double Multiple Stream Tube theory, developed by Parashivoiu [3] and based on the Boundary Element Momentum method. In the DMST, the rotor area is divided into two sections, upstream and downstream, based on the incoming flow. Then each side is divided into N_{st} streamtubes, each of them corresponding to an angle $\Delta\theta$. The performance parameters are determined by integrating the forces calculated within discrete streamtubes across complete rotations. The principle of momentum conservation is employed within each streamtube.

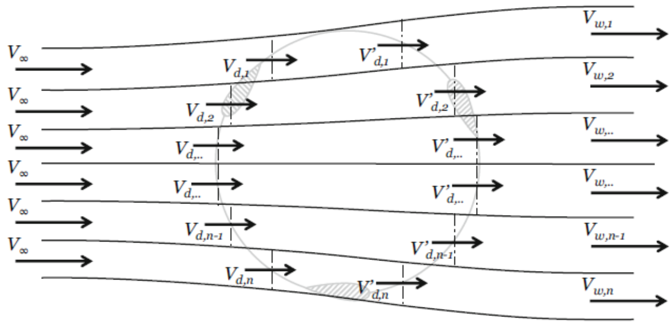

Figure 2. Double Multiple Stream Tube model, from [18].

The assumption made is that the wake, formed through the interaction of the wind with the turbine blades during the upwind pass, expands fully, and the ultimate wake velocity is attained before the blade engages with it during the downwind pass. The set of equations from the DMST model is utilized for both the upstream and downstream sides. Nevertheless, the free stream wind velocity, denoted as V_∞ in the upstream, is substituted with the wake velocity, denoted as V_e in the downstream.

The VAWT is modelled as a drag disk, that slow the wind speed V_∞ to V_i in the upstream streamtubes, and the wake velocity to V_e in the downstream streamtubes. Their relationship are quantified in the following equations by using a non-dimensional quantity, the induction factor a:

$$V_i = V_\infty\,(1 - a) \tag{1}$$

$$V_e = V_\infty\,(1 - 2a) \tag{2}$$

The relative wind speed, experienced by the blade, can be expressed as:

$$\overrightarrow{V_{rel}} = \vec{V} + \vec{\omega} \cdot \vec{R} \tag{3}$$

By defining the tip-speed ratio (λ) as:

$$\lambda = \frac{R\,\omega}{V_\infty} \tag{4}$$

The relative wind speed module is equal to:

$$V_{rel} = V_\infty \sqrt{[(\lambda + (1-a)\cos\theta]^2 + [(1-a)\sin\theta]^2} \tag{5}$$

Where θ is the azimuth angle. The other important parameter that affects the lift and drag forces on the blades is their angle of attack, α. The turbine blades' azimuthal positions change continuously during its rotation and so does the attack angle, given as follows:

$$\alpha = \tan^{-1} \frac{(1-a)\sin\theta}{\lambda+(1-a)\cos\theta} \tag{6}$$

The lift and drag coefficients, C_L and C_D can be obtained throw databases or via experimental, depending on the blade Reynolds number, Re_b. In this study, data have been downloaded from the software QBlade. The normal force coefficient C_N is formulated as:

$$C_N = C_L \cos\alpha + C_D \sin\alpha \tag{7}$$

The tangential force coefficient is given as follows:

$$C_T = C_L \sin\alpha - C_D \cos\alpha \tag{8}$$

The procedure for calculating the thrust and power coefficient, as well as the forces generated by the wind, is iterative and similar to the one proposed in [19], [20]. As an initial hypothesis, an induction factor a of zero is assumed. The convergence criterion involves the calculation of the thrust coefficient C_{TH} through the momentum theory and the blade-element equation, as reported in [18]. By solving both the equation it is possible to resolve the value of a:

$$\begin{cases} C_{TH,\ MOM} = 4a\,(1-a) \\ C_{TH,\ BEM} = \frac{Bc}{R}\,\frac{1}{2\pi}\,(\frac{V_{rel}}{V_\infty})^2(-C_T\,\frac{\cos\theta}{\sin\theta} + C_N) \end{cases} \tag{9}$$

for the upwind,

$$\begin{cases} C_{TH,\ MOM} = 4a\,(1-a) \\ C_{TH,\ BEM} = \frac{Bc}{R}\,\frac{1}{2\pi}\,(\frac{V_{rel'}}{V_e})^2(-C_T\,\frac{\cos\theta}{\sin\theta} + C_N) \end{cases} \tag{10}$$

for the downstream.

