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A novel numerical strategy for the simulation of irregular nonlinear waves and their effects on the dynamic response of offshore wind turbines

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ABSTRACT

We present a novel numerical procedure for the prediction of nonlinear hydrodynamic loads exerted on offshore wind turbines exposed to severe weather conditions. The main feature of the proposed procedure is the computational efficiency, which makes the numerical package suitable for design purposes when a large number of simulations are typically necessary. The small computational effort is due to (i) the use of a domain-decomposition strategy, that, according to the local wave steepness, requires the numerical solution of the nonlinear governing equations only on a limited number of reduced regions (sub-domains) of the whole space–time domain, (ii) the choice of the particular numerical method for the spatial discretization of the governing equation for the water-wave problem. Within the potential flow assumption, the Laplace equation is solved by means of a higher-order boundary-element method (HOBEM). For the time evolution of the unsteady free-surface equations the 4th-order Runge–Kutta algorithm is adopted. The compound solver is successfully applied to simulate nonlinear waves up to overturning plunging breakers, that may cause severe impact loads on the wind turbine substructure.

Emphasis is finally given to wind turbine exposed to realistic environmental conditions, where the proposed tool is shown to be capable of capturing important nonlinear effects not detected by the linear models routinely adopted in the design practice.

1. Introduction and background

The quick growing demand for offshore wind energy power production requires the development of more accurate numerical tools to investigate the effects of the complex environmental conditions acting on wind turbine structures, exposed to rough wind and sea conditions. While reliable numerical models are typically used for the aero-elastic problem, overly simplistic linear theoretical models are adopted for the wave-induced loads. A novel numerical algorithm, able to predict nonlinear wave loads acting on offshore wind turbines exposed to severe sea states, has been recently proposed in [1–3], where the coupling with an open-source hydro-aero-elastic solver enables a reliable estimation of the structural response of the system.

The wave algorithm, was efficient in capturing the hydrodynamic contributions associated with plunging breaking waves [4,9]. When a wave is breaking close to a wind turbine tower, internal forces may undergo a leap of three times the typical peaks due to non-impulsive loads [3]. Further, the local load, i.e. the impact pressure, may be as much as ten times larger than the non-impact pressure and it rises in few milliseconds [15,16]. However, the proposed algorithm was applied only for sea states characterized by extreme environmental conditions. The nonlinear solver was used on very short time intervals and for small sub-domains where impact phenomena are expected.

To fully account for the nonlinear effects, the numerical solver should be used on the entire fluid-domain and for the whole time evolution. Further, in a real sea state many runs should be considered to get a response statistically representative, resulting in an unfeasible approach at the design stage. To circumvent this problem, the strategy proposed in the present paper aims to match the wave kinematics solver with the local wave steepness: a domain-decomposition approach, which couples a linear (analytic) and fully nonlinear high-order boundary-element (HOBEM) solver, is developed. Similar strategies, although based on the coupling of several local solvers (with different theoretical models), have been proved to be efficient for the prediction of ship motion in rough sea state [5–8].

Compared with the algorithm developed in [1,3] the present strategy proposes a novel, efficient and smooth transition from

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the linear to the nonlinear solution (and vice versa), both in time and space. Then, the new method is suitable for simulating nonlinear sea states for a sufficiently long time and for a large computational domain so that all nonlinearities (from weakly to fully nonlinear) are properly predicted. As a consequence, the present algorithm can account for nonlinear hydrodynamic effects associated with a wider range of environmental and operative conditions, including the turbine during the power production stage. The originalities of the proposed simulation strategy lie in (a) the possibility of accounting for the effects from weakly up to fully nonlinear (impacts) waves; (b) the low computational effort required for the compound simulation. Finally, (c) the coupling of the fully nonlinear hydrodynamic algorithm with the open source FAST solver allows to assess the effects of the new hydrodynamic model on the global structural response. The latter results in an additional original aspect because the design approaches employ the standard linear wave theory and, in few cases [13], nonlinearities are limited to the second-order.

The paper is structured as follows – Section 2 presents the global simulation framework. Sections 3 and 4 deal with the verification of both the HOBEM solver and the transition scheme from linear to fully nonlinear sub-domain. A short description of the baseline turbine model given in Section 5 introduces some realistic cases shown in Section 6. Finally, conclusions are discussed in Section 7.

2. Mathematical and numerical modeling

2.1. Global simulation strategy

The global strategy is based on the coupling between the NREL open-source FAST software [10,11], used for the aero-elastic simulation, and free-surface potential-flow models (linear and fully nonlinear), used to predict the wave kinematic parameters essential to estimate the wave-induced loads on the turbine substructure.

FAST is based on a combined modal and multibody dynamics formulation to model the rigid and flexible bodies composing a wind turbine. The capability to couple several aspects of the physics of a wind turbine (i.e. aerodynamics, structural elasticity of the blades and tower, hydrodynamics, control system), is one of the main feature of FAST. Flexible beam elements, suitably formulated in terms of generalized coordinates and using a linear modal representation (assuming small deflections), are used to reproduce the two flapwise bending modes and one edgewise bending mode for each blade and two fore-aft and two side-side bending modes for the tower.

