Verification of SIMPACK-MoorDyn coupling using 15 MW IEA-Wind reference models Activefloat and WindCrete

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Abstract. The modelling of mooring lines and their behaviour is essential for the research and development of Floating Offshore Wind Turbines (FOWTs). Mooring lines’ dynamics impact the platform motions and hence the loads on the turbine’s blades. Therefore, coupling the mooring lines’ dynamics in the aero-hydro-servo-elastic models is a necessity. In this paper we couple MoorDyn to SIMPACK which is a multibody system simulation software. Afterwards, we verify the coupling by comparing the results to OpenFAST v2.1. The IEA Wind 15 MW reference wind turbine coupled to Activefloat and WindCrete floaters, introduced in COREWIND project, are used for the verification process. The two floaters have two different mooring configurations; WindCrete is a spar floater with a symmetric delta shape catenary mooring line system, while Activefloat is a semi-submersible with simple catenary mooring configurations. During the verification, both steady and dynamic load cases are used for the responses of two mooring systems. After the verification, the coupling procedure is open access and can be used to model new innovations in FOWTs using SIMPACK benefiting from the tool’s flexibility.

1. Introduction
Fixed bottom offshore wind energy is constrained by a maximum sea depth of 50m. This constraint rules out 80% of the wind energy capacity in Europe which lies in deep water. Therefore, the development and innovation in Floating Offshore Wind Turbines (FOWTs) is necessary for green energy transition. Hence, flexible numerical tools are needed to validate these innovations. SIMPACK [1] is a multibody system simulation software, which is well suited for modelling innovations in wind energy due to its flexibility as a general multibody system software, which is not wind energy specific. It can be coupled to other software like AeroDyn and HydroDyn, as well as user defined forces. Moreover, the different parts of the turbine can be modelled as rigid or flexible as defined by the user. In this paper we present the coupling of MoorDyn to SIMPACK in order to include the dynamic mooring lines effects on the FOWT system.

The verification of the coupling procedure is done by comparing the results of SIMPACK 2019.2 to OpenFAST v2.1 [2]. For the aerodynamic loads calculation both SIMPACK and OpenFAST use Aerodyn v15 [3], and for the hydrodynamic loads calculations both tools use Hydrodyn [4]. However the Aerodyn and Hydrodyn versions coupled to the tools are different. The versions of AeroDyn and HydroDyn coupled to the numerical tools are shown in Table 1. MoorDyn [5, 6] standalone version, which is coupled to SIMPACK, is coded in C++ while the
OpenFAST version is coded in FORTRAN. However, both codes are similar and deliver the same results as shown in this work. OpenFAST uses a user-defined modal formulation for the blades and the tower, while SIMPACK calculates the mode shapes directly from the multibody system. Therefore, the number of modes of the tower in SIMPACK is set to four and the blade modes are set to three similar to OpenFAST. The modal frequencies for the blade and the tower are exactly equal for both models.

| AeroDyn      | OpenFAST v2.1 | SIMPACK 2019.2 |
|--------------|---------------|----------------|
| HydroDyn     | OpenFAST v2.1 | v2.02.02a-gjh   |
| MoorDyn      | OpenFAST v2.1 | v1.01.00C       |

MoorDyn is a dynamic lumped mass tool used to model mooring line systems. Each line is divided into \( n \) equal sections defined by the user. At the first time step, MoorDyn calculates the static equilibrium of each line. Then, at every time step the velocity and the position of the floating platform are used by MoorDyn to calculate the axial tension of each node the mooring lines. The buoyancy, damping and inertia forces are considered in MoorDyn calculations, while the wave forces, and the torsion degree of freedom of the lines are not considered. MoorDyn also accounts for seabed friction. The seabed friction implementation in MoorDyn is presented in [7].

The verification process is carried out using the IEA Wind 15 MW reference wind turbine [8] coupled to two floaters; WindCrete and Activefloat. The two floaters were developed with the EU Horizon 2020 project COREWIND. COREWIND aims at decreasing the cost of mooring lines and cables by 15\% through innovations and breakthroughs in mooring and cables design and installation. These innovations can be simulated later within SIMPACK using its flexibility to include new parts to the wind turbine numerical model. This was the main motivation behind the coupling procedure presented in this paper.

The paper is structured as follows, in the first part we briefly introduce the 15 MW reference, and the two floaters with an emphasis on their mooring systems’ designs. Afterwards, we explain the coupling procedure between SIMPACK and MoorDyn. Then we present the site specific load cases we chose for the verification process. The next section shows the verification results against static and dynamic simulations. Finally, we present our conclusion and our future goals.