From equations 9 and 10, it is possible to obtain the value of the induction factor for each streamtube, both upstream and downstream. Subsequently, it is possible to calculate the forces acting on the turbine, in particular the tangential force F_T, responsible for the torque extracted from the wind and therefore the power generated, and the normal force F_N. Finally, by summing the upstream and downstream contributions for all the streamtubes, it is possible to determine the value of the torque coefficient C_Q and the power coefficient C_P.

Some corrections have been applied to the proposed methodology, including Glauert correction and the dynamic stall, as well as the blade pitch mechanism to allow the blades to rotate along the pitch angle to reduce the thrust force and to keep a constant power.

3.1. Glauert correction

When the value of the induction factor a is higher than 0.4, the momentum theory, and thus the BEM theory, cease their validity, because upstream flows appear in the far wake, increasing the real thrust on the rotor [21]. Glauert correction is applied to the thrust coefficient C_{TH}:

$$C_{TH} = \begin{cases} 4a\,(1-a)\,F_P & for\ a \le 1/3 \\ 4a\,(1-0.25\,(5-3a)\,a)F_P & for\ a > 1/3 \end{cases} \tag{11}$$

3.2. Dynamic stall

Dynamic stall occurs when the blade rapidly changes the angle of attack and it affects the performances of a VAWT, in which the angle of attack periodically changes, especially at low TSRs. Dynamic stall presents a hysteresis behavior of the flow passing through the blades, whereas the flow does not immediately react to the variation of angle of attack [22]. To address dynamic stall, the model developed by Masse [23] is adopted. This model interpolates between the dynamic force coefficients obtained from Strickland's modified Gormont dynamic stall model and the static blade polars [24].

$$C_{[L/D]mod} = \begin{cases} C_{[L/D]mod} + \left[\frac{A_M\,\alpha_{SS} - \alpha}{A_M\,\alpha_{SS} - \alpha_{SS}}\right]\left(C_{\left[\frac{L}{D}\right]dyn} - C_{\left[\frac{L}{D}\right]stat}\right) & for\ |\alpha| \le |A_M\,\alpha_{SS}| \\ C_{[L/D]dyn} & for\ |\alpha| > |A_M\,\alpha_{SS}| \end{cases} \quad (12)$$

The influence of dynamic stall is evident for low TSR values, as visible in Figure 3, while it is less relevant for high TSR values.

