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Development of *MOST*, a fast simulation model for optimisation of floating offshore wind turbines in *Simscape Multibody*

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Abstract. the paper presents the development of an innovative non-linear, time domain numerical model for the simulation of offshore floating wind turbines, named MOST. The model is able to evaluate the movement of the platform in six degrees of freedom, the power production and the load cycles acting on the blades. MOST is implemented in Matlab-Simulink environment using Simscape Multibody. The aerodynamics is modelled with the blade element momentum theory and the hydrodynamics is modelled using WEC-Sim, a Simscape library developed by NREL and SANDIA. The use of Simscape offers great flexibility to quickly introduce complex dynamic systems such as hybrid wave-wind platforms, flexible platforms, or sea water active ballast systems. Additionally, Matlab provides useful toolboxes and extensive libraries for advanced control systems, linearisation analysis, parallelisation and generation of C code. The results of MOST are then compared to FAST, an open-source code widely used in the academic research. The case study is a 15 MW reference wind turbine installed on the Volturn US platform. The comparison shows a good agreement between the two codes with a significant reduction of the simulation time.

1. introduction

Floating offshore wind turbines represent a very promising technology in the field of renewable technologies: they allow the exploitation of vast areas of the sea at a great distance from the coast, characterized by more consistent wind speed and availability, reducing visibility from the coast, and increasing electrical productivity. The traditional depth limits imposed by fixed structures are overcome, allowing installations in deep seas such as the Atlantic Ocean and the Mediterranean Sea [1].

Reliable and fast numerical models for simulating the system are essential to ensure optimal platform design. These models must be able to compute the movements of the platform, the mechanical stresses acting on the components and to estimate energy productivity with the required accuracy.

FAST, an open-source software developed by NREL, represents the state of the art for offshore wind turbines simulations [2]. Numerous experiments have been conducted to validate the FAST code [3]–[6]. However, Fast is difficult to access, as well as complex to implement and modify.

This article presents an innovative non-linear time domain model written in Matlab-Simulink environment, named MOST (Matlab for Floating Offshore wind turbine). The model computes the motion of the platform, the power production, and the mechanical stresses acting on the blade root. The results are then compared with FAST to verify the accuracy and simulation time.

The reason to develop a new alternative model compared to similar open-source programs derives from the need to have a user-friendly, flexible and multifunctional model: thanks to the extensive libraries in Simulink, it is possible, for example, to integrate the platform with the dynamics of wave energy converters (WEC), to simulate an active control of the water ballast, to simulate flexible platforms such as *Spiderfloat* [7], or to simulate a platform with two turbines.
The Simscape Multibody library was used in this context, which easily allows to build a dynamic model in six degrees of freedom.

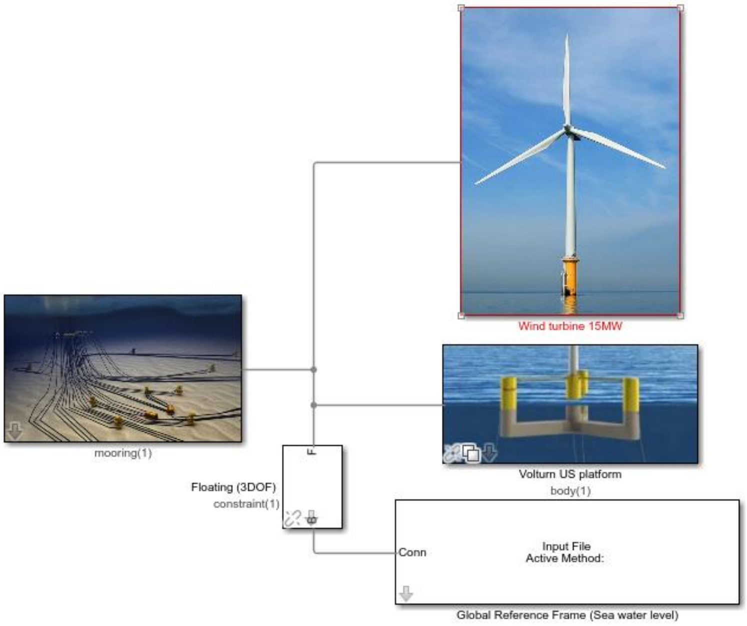


Figure 1*: numerical model in Simulink environment*

2. Numerical model development

The numerical model includes:

1. Dynamic module, that computes the motion of the platform in 3 or 6 degrees of freedom and the total forces acting on the blades, tower, shaft and bearings including the aerodynamic and hydrodynamic forces, inertial, centrifugal and gyroscopic forces.
2. Aerodynamic module, that computes the aerodynamic forces using look-up tables of precalculated values that follow the blade element momentum theory.

3. Hydrodynamic module, that is computed using Wec-sim [8], a Simscape library developed by the collaboration between NREL and SANDIA.
4. Mooring module, that includes two options: a quasi-static mooring matrix that considers the non-linear stiffness of the chains and Moordyn that is included in Wec-sim library.
5. Control system module, that evaluates the blade pitch and generator torque response; The default control algorithms implemented are the baseline control and ROSCO control.

2.1 Aerodynamics
The aerodynamic forces are calculated using the blade element momentum theory as described in the FAST's aerodyn15 module, which represents the standard model of aerodynamic modelling. Unlike FAST, the aerodynamic forces are computed using a look-up table. The contribution of each blade to the axial and tangential forces and moments is a function of three input variables: the average wind speed on the blade, the rotor angular speed and the blade pitch. In order to decrease the points necessary for discretization, the angular speed and the blade pitch are discretized around the steady state points, thus excluding the points that are never reached in operating conditions. The number of points is evenly spaced.

Discretisation parameters	Wind speed	Rotor speed error respect to steady state	Blade pitch error respect to steady state
Interval	3÷25 m/s	± 1.5 RPM	± 12 deg
Number of points	45	5	25

***Table 1**: discretisation parameters for the aerodynamic forces*

The steady state values of a same turbine can vary with different types of control. In this case, the steady state values are taken from FAST simulations implemented with the baseline controller as described in [9]. The simulation is realised with a fixed tower and the precone and tilt angle of the rotor are null. The wind is steady and there is no shear effect. The gravity acceleration is set to zero to exclude the gravitational forces. The axial and tangential forces and moments are taken from the outputs of FAST, specifically RootFxc1, RootFyc1, RootMyc1, RootMxc1. The simulation lasts 90 seconds to overcome the transient effects. The last value of simulation is taken as steady state point. The rotor speed and blade pitch are obtained for each wind speed.

The points outside the steady state values are taken by disabling the rotor degree of freedom and manually setting the rotor speed and the blade pitch. The figures (3) summarize the trends of torque and axial thrust acting on the entire rotor considering an average wind speed.

