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EOLIEN FLOTTANT : APPROCHE SIMPLIFIÉE DU COUPLAGE AERO-HYDRODYNAMIQUE EN VUE D'OPTIMISER LA CONCEPTION DU FLOTTEUR

FLOATING OFFSHORE WIND: SIMPLIFIED APPROACH OF AERO-HYDRO COUPLING TO OPTIMIZE THE DESIGN OF THE FLOATING SUPPORT STRUCTURE

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Résumé

De nombreux paramètres interviennent dans la conception d'une éolienne offshore flottante : la modélisation du vent, les chargements aérodynamiques, la résistance structurelle, le système de contrôle, les chargements hydrodynamiques ainsi que les caractéristiques du système d'ancrage doivent être pris en compte. Des outils de simulation complets tels que FAST ou Bladed répondent aujourd'hui à ces problématiques et permettent de mieux comprendre le comportement réel d'une éolienne flottante, mais leur durée de calcul couplée au nombre de simulations prévues dans les standards éoliens est fortement pénalisante dans les processus d'optimisation. L'objectif de l'étude présentée est de proposer une approche simplifiée et rapide de la modélisation d'une éolienne flottante, basée sur une force de poussée intégrée et le calcul d'un vent équivalent.

Summary

The design of a Floating Offshore Wind Turbine involves many different aspects: wind modelling, aerodynamic loadings, structural resistance, control process, hydrodynamic loading and mooring properties. In particular, the coupling effect between aerodynamic and hydrodynamic loads has to be taken into account in the design of FOWT support structure. Today, comprehensive tools such as FAST or Bladed have emerged to help understand the true behaviour of a FOWT in presence of waves and wind conditions. However, the modelling of aerodynamic loads (based on BEM and GDW theories) leads to highly time-consuming simulations. The aim of this study is then to develop a simplified coupled model with an integrated thrust depending on the wind condition and on the controller process to allow an efficient optimisation of the platform design process.

I – Introduction

While the offshore wind turbine market is growing, the wind farm projects are moving towards deeper waters further away from the coast, where the wind is stronger and where the possible concerns about natural landscape disappear. However, such a change can happen only with a new type of support platform for the wind turbines, more economical in deep water than the bottom-fixed turbines: the floating turbines. This new design is becoming today a commercial reality: the floating offshore wind industry is moving away from proof-of-concept single turbine deployment to precommercial pilot projects. In order to reach this objective, technical studies increasingly detailed are produced by various companies and research laboratories around the world.

The design of a Floating Offshore Wind Turbine (FOWT) involves many different aspects: wind modelling, aerodynamic loadings, structural resistance, turbine control process, hydrodynamic loadings and mooring behaviour. Because of the floating platform degrees of freedom and the turbine controller system, an aero-hydro coupling effect prevents the designer to study them separately [4]. To ensure a good optimisation and a realistic modelling, the floating wind turbine has to be analysed as a whole.

Comprehensive tools such as FAST or Bladed software have emerged to help understand the real behaviour of a FOWT in presence of waves and wind conditions. However, the modelling of aerodynamic loads (based on BEM and GDW theories) leads to highly time-consuming simulations. This is a real issue regarding the industrial design of a FOWT sub-structure: indeed, the design load case matrix may request more than 2,000 cases to be checked. The optimization process of the floating turbine platform design is then seriously limited. This is where the simplified model approach can be of great help.

The aim of this paper is to present a methodology based on a simplified coupled model which depends on the wind conditions, allowing an efficient optimisation of the platform design process. The study has been carried out for a semisubmersible concept developed by DORIS Engineering. The simplified model is based on an integrated calculation of the thrust force [1] and a major improvement is also proposed: the calculation of an equivalent wind speed at hub which allows to compute the full field wind speed.

II – Methodology

II – 1. Principles

The simplified approach is based on an idea developed in [1]. The thrust, instead of being calculated with a complex Blade Element Momentum theory, is computed as a uniform force on all the rotor disk. The formulation of this integrated thrust is detailed in section II. 4.4. “Aerodynamic Modelling” below.

Two different simplified models of the full turbine have been developed:

0. A basic simplified model, defined in [1], with an integrated thrust depending on the relative wind speed,
1. An improved simplified model with an equivalent wind calculation to represent more accurately the 2D wind speed fields.

To assess the capabilities and accuracy of such an approach, a fully coupled FAST-OrcaFlex solution has been developed as a reference model. A code-to-code comparison has been done between the fully coupled model and the two simplified models for two different sets of load cases:

- A first set of load cases issued from [1] to ensure that the basic simplified approach is in line with the reference article,
- A second set of load cases issued from the IEC 61400-3 standard requirement to assess more globally the capabilities of the simplified approach.