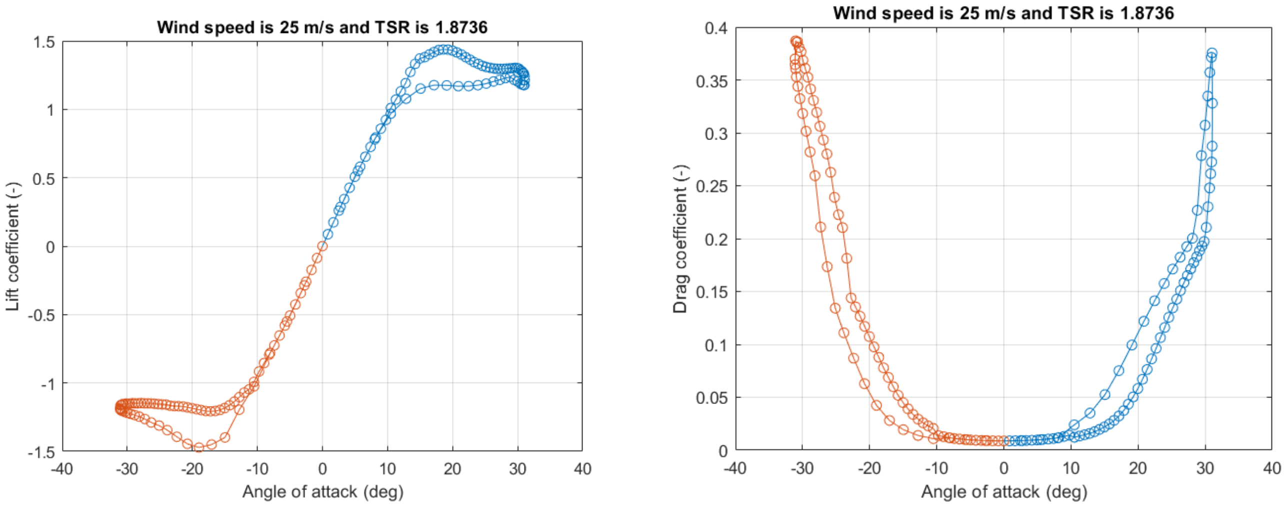

Figure 3. Influence of dynamic stall on lift and drag coefficients for low TSR.

3.3. Blade pitch mechanism

To reduce the thrust acting on the VAWT at high speeds and regulate the power, a blade pitch mechanism was introduced. It is a mechanism that acts for wind speeds higher than the nominal one and allows to reduce the peak of the thrust force acting on the turbine blades and to guarantee a constant power output. Figure 4 shows the trend of the blade pitch angle as the wind speed varies.

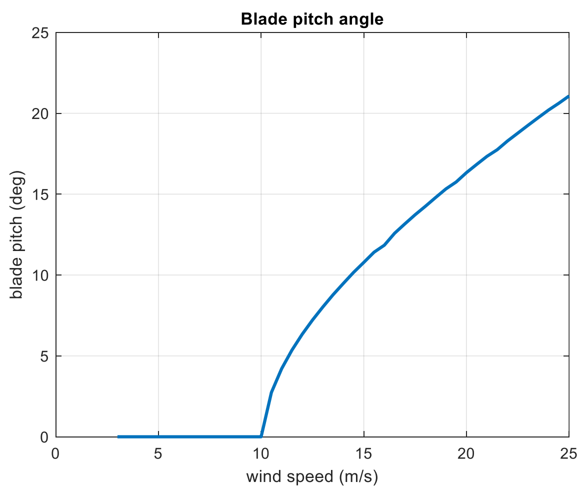

Figure 4. Blade pitch angle in function of the wind speed for the 6 MW VAWT.

4. Results and discussion

This paragraph reports some of the results obtained with the developed numerical model. First of all, the aerodynamics of the VAWT is analysed, considering the trend of the aerodynamic forces and power as the azimuth angle varies. Subsequently, the trend of the thrust and power coefficients as the TSR varies are reported and compared with QBlade. Finally, an analysis of the complete floating VAWT system is reported, considering the combined effect of waves and wind.

4.1. Aerodynamic forces and power

Figure 5 shows the trends of the tangential and normal force as the azimuth angle varies for three TSR values. The TSR values considered correspond respectively to wind speeds equal to 10 m/s (TSR = 4), 15 m/s (TSR = 3) and 21 m/s (TSR = 2), having considered a rotor speed of 6.6 rpm. The forces have a similar trend in the three cases, with higher values at higher wind speed, i.e. at a TSR of 2.