2. Introduction to the models
The IEA Wind 15MW reference wind turbine presented in [8] is used to verify the coupling introduced in this paper. The main parameters of the Rotor Nacelle Assembly (RNA) of the reference model are shown in Table 2. The reference 15 MW is coupled with the spar platform WindCrete and the semi-submersible platform Activefloat. In this paper, the floaters design for the Gran Canaria site introduced in [9] are used with sea bed depth of 200m. The tower is redesigned for each floater in order to withstand the higher tower base loads in FOWTs. The OpenFAST coordinate reference system is used as the coordinate reference system in this paper.

The OpenFAST coordinate reference system is used as the coordinate reference system in this paper. A re-tuned version of the NREL’s Reference OpenSource Controller (ROSCO) [10] is used to provide torque control below rated wind speed and pitch control above rated wind speed. The tuning method used is explained in [11]. The same re-tuned version is used for both Activefloat and WindCrete floaters. The OpenFAST models of both floaters are open access and can be found at [12, 13].
Table 2. Key parameters of the IEA Wind 15 MW reference wind turbine

| Parameter                  | Value   |
|----------------------------|---------|
| Rated power                | 15 MW   |
| Cut-in wind speed          | 3 m/s   |
| Rated wind speed           | 10.59 m/s |
| Cut-out wind speed         | 25 m/s |
| Rotor diameter             | 240 m   |
| Minimum rotor speed        | 5.0 rpm |
| Turbine class              | IEC Class 1B |
| Rated thrust               | 2.4 MN  |
| Blade mass                 | 65 t    |
| Mass of RNA                | 1016 t  |

2.1. WindCrete

WindCrete is a monolithic spar design by Universitat Politècnica de Catalunya (UPC) out of concrete without connection points between the tower and the platform to avoid having weak points in the structure [14, 15]. The draft of the spar model is 155m and the hub height is 135m. At the bottom of the spar, a ballast is added to increase the hydrostatic stiffness in the pitch direction. The tower has a conical shape of diameter of 13.2m at sea water level and 6.5m at the top of the structure. Further details on the WindCrete design concept and its hydrodynamic and hydrostatic properties can be found in [11].

Station keeping of WindCrete is achieved using a three catenary lines symmetric delta shaped mooring system. Each line is composed of a single chain at the bottom with a length of 565m, connected to a delta shape connection with a length of 50m. The three lines are made entirely of one type chain with a diameter of 160mm, dry weight of 561.25kg/m, and axial stiffness of 2.304E+09N. The delta shaped lines fairlead and anchors positions are introduced in Table 3. For each mooring line in there exists two fairlead connections to the floater, throughout the paper we will refer to them as "a" and "b". For example, the first fairlead connection of the first line will be referred to as "Fairlead1a". The mooring system design presented here is a preliminary design and is not verified against ultimate and fatigue limit state loads.

Table 3. WindCrete mooring system's fairlead and anchors positions

| Line | Anchor coordinates [m] | Fairlead coordinates [m] |
|------|-------------------------|--------------------------|
|      | X  Y  Z                 | X  Y  Z                  |
| 1    | -600 0.0 -200          | -4.65 8.05 -90.0        |
|      |                         | -4.65 -8.05 -90.0       |
| 2    | 300 -519.61 -200       | -4.65 -8.05 -90.0       |
|      |                         | 9.3 0.0 -90.0           |
| 3    | 300 519.61 -200        | 9.3 0.0 -90.0           |
|      |                         | -4.65 8.05 -90.0        |

2.2. Activefloat

Activefloat is a semi-submersible floating structure, designed by Cobra and Esteyco in COREWIND project. It has three external vertical columns which form an equilateral triangle and are connected to the tower in the center by pontoons. Heave plates are added at the bottom of each of the vertical columns to increase the vertical damping. In this work the floater has an active ballast system which means that water is exchanged between the columns by pumps in order to keep the mean pitch at zero. The tower is a conical steel tower with hub height of
135m. Further details on the Activefloat design concept and its hydrodynamic and hydrostatic properties can be found in [11].

A symmetric catenary three lines mooring system is attached to Activefloat for station keeping. The unstretched length of each line is 614 m and the mass per length is 561.3 kg/m. The axial stiffness is 2.304E+09N, and the lines anchor radius is 557.5m. The fairlead and anchor positions are shown in Table 4. The Activefloat mooring system design presented here is a preliminary design and is not verified against ultimate and fatigue limit state loads.