II – 2. System Description

This study is based on a FOWT composed of the National Renewable Energy Laboratory (NREL) 5-MW baseline wind turbine and of a floater designed by DORIS Engineering. Its general properties are detailed in the following subsections. A general arrangement is shown on the following figure.

Property	Unit	Value
Displacement	t	4 510
Operating Draft	m	10.9
Heave Period	s	10.6
Pitch Period	s	18.2
Roll Period	s	17.6

Table 1 – Global properties of DORIS calibrated platform

Figure 1 – DORIS Engineering's FOWT concept

The floater developed by DORIS Engineering consists of a semi-submersible platform concept: it is a buoyancy stabilised platform which floats semi-submerged on the surface of the water whilst anchored to the seabed with mooring. The design comprises a hull with three columns: the largest one supports the turbine and the two smallest ones improve the stability of the structure. A static ballast is used to achieve the desired static equilibrium and each column has at its base a heave plate in order to provide a better dynamic stability. The eccentricity of the turbine provides several advantages. First, the absence of a central support, which does not have a negative impact on the global stability while providing significant savings on material quantities. The simplification of the installation is another positive aspect to be mentioned. The diameter difference between the three columns also provides some interesting benefits. The amount of steel is minimised for a constant hydrostatic stiffness. In addition, this arrangement decreases the distance between the global centre of mass and the centre of buoyancy, which helps to reduce the amount of static ballast needed for the static equilibrium.

The semi-submersible platform is anchored to the seabed with mooring. The present study considers a 50-meter water depth. A basin test campaign has been performed by Oceanide to validate the concept. A view of the basin test prototype is shown on Figure 3. The tank tests have been used to calibrate the hydrodynamic model used in this study.

The turbine considered in the numerical model is based on the specification of the NREL offshore 5-MW baseline wind turbine, which is a representative utility-scale, multimegawatt turbine. The detailed description of this turbine can be found in [2]. The tower properties are based on the OC4 tower description detailed in 13[3]. The tower used in the present work is slightly different though since the draft of DORIS concept is slightly different from the OC4 platform.

The NREL 5-MW wind turbine uses a conventional variable-speed, variable blade-pitch-to-feather control system. Modifications have been made to the original control system of the NREL 5-MW turbine for the OC3-Hywind project to resolve an issue of negative damping. These modifications include a reduction of gains in the blade-pitch-to-feather control system and a change in the generator torque control strategy when operating at rated power. The FAST-OrcaFlex model considered in this study includes this OC3-Hywind control system. More details can be found in [3].

II – 3. Software Description

The FAST (Fatigue, Aerodynamics, Structures and Turbulence) Code is a NREL open source program used by academics and in industry for modelling wind turbines. It is a comprehensive aero-elastic simulator capable of predicting both the extreme and fatigue loads for the most common wind turbine configurations and control scenarios. OrcaFlex is a time-domain, finite-element commercial software capable of modelling a wide range of marine systems, such as vessels, moorings or riser systems. This software is developed by Orcina and can be used to study the static or dynamic coupled behaviour of a surface vessel and its moorings. Unlike FAST, OrcaFlex has the advantage to offer an easy-to-use graphical interface, making the visualisation of the results much easier.

FAST offers several possibilities to model floating offshore wind turbines. HydroDyn and MoorDyn modules have been developed in order to integrate floating turbines in FAST. Another approach is to use the commercial software package OrcaFlex. A special DLL (FASTlinkDLL.dll) compiled by Orcina allows coupled simulation between FAST and Orcaflex. In the present work, all hydrodynamic and mooring loads are computed using OrcaFlex, while the turbine, tower, and floating platform structural dynamics, aerodynamics, and control and electrical-drive dynamics are computed by FAST. The coupling between FAST and OrcaFlex is ideal: FAST has many sophisticated features for modelling the aerodynamics, turbine structure and controller; the hydrodynamic module currently employs a simplistic quasi-static cable model to calculate the mooring forces of an FOWT. On the other hand, OrcaFlex can model a dynamic cable and its coupled behaviour with a surface vessel. OrcaFlex GUI also allows an easy management of platform hydrodynamic properties, cable configuration, as well as adequate visualisation of the simulation results.

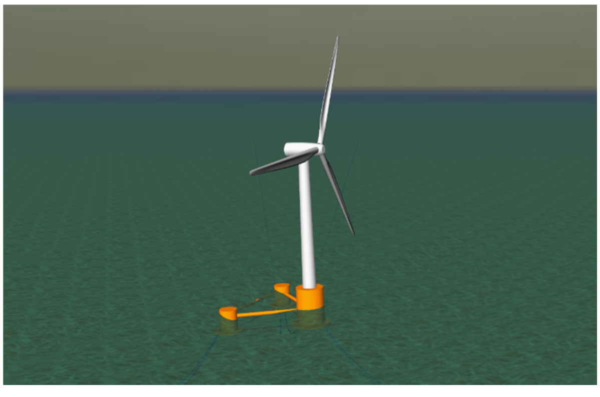


Figure 2 - Floating wind turbine modelling in OrcaFlex

The FAST-OrcaFlex combination has been verified in-house against the public results of the OC4 project. The results have proven that a FAST-OrcaFlex model provides a good representation of the floating wind turbine behaviour and can be used as a reference model to assess the results of the simplified model.