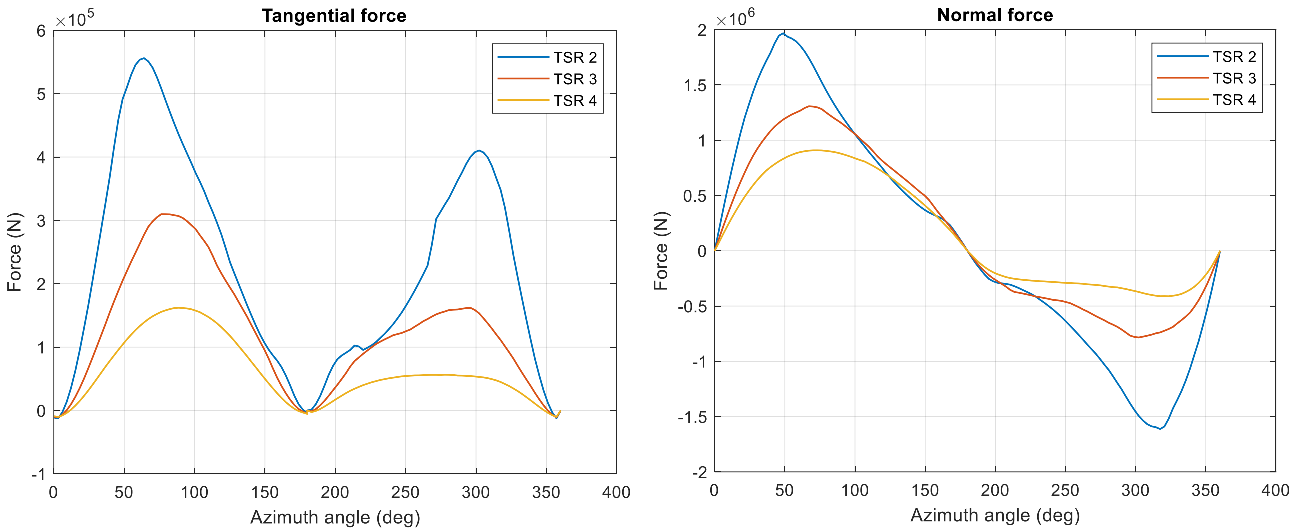

Figure 5. Tangential and normal forces at different TSR values.

Figure 6 shows the power as the azimuth angle varies. The presence of the three peaks is linked to the type of turbine considered, made of three blades. As in the previous image, the highest power values are those related to the highest wind speed, with a TSR of 2.

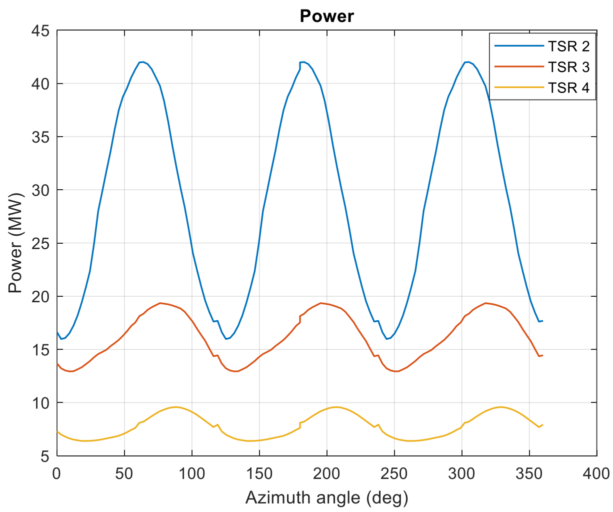

Figure 6. Power at different TSR values.

4.2. Comparison with QBlade
This paragraph shows the comparisons of the aerodynamic performances between the numerical model and QBlade. In Figure 7, the power and thrust curves are shown respectively as the TSR varies. As regards the power curve, the numerical model presents a good adherence to QBlade, albeit with a reduced overestimation. As regards the thrust curve, for low TSR values, up to 2.5, there is a good approximation, although it then differs more for higher values.