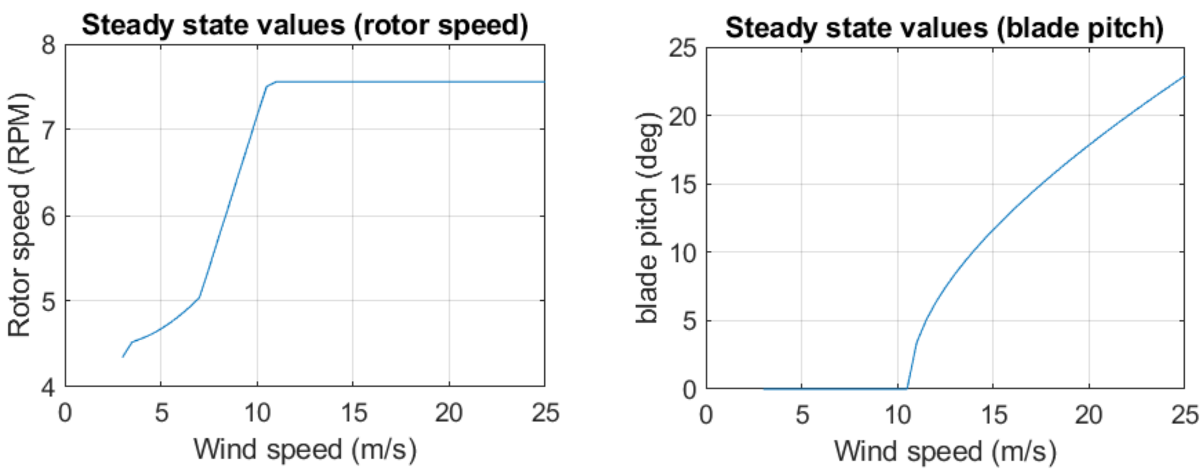
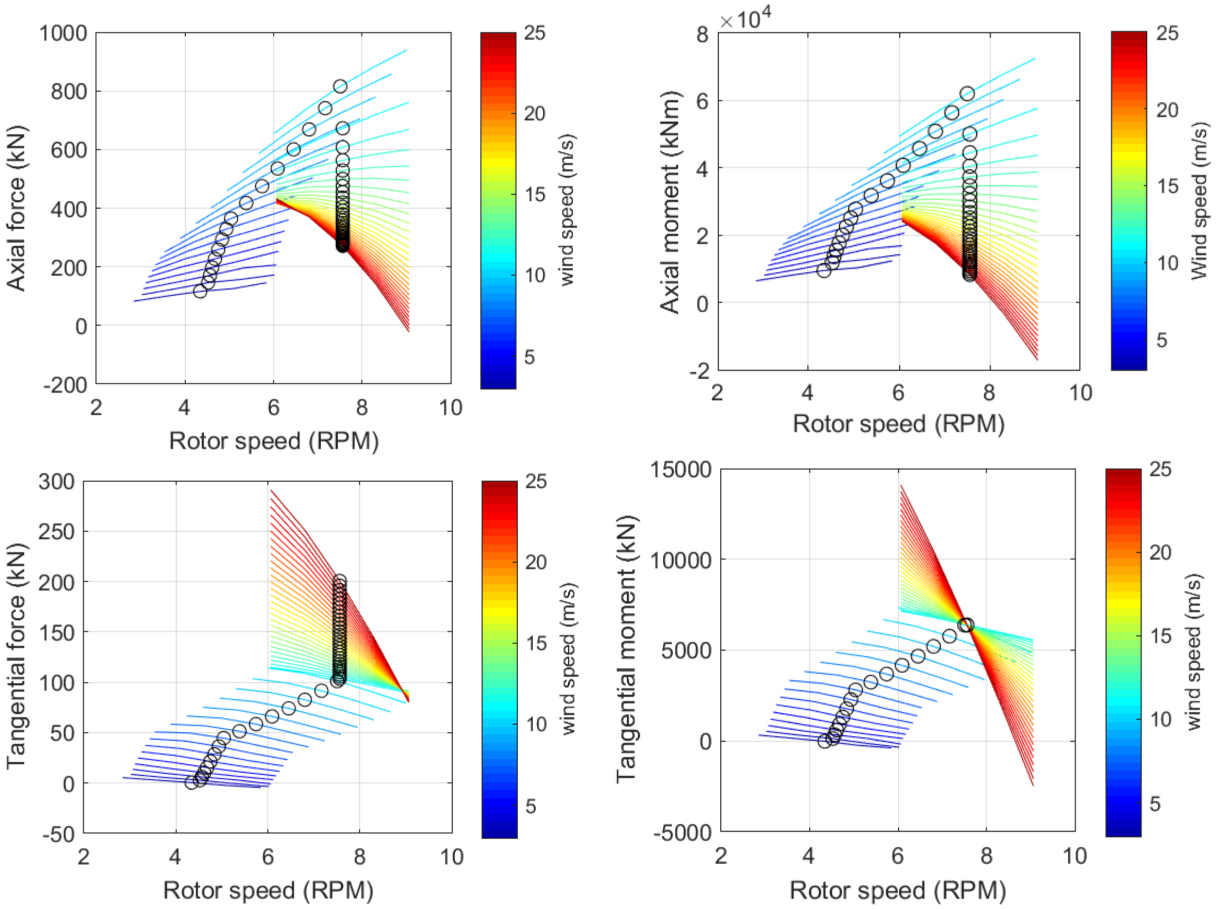