### Table 4. Activefloat’s mooring system

| Line | Anchor coordinates [m] | Fairlead coordinates [m] |
|------|------------------------|--------------------------|
|      | X         Y     Z     | X      Y      Z         |          |
| 1    | -600      0.0    -200 | -42.5  0.0    -15       |
| 2    | 300       -519.6152 -200 | 21.25  -36.806 -15      |
| 3    | 300       519.6152  -200 | 21.25  36.806  -15      |

### 3. The Coupling Process

SIMPACK has a co-simulation interface which allows it to be coupled with standalone codes through MATLAB Simulink [16], this co-simulation mode is known as SIMAT. In SIMAT, the FOWT model created in SIMPACK is exported to Simulink as an S-function, where the inputs, outputs and coupling time step of the S-function are defined inside the SIMPACK model. On the other hand, MoorDyn can be used within simulink as introduced in [17]. The MoorDyn simulink block requires the process time, the coupling time step, and the platform’s position and velocity at each time step as inputs. The outputs of the MoorDyn simulink block is a force vector \( \mathbf{F} = [F_x \ F_y \ F_z \ M_x \ M_y \ M_z]^T \) in the six Degrees Of Freedom (DOFs) of the floater [6].

In our coupling routine, the SIMPACK S-function is created with the simulation time, the platform position, and its velocity, as output signals. These signals are used as inputs for the MoorDyn simulink block at every time step. MoorDyn uses these inputs to calculate the dynamic response of the mooring system at every time step, and send the force vector \( \mathbf{F} \) back to SIMPACK’s S-function. The force vector is applied to the floating platform at mean sea water level in order to include the dynamic effect of the mooring system on the FOWT model. Moreover, the fairlead tensions and the anchor tensions are calculated within Moordyn and sent to the S-function. The co-simulation interface is illustrated in Figure 1, the block on the left side represents the SIMPACK’s S-function, and on the right side the MoorDyn block in Simulink.

### 4. Load cases

To verify the coupling procedure the load cases presented in Table 5 are chosen. All the load cases are simulated in OpenFAST and SIMPACK for both FOWTs and the results are compared. First, the natural frequencies of the floaters in the six DOFs are calculated using free decay tests. Then, the response of the floaters to irregular waves, with different significant wave height \( H_s \) and wave peak periods \( T_P \), in the absence of wind and with idling rotor are compared. Dynamic wind and wave simulation are done with Extreme Turbulence Model (ETM) wind fields at rated wind speed and Normal Sea State (NSS). The environmental conditions used for the latter load case represent the Gran Canaria site introduced in [9]. Irregular waves are generated using the Pierson-Moskowitz spectrum, and the turbulent wind fields are created following the International Electrotechnical Commission (IEC) standard 61400-3-1[18] for offshore wind turbines. The second order wave loads are not included in the simulations done during the verification process.
Simulation time, floater position and velocity

Mooring system’s force vector (\( \mathbf{F} \))

Figure 1. Structure of the coupling process

For all load cases, the wind and waves are aligned and coming from the upwind direction with zero degrees relative to the x-axis, with no nacelle yaw misalignment.

Table 5. Load cases used for model verification

| Description           | Duration [s] | Wind [m/s] | Wave          |
|-----------------------|--------------|------------|---------------|
| Surge decay           | 1500         | -          | -             |
| Sway decay            |              |            |               |
| Heave decay           |              |            |               |
| Roll decay            |              |            |               |
| Pitch decay           |              |            |               |
| Yaw decay             |              |            |               |
| Irregular waves       | 1500         | -          | \( H_s = 2m, \ T_p = 6s \)  
                        |              |            | \( H_s = 5m, \ T_p = 6s \)  
                        |              |            | \( H_s = 10m, \ T_p = 6s \)  
                        |              |            | \( H_s = 2m, \ T_p = 10s \)  
                        |              |            | \( H_s = 5m, \ T_p = 10s \)  
                        |              |            | \( H_s = 10m, \ T_p = 10s \)  
| ETM wind and NSS      | 5400         | 10.5       | \( H_s = 2m, \ T_p = 6s \)  
                        |              | 16         |               |