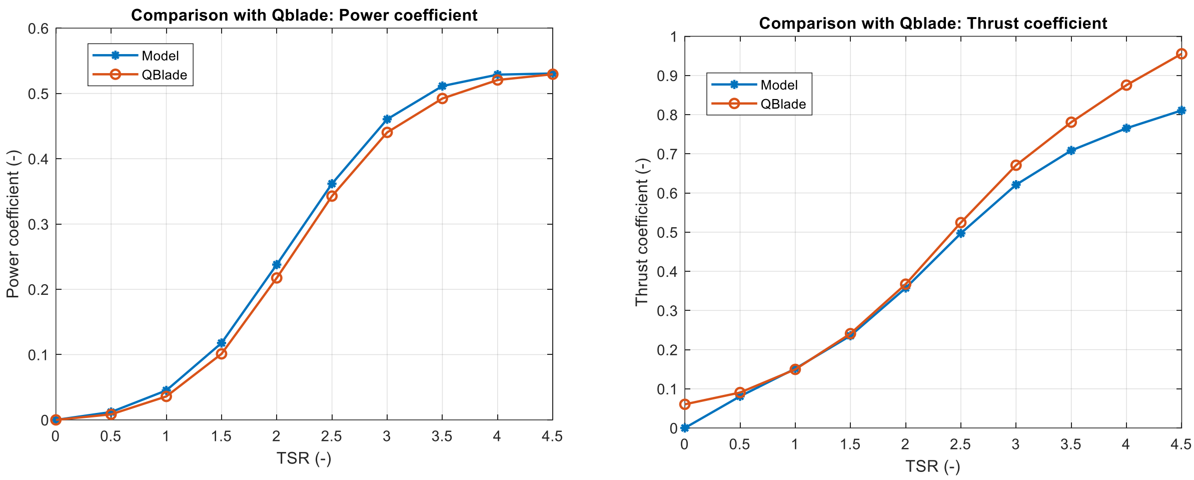

Figure 7. Comparison between the numerical model and QBlade for the power and thrust coefficients.

Figure 8 shows the trends of the rotor speed and the TSR as the wind speed varies. When the wind speed exceeds the cut-in speed, the turbine starts to rotate with a rotor speed of 2.1 rpm; as the wind speed increases there is an almost linear growth in the rotor speed until the nominal speed of 10 m/s is reached. For higher speeds, up to the cut-off speed, the rotor speed is constant and equal to 6.6 rpm.
As regards the TSR curve, up to the nominal speed, the TSR remains relatively constant, albeit with some oscillations regarding the numerical model, probably linked to the discretisation of the wind speed (1 m/s). For speeds higher than the nominal one, a decrease is observed, with a good approximation between the 2 curves.

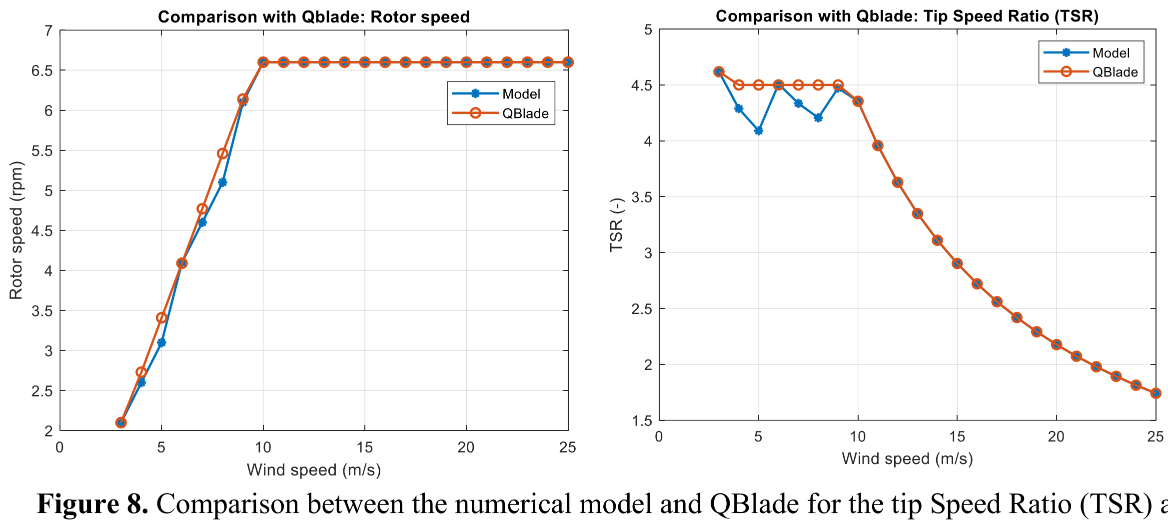

Figure 8. Comparison between the numerical model and QBlade for the tip Speed Ratio (TSR) and the rotor speed.

4.3. Floating VAWT simulations

The complete system, consisting of the 6 MW VAWT installed on the OC4 floating foundation, is simulated in an operational environment, considering an average wind speed of 12 m/s, and waves with 2 m wave height (H_S) and 7 s of wave period (T_p). The depth of the site is 200 m, while the mooring configuration includes 3 catenary lines arranged at 120° between them. In Figure 9, on the left the VAWT performances are reported, while on the right the foundation displacements.

