Proceedings of the ASME 2019
2nd International Offshore Wind Technical Conference
IOWTC2019
November 3-6, 2019, St. Julian's, Malta

IOWTC2019-7600

SIMULATION OF AN OFFSHORE WIND TURBINE USING A WEAKLY-COMPRESSIBLE CFD SOLVER COUPLED WITH A BLADE ELEMENT TURBINE MODEL

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ABSTRACT

The present study addresses the first steps of development and validation of a coupled CFD-BE (Blade Element) simulation tool dedicated to offshore wind turbine farm modelling. The CFD part is performed using a weakly-compressible solver (WCCH). The turbine is taken into account using FAST (from NREL) and its effects are imposed into the fluid domain through an actuator line model. The first part of this paper is dedicated to the presentation of the WCCH solver and its coupling with the aero-elastic modules from FAST. In a second part, for validation purposes, comparisons between FAST and the WCCH-FAST coupling are presented and discussed. Finally, a discussion on the performances, advantages and limitations of the formulation proposed is provided.

Keywords: Wind Turbine, CFD, Blade Element Method, Actuator-Line, Weakly-Compressible

NOMENCLATURE

D_{rotor}	Diameter of the rotor
D_{hub}	Diameter of the hub
Ω_N	Nominal rotational speed of the rotor
Ω	Rotational speed of the rotor
Fx	Axial force on a blade element
Fy	Tangential force on a blade element
β_1	Pitch angle of blade 1
T_{rot}	Torque of the rotor
P_{gen}	Power generated by the rotor
V_{in}	Inflow wind velocity magnitude
V_N	Rated wind speed of the rotor
$\vec{V}(elem, blade)$	Blade elements sampled wind velocities
MLS	Mean Least Square.

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INTRODUCTION

Wind turbines are currently set up as industrial farms on identified potential sites all over the world. In this configuration, machines interact with each other so a trade-off has to be found between a minimum inter-distance to increase the number of wind turbines on a given area, and a maximum to reduce the costs of production losses due to wake interactions. Recently, global control optimization strategies have been identified as a potential lead in order to further optimize wind farms. It is estimated that the production gain in a configuration impacted by wake interactions could reach 10% [1], i.e. 1 to 1.5% of the annual energy production (AEP) [2]. Dynamic control strategies could also be used to decrease the fatigue effects, therefore lowering the Operational Expenditures (OPEX).

Low fidelity methods are acceptable in the first approach and are suitable for the pre-design phase of a farm project: such methods are known to be fast and able to provide an approximate relative turbine positioning while minimizing the effects of masking (case where the wake of an upstream turbine impacts a turbine downstream). On the other hand, the theoretical models used to represent the turbines can lead to significant errors in the prediction of wakes (low degree of modelling), with coarse on-site resource consideration (currents, swells, turbulence). This makes it difficult to validate farm control strategies due to the presence of errors in the wake prediction and to a lack of consideration of the wake dynamics (often quasi-static models) [1].

An accurate final design tool taking into account a precise physics while remaining quick enough for industry is therefore essential to simulate these interactions in order to validate control strategies.

Previous work has been achieved in this way. For instance, the work of Storey *et al.* [3] uses a coupling between FAST and SnS CFD code which uses a central differencing scheme in space and a Crank-Nicolson scheme in time on a structured mesh. The solver is second-order accurate in space and time.

The work of Fleming et *al.* [4] uses a coupling between FAST and OpenFoam CFD toolbox. It adopts an incompressible LES finite volume approach on an unstructured mesh, with a second order accurate scheme both in space and time.

The CFD solver WCCH used in this study is developed by the LHEEA of Ecole Centrale Nantes (ECN) and uses a weakly-compressible Finite Volume approach applied on a Cartesian grid. The wind turbine is modeled by the NREL's aero-elastic tool FAST. The present work follows the developments undertaken in [5] on tidal turbines where a one-way coupling has been developed, leading to a good agreement with experiments. Here, a two-way coupling is introduced between both solvers, where the forces representing the HAWT are taken into account in the fluid domain through the use of actuator-lines.