II – 4 Modelling

II – 4.1. Structural Modelling

The easiest way to model a floating offshore wind turbine is to consider it as a simple rigid body. However, this method is questionable: the tower and the blades of the wind turbine have a slender structure, and their deflections have a significant effect on the system dynamics. The drive shaft can also be considered as a flexible part of the turbine. To improve the structural model, the FOWT has then to be considered as a multibody system (MBS): a group of interconnected rigid or flexible bodies, which may undergo large displacements and rotations. It is for instance possible to enable several degrees of freedom in FAST in order to model the turbine flexibility.

Meanwhile, while the fully coupled model is supposed to provide detailed information about the system and can be used for instance to check the integrity of the turbine, the simplified model only aims at calculating the platform motions to design the mooring system and the structural hull. The FOWT is then modelled as a simple rigid body in the simplified approach.

II – 4.2. Hydrodynamics

The hydrodynamic properties are defined in the OrcaFlex file and therefore are identical for both the fully coupled FAST-OrcaFlex model and the simplified model. A hybrid numerical model has been built to allow the calibration based on the tank test results. This model is composed of a panel model for all the columns to account for potential forces (Froude-Krylov, diffraction and radiations forces), and a Morison model to account for viscous forces at skirt locations and on the columns which may be of equal importance as potential forces. The braces between the columns are not taken into account in the hydrodynamic model.

Figure 3 – DORIS FOWT concept - Experimental model in test basin

The hydrodynamics database (load RAOs, added masses and radiation damping matrices, hydrostatic matrix, QTFs) from the panel model has been imported from a WAMIT analysis. The

Morison elements have been created in Orcaflex and calibrated based on the results of the basin test campaign.

II – 4.3. Mooring System

As for the hydrodynamics, the mooring system is defined in the OrcaFlex file and therefore is identical for both the fully coupled FAST-OrcaFlex model and the simplified model. The mooring system is represented as 3 horizontal springs with linear stiffness properties. A more detailed modelling with dynamic effects is possible with OrcaFlex, however it was not needed for this study.

II – 4.4. Aerodynamics

Aerodynamics modelling is the key subject of this code-to-code comparison work. In the fully coupled FAST-OrcaFlex model, the aerodynamic loads are calculated with the Blade Element Momentum (BEM) theory. The instantaneous position of elements, the relative wind speed and the blade shape definition are used at each step of time to compute the resulting drag and lift loads. This approach enables to consider the unsteady aero-elastic features such as the dynamic inflow and the dynamic response of the blades. The aerodynamic loads on the tower are neglected [1].

In the simplified model, the objective is to model the global response of the system. If we assume that the unsteady aero-elastic dynamic loads have a limited effect on the global motions, the aerodynamic loads can be simplified: the torque is neglected and the thrust is directly integrated on the rotor disk and applied as a unique force at the turbine hub [1]. For each time step, the thrust is then calculated as a function of the relative wind speed. This function is presented on the following figure and is dependent on the turbine specificities. The curve has been calculated using the FAST-OrcaFlex model to compute the thrust for different steady winds. This definition directly takes into account the spatial variation of the mean wind speed. The gyroscopic moment, depending on the platform pitch angular velocity, has also been considered.

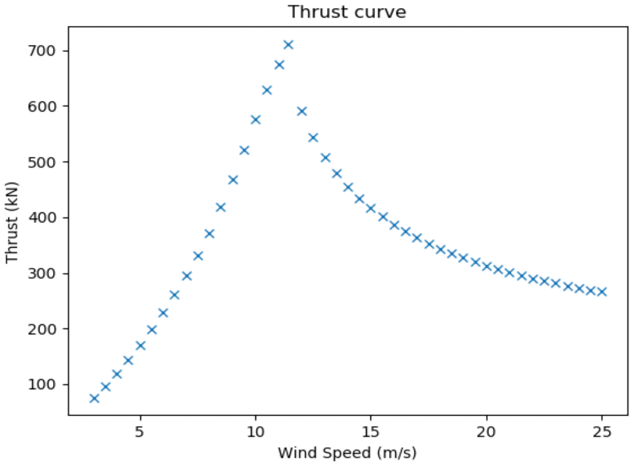


Figure 4 – Thrust curve for the NREL 5MW turbine

II – 4.5. Controller System

The fully coupled FAST-OrcaFlex model uses the Bladed-style DLL controller developed by the NREL for the OC3 project. It is based on an onshore turbine-type PID controller tuned for offshore wind turbines to avoid a negative damping effect when the wind speed is above rated.