5. Verification of the Activefloat and WindCrete models

In this paper, when we compare the OpenFAST and SIMPACK results, we focus on the platforms’ motion responses as well as the mooring lines fairlead tensions values. The Mean Absolute Error (MAE), and the Root Mean Square (RMS) error are used to compare the time series of outputs of OpenFAST and SIMPACK simulations. The RMS error and MAE are introduced in equations 1, and 2 respectively, where \( x_1 \) is the OpenFAST time series, \( x_2 \) is the SIMPACK time series and \( n \) is the number of simulation points.

\[
RMS\ error = \sqrt{\frac{\sum_{i=1}^{n}(x_1 - x_2)^2}{n}}
\]  

(1)
\[ MAE = \frac{\sum_{i=1}^{n} |x_1 - x_2|}{n} \]  

(2)

5.1. Decay Tests

Free decay tests are carried out to verify the SIMPACK-MoorDyn model response. The system is excited in each DOF of the platform separately and left to oscillate freely. The natural frequencies (NFs) for the SIMPACK-MoorDyn and the OpenFAST models are identical for all DOFs, and can be seen in Table 6. The RMS error, and the MAE show that the difference between the time series response is small and can be neglected for all DOFs except for sway and yaw DOFs response for Activefloat. We had a closer look at the sway response in Figure 3. The response shows that fairlead1 tension time series is different in SIMPACK than OpenFAST. We currently suggest it comes from the differences between MoorDyn standalone version and the version coupled to OpenFAST. However, the difference in the fairlead tensions does not affect the mean equilibrium position of the floater, or its natural frequency in sway DOF. This is because both fairlead tensions have equal mean values.

**Table 6. Decay tests results**

| DOF     | Floater   | NF [Hz] | RMS error [m] | MAE [m] |
|---------|-----------|---------|---------------|---------|
| Surge   | Activefloat | 0.0061  | 0.0849        | 0.0626  |
|         | WindCrete  | 0.0122  | 0.0780        | 0.0597  |
| Sway    | Activefloat | 0.0061  | 0.2692        | 0.2229  |
|         | WindCrete  | 0.0122  | 0.0716        | 0.0589  |
| Heave   | Activefloat | 0.0549  | 0.0013        | 0.0012  |
|         | WindCrete  | 0.0305  | 0.0732        | 0.0599  |
| Roll    | Activefloat | 0.0122  | 0.0907        | 0.0459  |
|         | WindCrete  | 0.0244  | 0.0366        | 0.0317  |
| Pitch   | Activefloat | 0.0305  | 0.0052        | 0.0038  |
|         | WindCrete  | 0.0244  | 0.0555        | 0.0464  |
| Yaw     | Activefloat | 0.0122  | 0.2299        | 0.2011  |
|         | WindCrete  | 0.0916  | 0.0412        | 0.0200  |

**Figure 2.** WindCrete surge decay (surge motion left side and fairlead1a tension right side)

The WindCrete surge decay time series is shown in Figure 2, the left side represents the time series of the surge DOF, and the right side represents the Fairlead1a tension. The surge
Figure 3. Activefloat sway decay (sway motion left side and fairlead1 tension right side)

decay includes not only one harmonic, but a superposition of multiple frequencies because it is measured at the mean sea level and not at the center of gravity (CG) of the FOWT system.

5.2. Irregular waves
Irregular waves with \( H_s = [2, 5, 10] \) m and \( T_p = 6 \) s, and \( H_s = [2, 5, 10] \) m and \( T_p = 10 \) s are simulated to verify the SIMPACK-MoorDyn model response against irregular waves in the absence of wind. The simulations were done for a duration of 1500s, and the RMS error and MAE are shown in Table 7. The surge, heave, and pitch DOFs are used as example because they are the DOFs with the biggest excitations when the wave heading is zero. The RMS error as well as the MAE values are very small and both models are behaving similarly. The time series of WindCrete and Activefloat for the pitch heave and surge as well as the fairlead tensions of the mooring lines can be seen in Figures 4, and 5 respectively.

Figure 4. WindCrete response to irregular waves \( (H_s=10 \text{m}, T_p=6 \text{s}) \) in absence of wind
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5.3. Operation at ETM wind and NSS
The response of the SIMPACK-MoorDyn model in an ETM wind field, and NSS is verified against the OpenFAST model. The response of the model is checked below rated wind speed (8m/s), at rated wind speed (10.5m/s), and above rated wind speed (16m/s). In this load case, the simulations are done for 5400s and the first 1800s are cut out to remove the transient effects. The RMS error as well as the MAE between the models are shown in Table 8. Figures 6, and 7, show the time series response of the platforms in surge, heave and pitch as well as their fairlead tensions at rated wind speed.