METHODS

The Weakly-Compressible Cartesian Hydrodynamic solver (WCCH) is a cell-centered Finite Volume CFD solver based on the compressible Navier-Stokes equations, within an explicit formalism [6]. An originality of this method is the use of a weakly-compressible scheme, able to deal both with incompressible and truly compressible medium. It has originally been developed for hydrodynamic applications such as tidal turbines where a weakly-compressible approach was considered so that the fluid flow that can be considered as incompressible was treated as compressible with a low Mach number ($Ma \leq 0.1$). For wind turbine applications where the Mach number is slightly higher ($Ma \approx 0.2$), and for which compressibility effects could arise when approaching $Ma=0.3$, the use of a compressible solver may be of interest to take into account compressibility effects in the flow. WCCH is capable of considering the fluid as either incompressible or compressible depending on the speed of sound. In this paper a speed of sound of 340 $m.s^{-1}$ is considered.

In order to reduce the CPU time, the solver is built on a parallel framework using a domain decomposition strategy (MPI library), including Adaptative Mesh Refinement (AMR) on a Cartesian grid. The mesh resolution around the turbine is chosen in order to obtain a minimum of 64 cells in the turbine diameter as proposed in [5]. A spatial convergence study proved that increasing the resolution does not bring a sufficient improvement with respect to the related growth in CPU time. A total number of 400000 cells are used on a cubic domain of size $4D_{rotor}$. Only the mesh around the turbine is finely refined as the study focuses on the blade element forces calculated by FAST through the WCCH-FAST coupling. The study of the wake will be the topic of a future paper. The simulations were performed on the Liger cluster of Centrale Nantes (France) up to 240 cores. We do not give details about the CPU performances in this study as we consider this is not the purpose of this work. Indeed, we do not take into account the full-length wake of the wind turbine yet. A full analysis on this aspect will be provided in our next paper.

In the context of multiple wind-turbine applications, the wake advection should be sufficiently accurate to correctly predict the wake-wake and wake-turbine interactions, to allow eventually the optimization of a given farm. A preliminary work on the improvement of the order of the spatial interpolation scheme (WENO5 scheme) has been performed in order to increase the accuracy and to reduce the numerical diffusion [5,6]. A 4th-order Runge-Kutta scheme (RK4) is used to perform the temporal integration of the equations. A LES method based on the Smagorinsky sub-grid scale model is adopted in this study.

The HAWT modeled by FAST [7] is taken into account in the Navier-Stokes equations as source terms applied on the Cartesian grid using the actuator-line theory [8], while the hub is modelled using an Immersed Boundary Method [6].

The interest of WCCH lies in obtaining a fully explicit code, with a relative simplicity of parallelization and algorithmic developments, good parallel performances, a relative simplicity to increase the order of the spatial scheme, with no linear system to be solved [6].

The two-way coupled formulation (WCCH-FAST) allows a comprehensive wind turbine modeling where the turbine behaves dynamically depending on the incident flow (blade pitching, generator torque regulation), while its wake and the incident flow are calculated through the CFD solver. This formulation provides both turbine loadings and its effects on the wake, thus showing good perspectives for control and layout optimization of wind turbine farms.

Figure 1 and 2 describes the coupling of the fluid solver (WCCH) with the turbine solver (FAST). Figure 1 provides an architectural view of the coupling, showing the information exchanged between each solver.

FAST is a combination of several modules, each one addressing a specific part of the wind turbine. In a first attempt, the present coupling only considers a reduced number of these modules. The coordinates of each element are sent from ElastoDyn to WCCH, and the blade element forces are sent from AeroDyn to WCCH. The time-step is imposed by FAST to the coupling by an initial exchange performed during the initialization phase. Then, the WCCH time-step is taken as a subdivision of the FAST time-step while satisfying the CFL condition required by the explicit feature of WCCH [6].