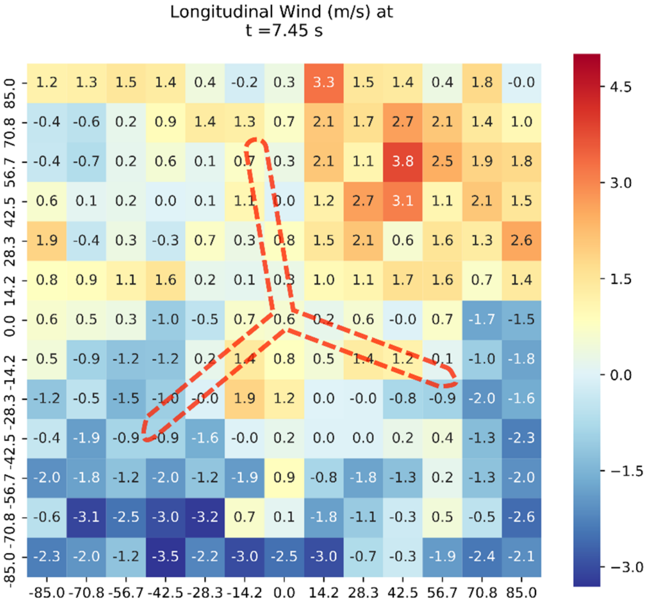
In the simplified model, the thrust definition does consider the controller strategy: the thrust is decreasing for wind speed above the rated speed as the blade pitch controller reacts. However, to avoid dynamic effects such as the negative damping issue, a filter system has been implemented to remove the platform pitch natural frequency of the relative wind speed.

II – 4.6. Wind Modelling

The fully coupled FAST-OrcaFlex model can be used with a 3-dimensional turbulent wind field that covers the entire rotor plane. The vertical wind shear is also included. However the simplified model can only use one wind time series at the hub position. In order to model the complete wind field encountered by the rotor by a single wind time series, a pre-processing is done to convert the turbulent wind field in an equivalent wind speed as defined in [5]. The idea is to express an equivalent wind speed as the mean of the contribution from the three blades:

$$v_{eq}(t,\theta) = \frac{1}{3(R-r_0)} \sum_{n=1}^{3} \int_{r_0}^{R} v(t,r,\theta_n)\, dr$$

Where v_{eq} is the equivalent wind speed, θ is the blade azimuth, R is the rotor radius, r_0 is the blade root radius and $v(t,r,\theta_n)$ is the 3-dimensional turbulent wind field. With this definition, the equivalent wind speed is calculated for each time, assuming that the rotor has a constant angular speed consistent with the mean wind speed. Figure 5 - Turbulent wind speed in the rotor plane (m/s)Figure 5 represents the rotor plane with the turbulent wind field. This wind modelling aims at improving the modelling of the spatial turbulence variations.



	-85.0	-70.8	-56.7	-42.5	-28.3	-14.2	0.0	14.2	28.3	42.5	56.7	70.8	85.0
85.0	1.2	1.3	1.5	1.4	0.4	-0.2	0.3	3.3	1.5	1.4	0.4	1.8	-0.0
70.8	-0.4	-0.6	0.2	0.9	1.4	1.3	0.7	2.1	1.7	2.7	2.1	1.4	1.0
56.7	-0.4	-0.7	0.2	0.6	0.1	0.7	0.3	2.1	1.1	3.8	2.5	1.9	1.8
42.5	0.6	0.1	0.2	0.0	0.1	1.1	0.0	1.2	2.7	3.1	1.1	2.1	1.5
28.3	1.9	-0.4	0.3	-0.3	0.7	0.3	0.8	1.5	2.1	0.6	1.6	1.3	2.6
14.2	0.8	0.9	1.1	1.6	0.2	0.1	0.3	1.0	1.1	1.7	1.6	0.7	1.4
0.0	0.6	0.5	0.3	-1.0	-0.5	0.7	0.6	0.2	0.6	-0.0	0.7	-1.7	-1.5
-14.2	0.5	-0.9	-1.2	-1.2	0.2	1.4	0.8	0.5	1.4	1.2	0.1	-1.0	-1.8
-28.3	-1.2	-0.5	-1.5	-1.0	-0.0	1.9	1.2	0.0	-0.0	-0.8	-0.9	-2.0	-1.6
-42.5	-0.4	-1.9	-0.9	-0.9	-1.6	-0.0	0.2	0.0	0.0	0.2	0.4	-1.3	-2.3
-56.7	-2.0	-1.8	-1.2	-2.0	-1.2	-1.9	0.9	-0.8	-1.8	-1.3	0.2	-1.3	-2.0
-70.8	-0.6	-3.1	-2.5	-3.0	-3.2	0.7	0.1	-1.8	-1.1	-0.3	0.5	-0.5	-2.6
-85.0	-2.3	-2.0	-1.2	-3.5	-2.2	-3.0	-2.5	-3.0	-0.7	-0.3	-1.9	-2.4	-2.1