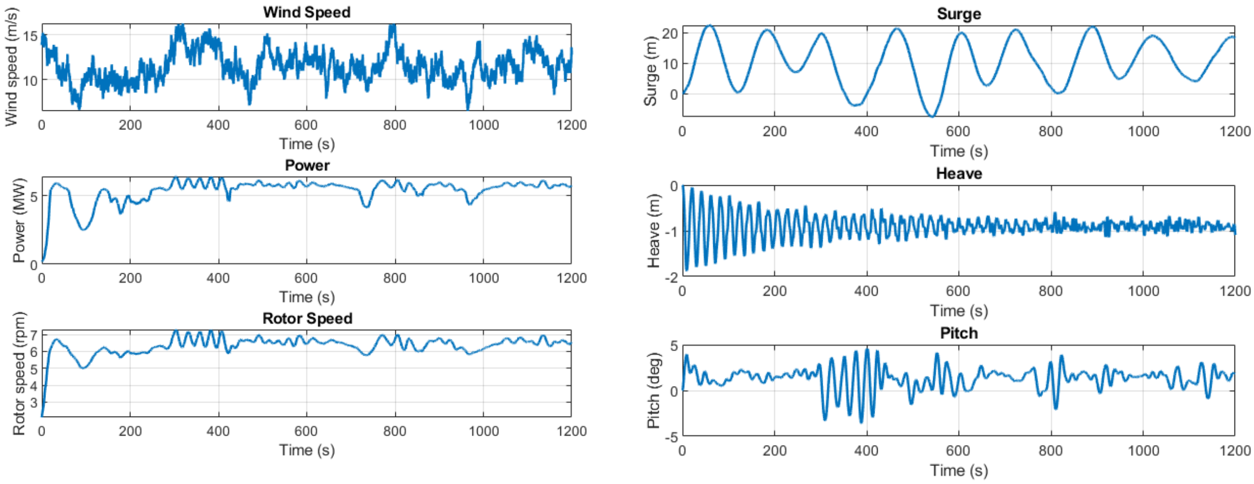

Figure 9. Wind turbine performances and platform displacements for H_s = 2 m, T_p = 7 s and wind speed of 12 m/s.

The wind speed profile is generated by using the TurbSim software, developed by NREL, considering 12 m/s as the average value. The turbulence model considered is a Kaimal, with a IEC turbulence characteristic B of 0.14. The power law exponent considered is equal to 0.11.

After an initial transient, due to the fact that the turbine starts from standstill, the trends of power and rotor speed settle around nominal values, reproducing a dependence on wind speed.

Regarding displacements, the surge exhibits an excursion of approximately 25 m. The heave, after an initial transient, reduces the oscillation amplitude, stabilizing towards a value of about -1 m. The pitch, ranging between +/- 5°, alternates between phases with relatively constant values and phases with many peaks, in proximity of higher wind speeds (around 400 s and 800 s).

5. Results and discussion

The aim of this work is to present a numerical model developed for the analysis of floating VAWT developed in the Matlab - Simscape environment. As regards aerodynamics, starting from the Double Multiple Stream Tube model, dynamic stall and Glauert correction were implemented, as well as providing a variable blade pitch angle, to limit the thrust acting on the turbine and loads.

The comparison with the QBlade demonstrates a good agreement regarding the power curve, while regarding the thrust curve, consistent differences were observed for high TSR values.

The simulation of the floating VAWT demonstrates a strong dynamic response from the system, indicating a reliance on wind speed. However, further analysis could be conducted by incorporating and designing a dedicated foundation and mooring system for VAWTs.

Among the advantages of the numerical model, the most relevant is its flexibility: each Simulink block can be accessed by the user who can modify governing equations, wind turbine, foundation and mooring layout. Moreover, the adoption of look-up tables for the aerodynamics, while on the one hand simplifies and reduce the accuracy, on the other hand reduces the computational time, making this tool useful for preliminary design and optimization evaluations of floating VAWT projects.

Some limitations to be addressed, compared to QBlade, concern the lack of a user interface, and the absence of more advanced aerodynamics theories, such as the Lifting Line Free Vortex, for exhaustive analysis, like the wake dynamics evolution.

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