***Figure 2**: rotor speed and blade pitch steady state values from FAST*



Figures 3: *Trend of the axial and tangential forces and moments for IEA 15 MW reference wind turbine as a function of rotor speed and wind speed. The blade pitch corresponds to its steady state value for each wind speed. The black circles represent the values of the forces in steady state conditions.*

The axial and tangential forces and moments are applied at the blade root. As expected, when the rotor reaches the rated speed (7.56 RPM), the tangential moments (that gives the torque to the electric generator) above the rated wind speed (10.59 m/s) converge to the same value of the torque, giving the rated power output. The slope of the tangential moment changes with the wind speed because the power to pitch sensitivity increases with the blade pitch, as described in paragraph 1.3. The axial force (that gives the thrust on the rotor) and moment decrease when the blade pitch increases.

The wind speed is calculated with the NREL Turbsim software [10]. The wind is represented as a two-dimensional grid 270 m x 270 m with a discretization of 17 x 17 points. The mean wind speed refers to the speed at 100 meters above the sea water level. The wind profile is a power law with an exponent of 0.14.

The average wind speed is determined by interpolating four points for each blade in the wind grid along the blade length, specifically at 50, 70, 90, 110 meters. The reason of a discretisation starting from the middle of the blade and not from the root is that the wind speed has more influence at the final section of the blade, and indeed it gives a better adaptation to the FAST results. The horizontal hub speed, due to surge and pitch oscillation, is added to the wind speed.

The aerodynamic forces do not take into account the flexibility of the blade and tower (rigid body assumption), the deflection of the wake due to the rotor misalignment with respect to the wind, and the wake dynamics.

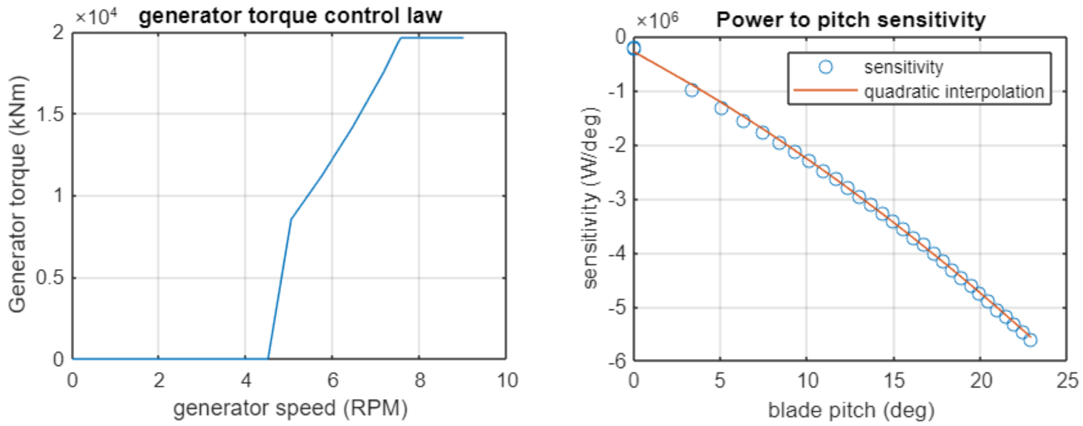
2.2 Hydrodynamics and mooring

The hydrodynamics of the floating structure is computed using WEC-Sim [4]. WEC-Sim solves the dynamics of the floating bodies in time domain from a frequency-domain boundary element method. The hydrodynamic properties (linear hydrostatic, added mass, radiation damping, and wave excitation coefficients) can be evaluated with external softwares like Wamit, Ansys Aqwa, Nemoh, or Capytaine. The results of this tool have been validated in previous articles [11], [12].