Figure 5 - Turbulent wind speed in the rotor plane (m/s)

III – Results

III – 1. Comparison with the reference article [1] (Karimirad (2012))

The first step to verify the validity of the simplified model was to compare the results with the reference article [1]. Eight load cases (four load cases with steady winds and four load cases with turbulent winds) have been run with the fully coupled FAST-OrcaFlex model and the simplified model. All the wave time series have been generated with a JONSWAP spectrum and a gamma coefficient of 1. The duration of 4,600 seconds has been chosen to study a 1-hour sea state taking into account a 1,000 seconds transient. The load cases are detailed in the Table 2.

N°	Name DLC	Type of Wind	Wind speed at hub (m/s)	H_s (m)	T_p (s)
1	Uniform_8	Uniform	8	2.5	9.8
2	Uniform_11.4	Uniform	11.4	3.0	10.0
3	Uniform_14	Uniform	14	3.6	10.2
4	Uniform_17	Uniform	17	4.2	10.5
5	NTM_8	NTM	8	2.5	9.8
6	NTM_11.4	NTM	11.4	3.0	10.0
7	NTM_14	NTM	14	3.6	10.2
8	NTM_17	NTM	17	4.2	10.5

Table 2 - Load cases extracted from [1]

The four steady wind load cases show a very good agreement between the fully coupled FAST-OrcaFlex model and the simplified model. A difference can be observed for the rated wind speed (11.4 m/s) which is due to the control system inertia in the fully coupled model: the thrust can exceed the theoretical maximum value. This is actually not allowed in the simplified model due to the thrust representation.

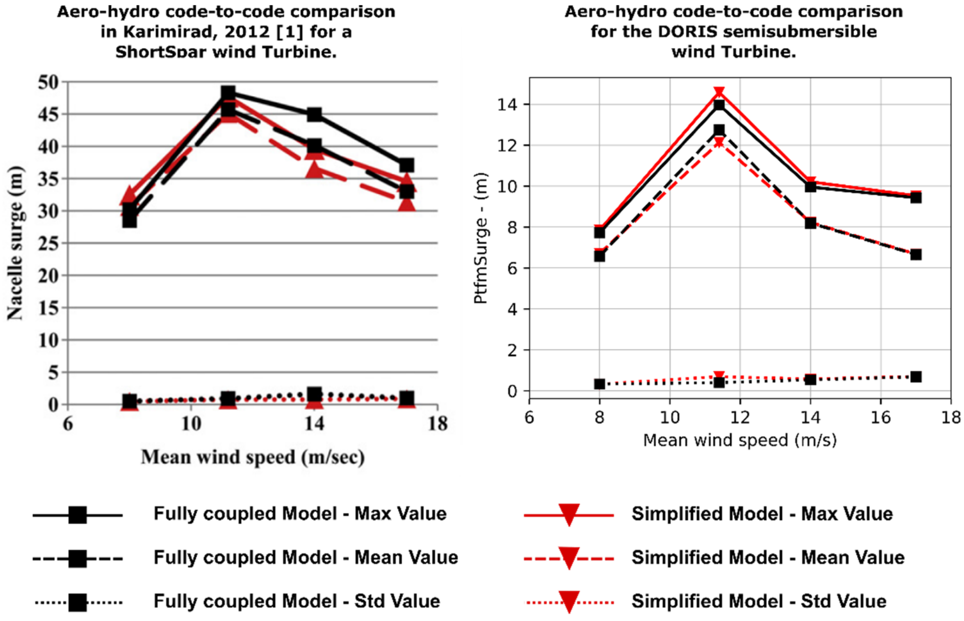


Figure 6 – Aero-hydro code-to-code comparison between the fully coupled model and the simplified model for steady winds

The turbulent wind load cases show a good agreement as well between the fully coupled FAST-OrcaFlex model and the simplified model. The same difference as previously mentioned can be observed for the maximum platform surge value at the rated wind speed (11.4 m/s).