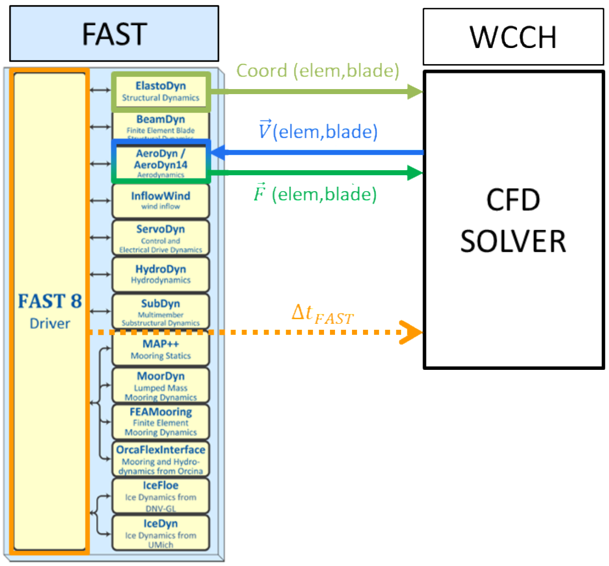

FIGURE 1: COUPLING OF THE FLUID SOLVER WCCH WITH THE TURBINE SOLVER FAST

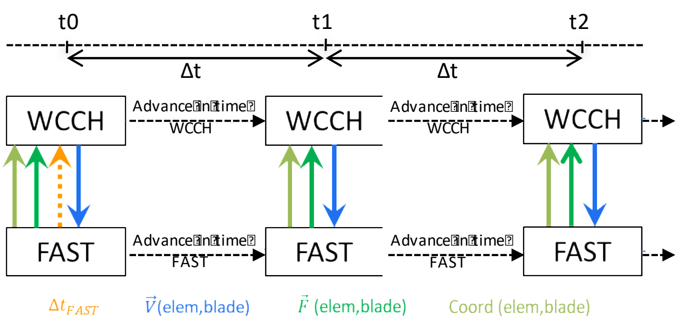

FIGURE 2: VARIABLE EXCHANGES BETWEEN WCCH AND FAST THROUGH TIME IN CPS

Figure 2 shows the variable exchanges through time for a Conventional Parallel Staggered algorithm (CPS) [9].

RESULTS

In this section, performance comparisons between FAST and the WCCH-FAST coupling are discussed.

An ideal NREL 5MW wind turbine benchmark is considered here, for which reference solutions are available for comparison purposes. In the latter, several assumptions are made: the wind turbine blades are rigid and the mast and the nacelle are not taken into account. As blades are taken as rigid, Elastodyn is only used to send the blade element coordinates to WCCH at the moment. Nevertheless, the coupling with this module will allow considering flexible blades in the future. Also, the following wind turbine parameters are considered: 3 blades, $D_{rotor}=126m$, $D_{hub}=3m$, $\Omega_N=12{,}1rpm$, steady uniform inflow wind of magnitude $V_{in}=12m.s^{-1}$.

Four gauges are used in order to validate our coupling. These gauges are located along one of the three blades of the wind turbine (blade 1) from the first blade element near the root, to the last on the tip. These gauges give access to local variables out of FAST like the axial and tangential forces Fx, Fy. Global behavior of the wind turbine is also monitored through the pitch angle of blade 1 β_1, the rotational speed of the rotor Ω, the torque of the rotor T_{rot} and the power generated by the rotor P_{gen}.

The operating point on which we validate the coupling is located in zone 3, which means the inflow wind velocity magnitude is greater than the rated incident wind speed of the wind turbine ($V_{in} > V_N$). The controller consequently uses the blade pitch in order to regulate the wind turbine behaviour.

First, a reference simulation has been realized using FAST alone. These results are then compared to WCCH-FAST coupling. The coupling has been validated through a step by step process in order to ensure its stability; First through a one-way coupling (results from Figure 3) where the sampled velocities were sent from WCCH to FAST but the forces from FAST were sent only once and for all to WCCH; Then switching to a two-way coupling without a controller (not shown here). Finally, we tested the two-way coupling with the NREL 5MW controller provided in the FAST v8 package (results from Figure 4).

The first tests have shown that direct sampling of the local blade element wind velocities was not giving a sufficient stability to the coupling. A temporal and a spatial averaging has been introduced on $\vec{V}(elem, blade)$. The temporal averaging is set at the initialisation step by choosing an angle value. It corresponds to the angle swept by the blades during a given period. Velocities are sampled at each blade node location during this period, kept in memory, and then averaged before being used at the next FAST time-step. This way the temporal averaging adapts to the variation of the rotational speed of the wind turbine. The spatial averaging is achieved using a compact regularizing kernel together with an MLS correction. We refer the reader to [5] for more details. Both the temporal and the spatial averaging use the velocity fields calculated by WCCH around the local blade element coordinates. Figure 3 shows a comparison of the axial forces Fx for a direct velocity sampling and with averaging for the one-way coupled version of WCCH-FAST. This study has been done before switching to the two-way coupled version to study the influence of the sampling method on the forces out of FAST thus ensuring the stability of the WCCH-FAST coupling. On the top left of Figure 3, the use of a direct sampling induces strong oscillations of the local blade velocities calculated in WCCH and sent to FAST. These oscillations lead to a strong variation of the forces calculated by the AeroDyn module of FAST.