The error values (Table 8) show that the models behave similarly except for surge and pitch DOFs of the WindCrete platform. The reason of this difference is not relevant to the SIMPACK-MoorDyn coupling, it is due to the difference in blade pitch angles in the two models. This is explained in Figure A1 shown in the appendix. The difference in pitch leads to a difference in thrust and hence a difference in the horizontal force in the x-direction leading to a difference in surge response, and a difference in the moment around the y-axis leading to a difference in the platform pitch response. This difference in blade pitch does not happen for Activefloat

Table 7. Irregular waves results

| Hs [m] | Tp [s] | Activefloat | WindCrete |
|--------|--------|-------------|-----------|
|        | Surge [m] | Heave [m] | Pitch [deg] | Surge [m] | Heave [m] | Pitch [deg] |
|        | RMS error | MAE | RMS error | MAE | RMS error | MAE | RMS error | MAE | RMS error | MAE | RMS error | MAE |
| 2 | 0.025 | 0.020 | 0.003 | 0.001 | 0.006 | 0.003 | 0.058 | 0.048 | 0.013 | 0.011 | 0.025 | 0.021 |
| 5 | 0.011 | 0.009 | 0.003 | 0.002 | 0.002 | 0.001 | 0.084 | 0.068 | 0.013 | 0.011 | 0.028 | 0.025 |
| 10 | 0.016 | 0.010 | 0.042 | 0.002 | 0.004 | 0.002 | 0.065 | 0.051 | 0.011 | 0.010 | 0.024 | 0.021 |
| 2 | 0.038 | 0.033 | 0.009 | 0.002 | 0.003 | 0.003 | 0.123 | 0.103 | 0.014 | 0.012 | 0.038 | 0.034 |
| 5 | 0.023 | 0.017 | 0.007 | 0.002 | 0.003 | 0.002 | 0.079 | 0.062 | 0.012 | 0.010 | 0.035 | 0.031 |
| 10 | 0.021 | 0.013 | 0.002 | 0.001 | 0.006 | 0.004 | 0.090 | 0.076 | 0.012 | 0.010 | 0.058 | 0.051 |

Figure 5. Activefloat response to irregular waves \((H_s=10\text{m}, \ T_p=6\text{s})\) in absence of wind

Table 7. Irregular waves results
simulations as shown in Figure A2 in the appendix. The difference in blade pitch is out of the scope of this work.

| Vw  | Activefloat | WindCrete |
|-----|-------------|-----------|
|     | Surge [m] | Heave [m] | Pitch [deg] | Surge [m] | Heave [m] | Pitch [deg] |
| RMS error | MAE RMS error | MAE | RMS error | MAE RMS error | MAE | RMS error | MAE RMS error | MAE |
| 8    | 0.133 0.102 | 0.002 0.002 | 0.059 0.046 | 0.456 0.170 | 0.070 0.045 | 0.182 0.052 |
| 10.5 | 0.142 0.110 | 0.002 0.002 | 0.142 0.086 | 0.155 0.119 | 0.039 0.030 | 0.081 0.060 |
| 16   | 0.142 0.115 | 0.002 0.002 | 0.112 0.088 | 0.130 0.106 | 0.052 0.043 | 0.075 0.062 |

**Figure 6.** WindCrete response to ETM wind and NSS

6. Conclusion
In this work, SIMPACK-MoorDyn coupling was introduced and verified against OpenFAST simulations. The verification was done using the IEA Wind 15MW reference model coupled to WindCrete and Activefloat platforms. The platforms have two different mooring systems configurations to prove the robustness of the SIMPACK-MoorDyn coupling performance at different mooring system designs. Free decay, irregular waves and operation at ETM and NSS were used as load cases during the verification process to check the coupling reliability and performance at different loading forces. Comparing the results with OpenFAST shows that the coupling procedure is credible and SIMPACK-MoorDyn provides similar results to OpenFAST. This model is now available and open access at [19] to be used by the research community. SIMPACK-MoorDyn coupling will be used in future work to model innovations in floating wind energy such as modelling light weight floaters as flexible beam elements, and modelling tuned liquid dampers for floating platforms.
Figure 7. Activefloat response to ETM wind and NSS

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Appendix

Figure A1. WindCrete response at ETM and NSS at wind speed of 8m/s
Figure A2. Activefloat response at ETM and NSS at wind speed of 8m/s
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