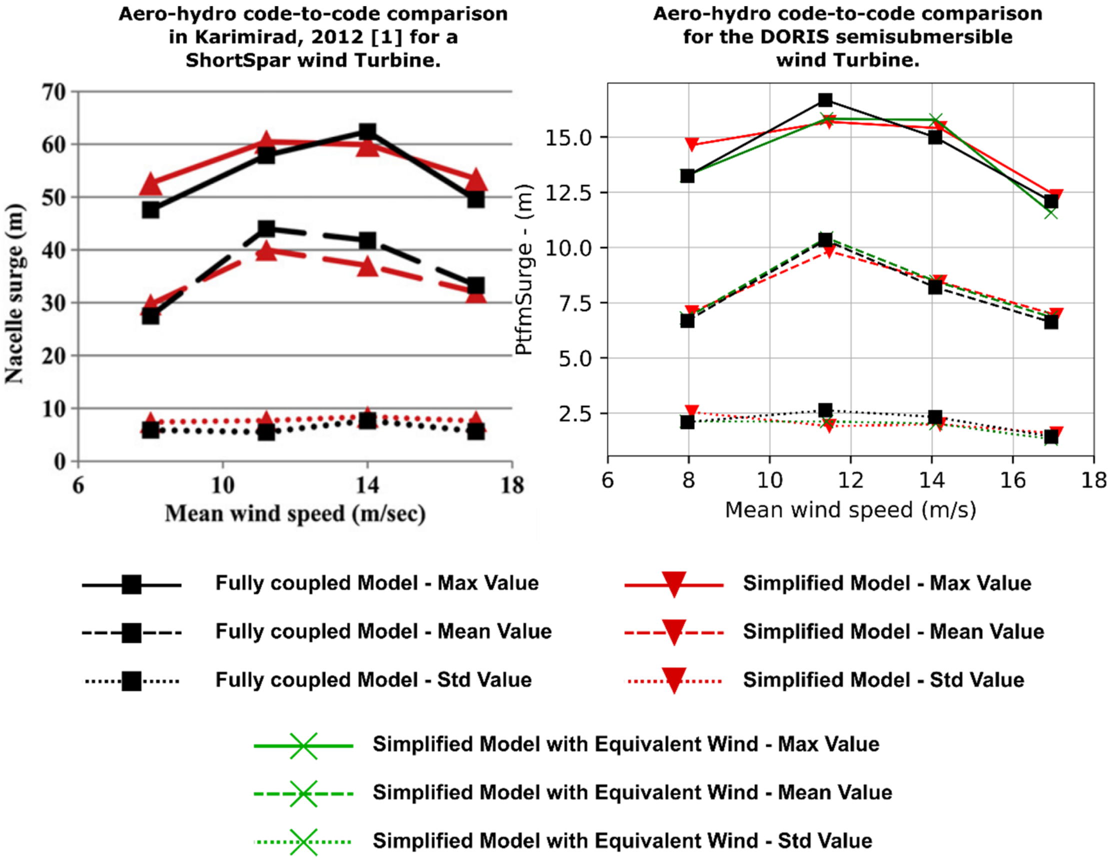


Figure 7 - Aero-hydro code-to-code comparison between the fully coupled model and the simplified model for turbulent winds

Even if the platform pitch is not presented in the article [1], it is also worth looking at this motion: leaving aside the difference at 11.4 m/s, the simplified model with the equivalent wind shows a very good agreement for the mean value. The difference observed for a wind speed of 14 m/s between the simplified model with an equivalent wind and the fully coupled model in the maximum values can be explained by a smoothing effect in the equivalent wind modelling.

