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A coupled floating offshore wind turbine analysis with high-fidelity methods

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Abstract

This paper presents results of numerical computations for floating off-shore wind turbines using, as an example, a machine of 10-MW rated power. The hydrodynamic loads on the support platform are computed using the Smoothed Particle Hydrodynamics method, which is mesh-free and represents the water and floating structures as a set of particles. The aerodynamic loads on the rotor are computed using the Helicopter Multi-Block flow solver. The method solves the Navier-Stokes equations in integral form using the arbitrary Lagrangian-Eulerian formulation for time-dependent domains with moving boundaries. The motion of the floating offshore wind turbine is computed using a Multi-Body Dynamic Model of rigid bodies and frictionless joints. Mooring cables are modelled as a set of springs and dampers. The loosely coupled algorithm used in this work is described in detail and the obtained results are presented.

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Keywords: Offshore wind turbine; floating; CFD; SPH; multi-body; dynamics; HMB3

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1. Introduction

Current trends suggest large development of on-shore wind turbine size and power capacity. Due to the fact that many high potential sites on land are already occupied, and others are hard to utilise owing to *e.g.* difficult access, high altitude *etc.*, a growing trend is to exploit the offshore wind potential and take advantage of the available space and steady winds. In the first six months of 2015 alone, Europe fully grid connected 584 commercial offshore wind turbines with a combined capacity of 2.3GW, and those are bottom-fixed machines. As of today, offshore wind represents 10% of the annual wind energy installations across Europe[1,2]. Estimates for the year 2030 predict up to 11.3% coverage of total European electricity demand by offshore wind[3]. Similar trends are seen in the US, where onshore and offshore wind energy can provide up to 20% of the US electricity by 2030[4].

Over the years offshore wind farms have moved further from the shore and into deeper waters. At the end of 2014, the average water depth of grid connected wind farms was about 23*m* and the average distance to shore about 33*km*.

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Projects under construction, consented and planned, confirm that average water depths and distances to shore are likely to increase[5]. Shallow water regions suitable for constructing seabed-fixed, offshore wind turbines are limited, and for sea depths exceeding $30 - 60m$, floating structures become more economic. Hence, emphasis is placed on the development of floating offshore wind turbines (FOWTs) with several prototypes already operational across the world[5].

Unlike onshore machines, the FOWT is a highly dynamic system subjected to the wind and wave loads and only constrained by mooring. Further, the rotor frequency is low due to the large size of the blades, and wave frequencies may come close or coincide with the rotational frequency of the rotor. Therefore, it is important to develop a method for the analysis of this air-structure-water system. The purpose of this paper is to present such an algorithm and obtained demonstration results. For this, the Helicopter Multi-Block (HMB3) flow solver[6] is used to solve for the aerodynamic forces acting on the wind turbine (WT) blades. Hydrodynamic forces on the support platform are solved using the Smoothed Particle Hydrodynamics (SPH) method [7,8]. Both solvers are coupled by exchanging information while the FOWT is represented by a lumped mass model.

2. Numerical methods

The HMB3 code is a 3D multi-block structured solver and solves the Navier-Stokes equations in the 3D Cartesian frame of reference. HMB3 solves the Navier-Stokes equations in integral form using the arbitrary Lagrangian-Eulerian formulation for time-dependent domains with moving boundaries [e.g.9–11]. The solver uses a cell-centred finite volume approach combined with an implicit dual-time method[12]. The HMB3 solver has a library of turbulence closures including several one- and two- equation turbulence models, and turbulence simulation is also possible using either the Large-Eddy or the Detached-Eddy simulation approach[13].

The water is modelled with the SPH method[7]. Each SPH particle represents the volume of the fluid and moves according to the Navier-Stokes equations solved in the Lagrangian form. SPH offers a variety of advantages for fluid modelling, particularly those with a free surface and moving bodies. Due to the Lagrangian nature of the SPH method, the free surface requires no special treatment. Further, submerged bodies can be represented with particles. Therefore, it is natural for the method to include floating objects.

The motion of the FOWT components is computed with a multi-body model (MBDM) of rigid bodies and frictionless joints. Mooring cables are modelled as a set of springs and dampers, according to Savenije [14]. The coordinate partitioning method [15,16] is used to solve the resulting system of mixed differential-algebraic equations. The time integration scheme is explicit with various methods up to the Runge-Kutta method of fourth order. The non-linear position equations are solved using a Newton-Raphson method with exact analytical Jacobian.

All solvers were validated separately before coupling. The HMB3 CFD solver has so far been validated for several wind turbine cases, including the NREL Annex XX experiments [17], and the pressure and PIV data of the MEXICO project [18]. The SPH method was validated against the experiments of Greenhow and Lin [19] for the high speed entry of a half-buoyant solid cylinder into calm water. The MBDM was validated using simple mechanical systems of known solutions [16] like 2D and 3D slider-crank mechanisms and gyroscopic wheels [20].

In the present work, the communication between the MBDM, SPH and HMB3 was established through the Message Passing Interface (MPI). Due to the Lagrangian nature of the SPH method, the submerged bodies can be represented with particles and do not require specific coupling. Therefore, by utilising MPI, the MBDM substituted the body motion routines of the SPH solver and reduced the number of coupled codes to two - SPH and HMB3. This implies that MBDM is advancing in time with the same integration scheme as SPH using a symplectic method in this case [21].

2.1. Coupling algorithm and its implementation

Different coupling methods have been extensively studied during the past two decades. The multi-physics problem with adjacent domains can be simulated in a monolithic or in a partitioned way. The former refers to the flow equations and structural equations being solved simultaneously, while the latter means that they are solved separately. Considering that two validated solvers (HMB3 and SPH) are available, the emphasis is placed on partitioned algorithms.