A Finite Element Method solver gives the mode shapes of the tower and the blades. Aerodynamic loads acting on the blades are calculated by means of a quasi-steady Blade-Element Momentum (BEM) theory, that is, assuming the blades long and slender. The BEM aerodynamic model includes also the tip and hub losses according to Prandtl corrections, as well as the dynamic stall. Irregular linear wave theory gives the wave kinematics as input for the calculation of the hydrodynamic loads.

The reader can refer to [10,11] and to [18,19] for further details on the mathematical and numerical model. In the present study, the focus is given on the numerical solver developed for the wave propagation.

2.1.1. Domain decomposition in space and time

Statistics of metocean data, or simplified sea state classification, provide values for the mean wind speed U, significant wave height H_s and peak spectral period T_p to be used as input to the model. A suitable wave spectrum is chosen and the 2D-linear theory is used to simulate a long-crested irregular sea [14] in a global space–time domain $\mathcal{D}(t) = [x_{\min}, x_{\max}] \times [0, T_{sim}]$, where $x_{\min}$ and $x_{\max}$ are the lower and upper spatial limits of the global domain and T_{sim} is the total simulation time.

A zero-crossing analysis of the wave elevation time history $\eta(x,t)$ in a small area around the monopile location x_t, identifies the array $\bar{t}^{up}$ of the up-crossing time instants necessary for the calculation of the local wave period $\overline{T}$ and of the local wave height $\overline{H}$ arrays (see Fig. 1). The dispersion relation enables computation of the wave number $\bar{k}$ and wavelength $\bar{L}$ arrays. By checking the local wave steepness at each wave cycle (i.e. between two consecutive up-crossing time instants), the time instant t_{i_b} when the local steepness exceeds a threshold value $ka_{\min}$ is estimated as follows

$$t_{i_b} = t_1^{up} + T_{i_b}/4 + \sum_{h=1}^{i_b-1} T_h \tag{1}$$

Once t_{i_b} is known, linear wave solution initializes and provides the boundary conditions (see bottom boxes in Fig. 2)) to the fully nonlinear potential-flow solver (see middle-left box of Fig. 2) used on a prescribed space–time sub-domain $\Omega_{i_b}(t) \subset \mathcal{D}(t)$

$$\Omega_{i_b}(t) = [x_t - \delta_1 x_t, x_t + \delta_2 x_t] \times [t_{i_b} - \delta_1 t_{i_b}, t_{i_b} + \delta_2 t_{i_b}] \tag{2}$$

where $\delta_1 x_t, \delta_2 x_t$ and $\delta_1 t_{i_b}, \delta_2 t_{i_b}$ are the spatial and temporal radii of the sub-domain, respectively (see upper part of Fig. 2).

Because of the domain decomposition strategy used, the simulation on each temporal sub-domain can be easily parallelized, further increasing the efficiency of the algorithm; however in the present work serial computations have been used.

2.2. Fully nonlinear water wave problem

The two-dimensional problem governing the nonlinear propagation of gravity waves is formulated within the potential-flow framework. For an inviscid fluid in irrotational flow, the potential function $\phi(t,p)$ describes the velocity field at time t in each point $p \in \Omega(t)$. For an incompressible fluid, the mass conservation reads

$$\nabla^2 \phi(t,p) = 0 \quad \forall p \in \Omega(t) \tag{3}$$

i.e. Laplace's equation is valid in the whole domain.

The two-dimensional domain $\Omega(t)$ is bounded by four boundaries: inflow $\Gamma_{i1}(t)$, rigid bottom Γ_b, outflow $\Gamma_{i2}(t)$, and free-surface $\Gamma_f(t)$ (Fig. 3). On each of them, suitable boundary conditions have to be enforced. In particular, the impermeability condition $\nabla\phi \cdot \bar{n} = 0$ is imposed on the rigid bottom, while the continuity with the linear wave kinematics has to be ensured on $\Gamma_{i1}(t)$ and $\Gamma_{i2}(t)$; finally, nonlinear kinematic and dynamic boundary conditions must be imposed on $\Gamma_f(t)$ (see Section 2.2.1).

2.2.1. Eulerian to Lagrangian formulation for the free-surface boundary conditions

Let us introduce the operator $\delta(\cdot)/\delta t = \partial(\cdot)/\partial t + \bar{v} \cdot \nabla(\cdot)$, where $\bar{v}$ can be either the velocity of the fluid particle $\nabla\phi(t,p)$ or zero. The kinematic and dynamic free-surface boundary conditions can be conveniently written as follows

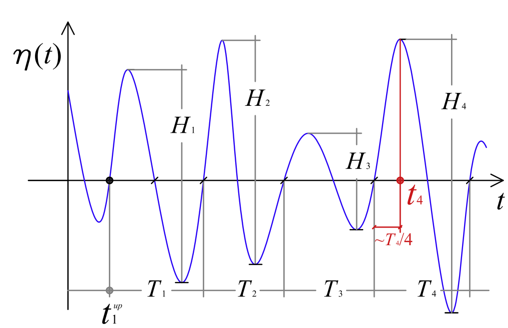

Fig. 1. Sketch of the zero-crossing analysis of the free surface elevation for the estimation of the time instant at which the nonlinear event occurs (example with $i_b = 4$).