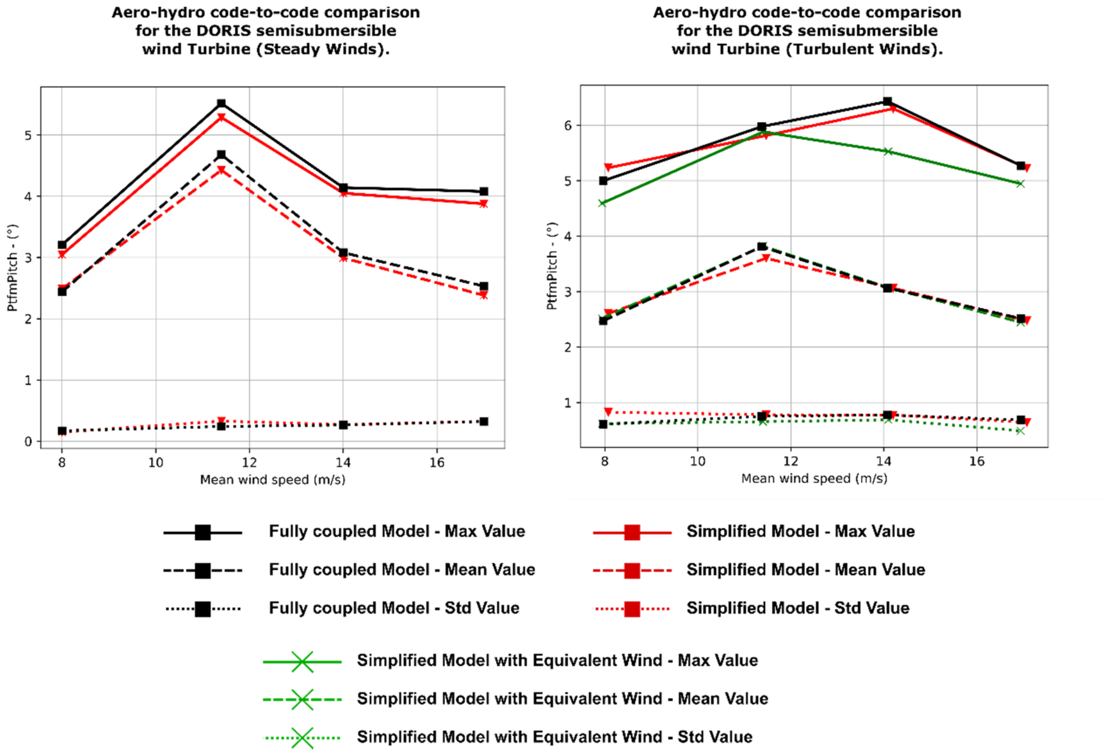


Figure 8 - Aero-hydro code-to-code comparison between the fully coupled model and the simplified model for the platform pitch motion

In order to assess the simplified model capabilities for fatigue studies, a rainflow-counting algorithm has been applied on the previous load cases. The rainflow counting method allows to reduce the spectrum of varying stress into a set of simple stresses, which helps to assess the fatigue life of a structure. The rainflow-counting algorithm has been applied to the tension of the same mooring line for the fully coupled model and the simplified model with and without the equivalent wind. The results, presented on the Figure 9, are very encouraging: the simplified model with the equivalent wind shows a closer agreement with the fully coupled model.

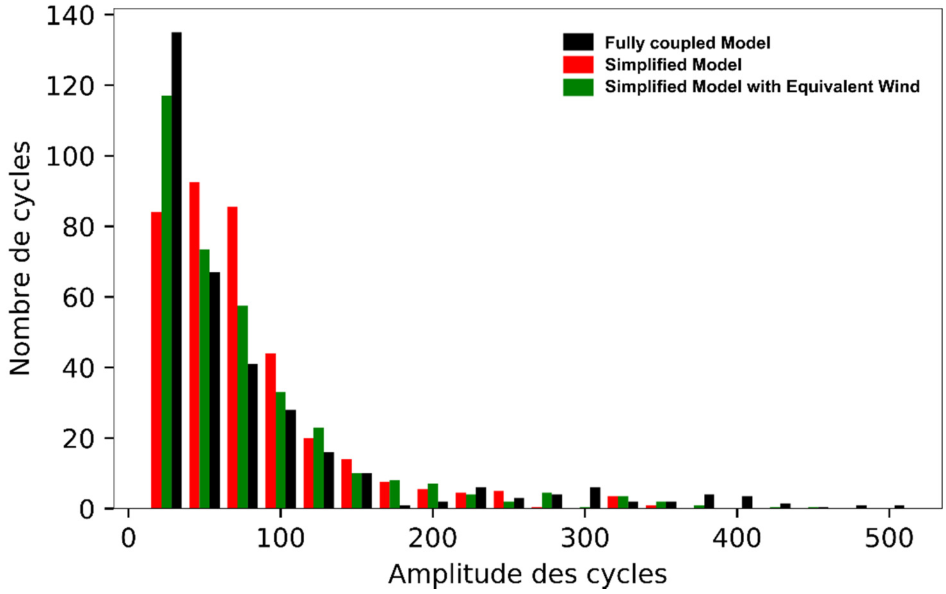


Figure 9 – Rainflow-counting algorithm on a mooring line tension (in kN) for the Load Case 6