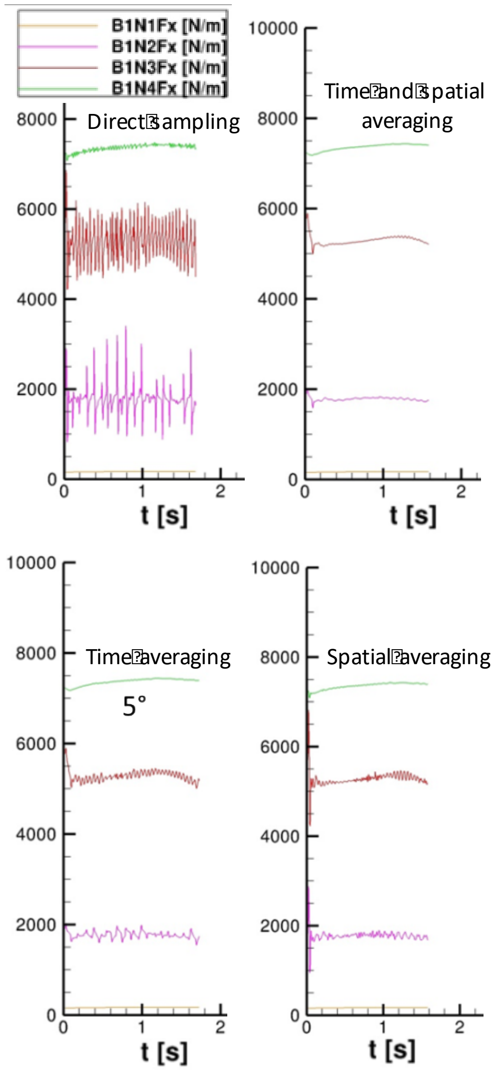

FIGURE 3: COMPARISON OF DIRECT AND AVERAGED VELOCITY SAMPLING WITH ONE-WAY WCCH-FAST COUPLING ON *Fx*.

The bottom left graph shows the enhancement provided by the time averaging alone. The bottom right graph presents the result obtained while applying the spatial averaging alone. These two corrections give good results independently but the variations observed are not sufficiently small to ensure a stable behaviour of the two-way coupled version of WCCH and FAST. The top right plot of Figure 3 is the combination of time and spatial averaging corrections. This is the configuration which gives the smallest variations on the four gauges of blade 1. The best stability has been reached for a swept angle that corresponds to 5° for the time averaging. In future simulations including turbulent incident winds, this angle will then be chosen small enough to keep a good description of the incident turbulent structures but great enough to ensure the stability of the coupling. Note finally that the velocity sampling is not performed exactly on the blade nodes but slightly upward the rotor (for stability reasons). A sensitivity study related to this sampling distance has been conducted and showed a good behaviour for a sampling achieved around $5\%D_{rotor}$ upward of the rotor rotational plane.

Figure 4 shows a comparison of the results obtained from FAST and the WCCH-FAST two-way coupled version on Fx, Fy, β_1, Ω, T_{rot} and P_{gen}. The results presented here include the NREL 5MW controller. It is important for us to ensure the stability of the coupling in the case where controllers are used: the coupling should remain stable enough to deal with strong unsteadiness of the incident flow and hence to adapt to strong variations of the wind turbine actuators (pitch angle and rotational velocity namely). On all the following graphs, the dashed curves represent the results from FAST and the solid lines the results from WCCH-FAST. The two topside graphs show the axial and tangential forces on the 4 gauges of blade 1. A fairly good agreement is observed on the 4 gauges for a physical time greater than 15 s.