Two options are implemented for the mooring: the first one consists of quasi-static mooring look-up tables that have been implemented within the Simulink model to account for the non-linear stiffness of the chains by solving the equations of the catenary [13]. The second one is Moordyn, a WEC-Sim built-in module in which the contributions of inertia and the viscous friction of the chains are considered.

2.3 Control

the control system is a baseline control, that is widely used in the wind industry. An in-depth analysis of this type of control can be found in [9]. The implementation of the baseline control for the 15 MW reference wind turbine is explained in this paragraph. The generator torque behaviour is described in the figure (4). It follows the optimal torque for the maximisation of the power extraction and depends only on the generator speed.



Figures 4*: generator torque control law implemented for the IEA 15 MW wind turbine and the power to pitch sensitivity and the quadratic interpolation used in the gain scheduled PI control system*

The blade pitch control is used for the power regulation above the rated wind speed and uses a gain scheduled PI control. The equation implemented for the blade pitch control is described by the following equations:

$$\theta = K_p \Delta\omega + K_I \frac{\Delta\omega}{s} \tag{1}$$

$$\Delta\omega = \begin{cases} \omega - \omega_0 & if\ \omega > \omega_0 \\ 0 & if\ \omega \leq \omega_0 \end{cases} \tag{2}$$

Where θ is the blade pitch, ω is the generator speed, ω_0 is the rated generator speed (7.56 RPM), K_P and K_I are the gains for the PI control.

$$K_P = \frac{K_P'}{\frac{dP}{d\theta}} \tag{3}$$

$$K_I = \frac{K_I'}{\frac{dP}{d\theta}} \tag{4}$$

$$\frac{dP}{d\theta} \cong c_1\theta^2 + c_2\theta + c_3 \tag{5}$$

$\frac{dP}{d\theta}$ is the power to pitch sensitivity and c_1, c_2 and c_3 are the coefficients for the parabolic equation that interpolates the power to pitch sensitivity. The values of K_P' and K_I' are obtained from an optimisation algorithm using MOST for the minimisation of the pitch rate of the platform. The same controller and parameters have been implemented in FAST.

Control parameters	c_1	c_2	c_3	K_p'	K_I'
values	2500 W/deg^3	173436 W/deg^2	290832 W/deg	49384000 s	3938500