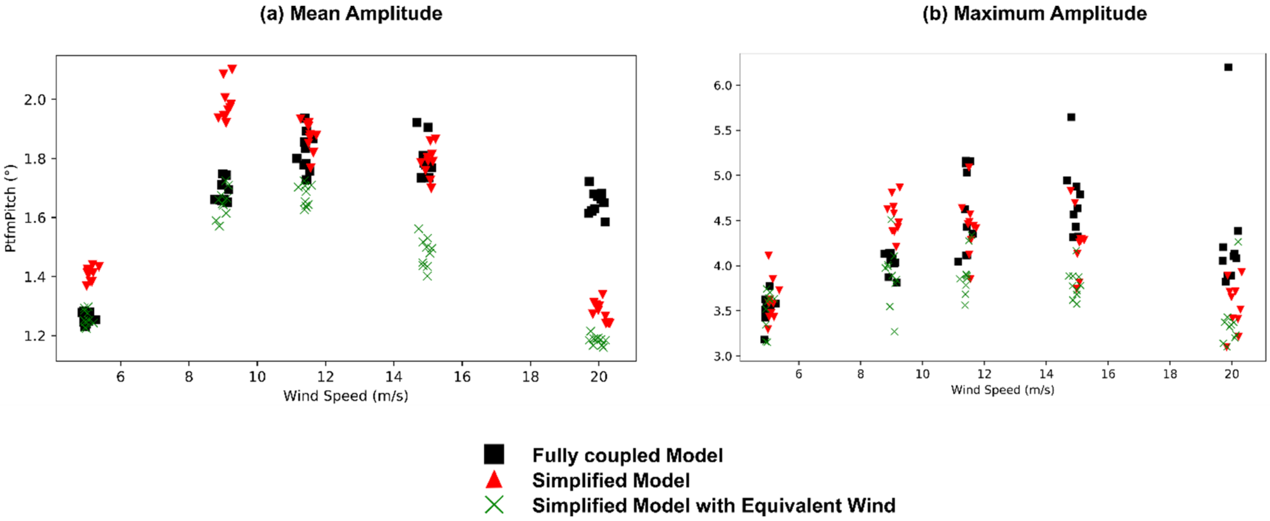
III – 2. Study on a larger set of load cases

In order to confirm the robustness of the previous observations, the calculation of a larger set of 50 load cases has been done with the fully couple FAST-OrcaFlex model and the simplified model, with and without equivalent wind. The wind speed is calculated according to the Normal Turbulence Model and 10 seeds have been considered for each of them. All the wave time series have been generated with a JONSWAP spectrum and a gamma coefficient of 2.87. The duration of 4,600 seconds has been chosen to study a 1-hour sea state taking into account a 1,000 seconds transient. The detailed load cases parameters are presented in the following table.

Name of DLC	Type of Wind	Wind speed (m/s)	Seed	Waves Type	H (m) / Hs (m)	T (s) / Tp (s)	Gamma
NTM_5	NTM	5	10	JONSWAP	6.0	10.0	2.87
NTM_9	NTM	9	10	JONSWAP	6.0	10.0	2.87
NTM_11.4	NTM	11.4	10	JONSWAP	6.0	10.0	2.87
NTM_15	NTM	15	10	JONSWAP	6.0	10.0	2.87
NTM_20	NTM	20	10	JONSWAP	6.0	10.0	2.87

Table 3: Load cases for the more extensive study

The analysis of the results for the large batch of load cases confirms the previous conclusion: the simplified model with the equivalent wind provides a good agreement for the low wind speeds (up to rated wind speed). For the highest wind speeds however, a smoothing effect disturbs the results.


(a) Mean Amplitude

(b) Maximum Amplitude

Figure 10 - Mean Amplitude (a) and Max Amplitude (b) of the platform pitch for each load case

III – 3. Computation time

The following table presents a comparison of the computation time for the fully coupled model and the simplified model. The computation time has been measured for the previous simulations, i.e. for 4,600 seconds of simulation. The simplified model allows to divide by at least four the computation time. An optimisation of the control system filter parameters and of the time step in the simplified model is planned in order to further decrease this computation time.

Model	Steady Wind	Turbulent Wind
FAST-OrcaFlex Fully Coupled Model	40 min	45 min
Simplified Model	6 min	10 min

Table 4 - Computation Time of the fully coupled and the simplified models

IV – Conclusions and perspectives

Two different simplified models have been presented in this work: a first one is based on the reference article [1] and the second one includes an equivalent wind calculation in order to model 2D wind speed fields. The aero-hydro code-to-code comparison has been done on a reduced set of load cases in a first step and then has been assesed on a larger batch to check the robustness of the first conclusions.

The simplified model shows a good agreement with the fully coupled FAST-OrcaFlex model, particularly for fatigue studies. The equivalent wind calculation provides an improvement of the simplified model for the wind speeds below the rated wind speed. For higher wind speeds, a smoothing effect weakens the results.

The next improvement in the development of the simplified model approach will take into account the rotor inertia and should improve the results regarding the high wind speeds. A more precise definition of the thrust function based on the platform acceleration is also under study.

Appendix A: Abbreviations

BEM	Blade Element Momentum
DLC	Design Load Case
FOWT	Floating Offshore Wind Turbine
GDW	General Dynamic Wake
IEC	International Electrotechnical Commission
NREL	National Renewable Energy Laboratory
NTM	Normal Turbulent Model
OC3	Offshore Code Comparison Collaboration
OC4	Offshore Code Comparison Collaboration Continuation

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