A transient zone is observed for both FAST and WCCH-FAST between 0s and 15s. This zone corresponds to the stabilization of the controller where some variations of Fx and Fy are observed. The amplitude of those variations is greater for WCCH-FAST. This difference is due to the induction models used inside FAST in order to calculate the velocities on the blade elements (not shown here). These models seem to stabilise the behaviour of the controller. In the WCCH-FAST coupling, the induction models are disabled and replaced by the CFD velocity sampling. The same behaviour is observed for the other variables (β_1, Ω, T_{rot} and P_{gen}). From 15s, the major difference is observed on Fx for gauge 4 (in green) which is located at the tip of blade 1. This zone experiences strong shears that remains difficult to capture, but a recent work has shown some improvement tracks we will follow in the near future. In this benchmark, the operational point has been chosen for V_{in} above the wind turbine's rated speed (zone 3). Hence, the power generated converge towards the rated power 5MW (bottom graph), and the aerodynamic performances of the blades are slightly lowered by pitching the blades (black curve in the third graph from the top). We observe that β_1 is slightly higher for WCCH-FAST compared to FAST. This goes together with the differences observed on Fx components: the results obtained by WCCH-FAST are slightly lower than those obtained with FAST alone as the lift forces on each blade elements are lowered due to the pitching. In the same time, the Fy obtained by WCCH-FAST and FAST are really close so T_{rot} and P_{gen} are equivalent for both formulations. The difference in pitching comes from the induced velocity sampled from the CFD domain, which is slightly higher than the one calculated by the momentum model of FAST (not shown here).

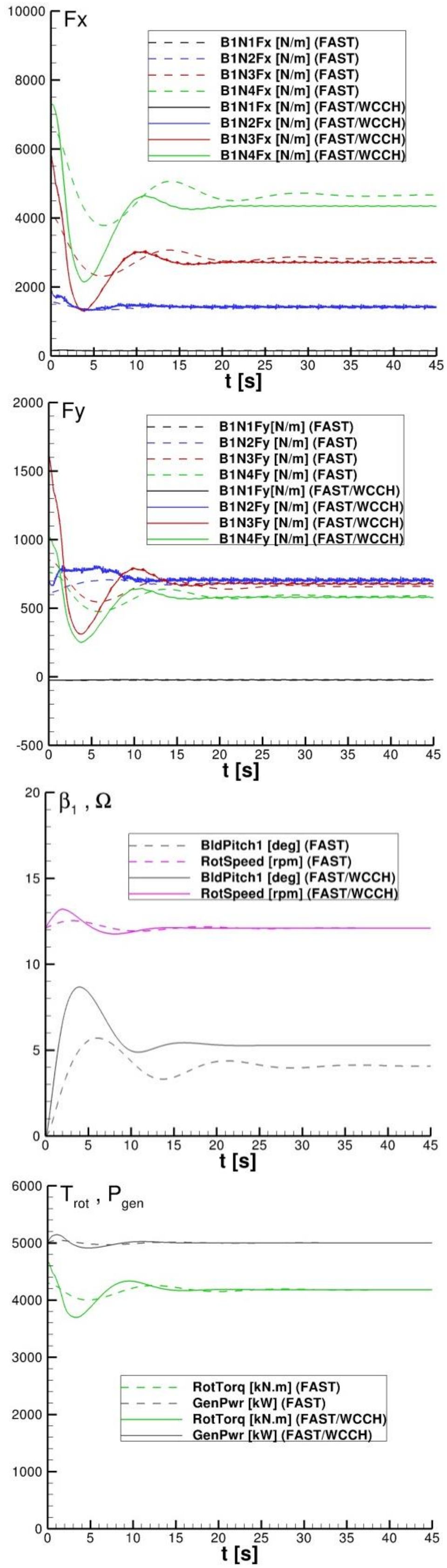

FIGURE 4: COMPARISON OF FAST AND TWO-WAY WCCH-FAST COUPLING ON *Fx*, *Fy*, β_1, Ω, T_{rot} and P_{gen}, WITH THE CONTROLLER.

CONCLUSIONS

A coupling between the CFD solver WCCH and turbine solver FAST has been proposed. The first validation step of this coupling shows encouraging results. A step by step approach has been followed, ensuring a stable behaviour of the coupling even in configurations including a controller. The comparisons performed showed that the major differences between FAST and WCCH-FAST are observed at the tip of the blades where strong shears occur and the physics is not easy to capture. Our recent work has shown some improvement tracks we will follow in the near future in order to improve the coupling. This study is a first step forward in the validation process of WCCH-FAST coupling which was required prior to studying the wake. This will be the topic of our next publication. Strong efforts will be undertaken at each development steps in order to achieve the best compromise between accuracy of the numerical model and computational costs.

ACKNOWLEDGEMENTS

This work was carried out within the framework of the WEAMEC (West Atlantic Marine Energy Community), and with funding from the Pays de la Loire Region, using the HPC resources of Centrale Nantes Supercomputing Center on the Liger Cluster.

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