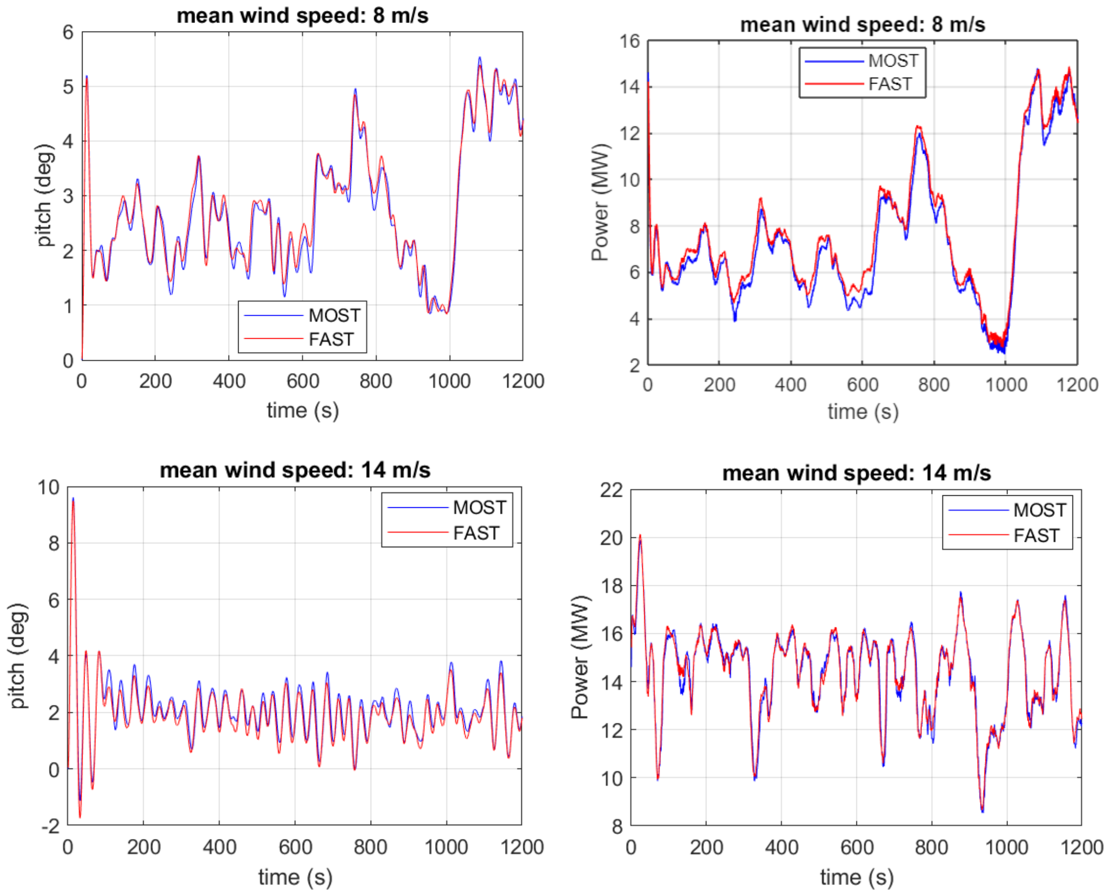
Table 2*: parameters for the baseline control implemented on IEA 15 MW wind turbine*

3. Results

To make a comparison between Fast and Most, we have considered a Volturn US platform [14], which supports the IEA 15 MW wind turbine [15]. Moordyn is used to simulate the mooring forces. The degrees of freedom of MOST and FAST are surge, heave and pitch. The wave forces are not considered (still water condition). The hydrodynamic properties of the platform are computed using Nemoh [16] and then imported to WEC-Sim as .h5 file. The time step of simulation is 0.05 seconds. Since the boundary element method does not consider the viscous forces, the quadratic drag of the structure needs to be estimated with an external software. In FAST, the quadratic drag matrix for the six degrees of freedom is estimated using OpenFOAM. Such matrix is then imported in WEC-Sim.

In the figures (5), the pitch of the platform and the power production are shown for two different mean wind speeds, under and above the rated wind speed (10.59 m/s): 8 and 14 m/s. additionally, in the figures (6) the axial force and moment are shown. The blade root forces consider all the forces acting on blade, including aerodynamics, gravitational forces, inertial forces, and gyroscopic moments. The main oscillations in the blade root forces are caused by the wind shear, the turbulence on the wind, and the periodic oscillations of the gravity moment due to the precone and tilt angle.

In this paragraph, a comparison of the time simulation is included (table 3). The choice of the mooring model is determinant in terms of computation time, since the choice of Moordyn takes about three times longer respect to the quasistatic matrix. The time of initialisation and execution of the Simscape model is three-five times longer than FAST, but it could be further reduced by generating a C code starting from the Simscape model.



Figures 5: *Platform pitch and power output comparison between MOST and FAST for the IEA 15 MW wind Turbine*

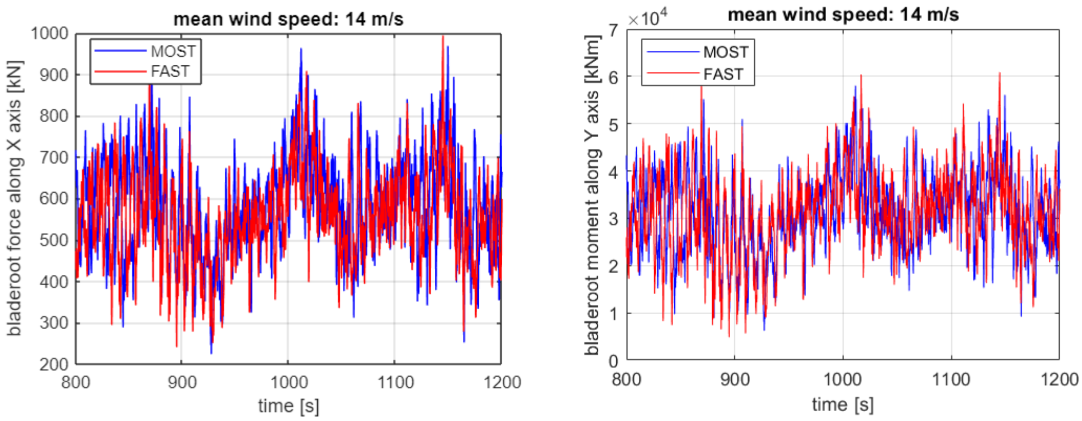


Figure 6: *axial force and moment comparison between MOST and FAST for the IEA 15 MW wind Turbine*

Simulation time (seconds)	Computation time (seconds)		
	FAST	MOST (Moordyn)	MOST (quasi-static mooring matrix)
1 (initialisation)	11	25	21
1200	122	106	40
3600	366	264	72

Table 3: *Simulation time comparison between FAST and MOST. The two options for the mooring have a significant impact on the simulation time. The time step of simulation is 0.05 seconds.*

Mean wind speed (m/s)	Pitch (deg)				Power (MW)			
	Mean		Standard deviation		mean		Standard deviation	
	MOST	FAST	MOST	FAST	MOST	FAST	MOST	FAST
5	0.527	0.492	0.370	0.355	1.756	1.860	0.921	0.866
8	2.738	2.794	1.142	1.129	7.383	7.726	2.905	2.876
11	3.469	3.263	1.143	1.111	13.63	13.83	2.421	2.245
14	2.112	1.942	1.060	1.046	14.38	14.40	1.848	1.798
17	1.522	1.369	1.127	1.167	14.42	14.43	1.910	1.891
21	1.141	0.996	1.341	1.336	14.58	14.63	2.492	2.449

***Table 4**: Platform pitch and power output comparison between MOST and FAST for different mean wind speeds. The mean value and standard deviation are used as comparison objects.*

4. Conclusion

The calculation of the aerodynamic forces carried out by the Aerodyn module represents the greatest cost in computational terms, because the pressure on the blade is computed at each node and it involves an iteration cycle. The simplification of aerodynamics through look-up tables using pre-calculated values is a big advantage for reducing the simulation time. In fact, the simulation time of the Simscape model is about three-five times faster than FAST. The results of the model however show a good agreement compared to the FAST results, considering the blades and tower as rigid bodies and neglecting other minor effects, like the tower shadowing and the wake dynamics. These simplifications are necessary to reduce the time computation, which is the primary goal of the model. Indeed, this model is intended to be used in optimisation algorithms for the platform design, control system parameters and wave energy converters in hybrid platforms, where the flexibility, expansibility, and computation cost are crucial, being able to explore preliminary designs in an efficient way, that are not possible with other codes like FAST. The model however leaves out important dynamic effects, especially the flexibility of the blades, that can be important for the load cycles. Such issue can be addressed in new developments of the model, for example introducing the modal analysis for the blades and the tower, modified and adapted to the usage of the look-up tables for the aerodynamic forces.

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