Numerical Simulation of Offshore Wind Turbines by a Coupled Aerodynamic, Hydrodynamic and Structural Dynamic Approach

A. Heege, P. Bonnet, L. Bastard, S. G. Horcas, J. L. Sanchez, P. Cucchini, A. Gaull;
SAMTECH Iberica

Abstract

The central point of the present publication is an implicitly coupled aerodynamic, hydrodynamic and structural dynamic approach dedicated to offshore wind turbine simulation. The mathematical approach relies on an implicit non-linear dynamic Finite Element Method extended by Multi-Body-System functionalities, aerodynamics based on the Blade Element Momentum theory, controller functionalities and hydrodynamic loads.

Offshore loads are formulated in terms of hydrostatic buoyancy and hydrodynamic wave loads which are approximated through Morison’s equation. Special attention is focused on the implementation of Morison’s equation in order to capture hydrodynamic coupling effects which are induced by the dynamic response of the offshore wind turbine.

Two distinct applications of offshore wind turbines are analyzed. First, a jacket-based offshore wind turbine is loaded hydro-dynamically through a wave field described by Airy’s linear wave theory. As a second example, the aerodynamic and hydrodynamic coupling effects are put in evidence by a transient dynamic analysis of a floating offshore wind turbine anchored to the seabed by structural cables.

Introduction

The operational deflection modes and associated dynamic loads of offshore wind turbines originate, on one hand, from the aerodynamic and hydrodynamic loading, and, on the other hand, from the proper dynamic response of the entire offshore wind turbine system, including all control mechanisms.

A decoupling of the dynamic offshore wind turbine system into sub-systems bears the risk of missing dynamic coupling effects which might prevail in many operational modes. In particular in the case of floating offshore wind turbines, a decoupled aero-elastic and hydrodynamic formulation does not permit to reproduce properly the global dynamic response of the wind turbine. This is because the speed variations which are induced in the rotor plane by dynamic deflections of the offshore wind turbine affect directly the rotor aerodynamics and associated controller actions on the blade pitch position and on the generator torque. As a consequence, an accurate tuning of controller parameters is difficult with simplified, decoupled offshore wind turbine models. In order to remedy these deficiencies, the proposed mathematical approach is specifically formulated in order to capture dynamic coupling effects which might be
induced simultaneously by aero-elastic and hydrodynamic loading of offshore structures. Accordingly, the relative velocity and acceleration fields induced by a floating and/or vibrating offshore wind turbine are accounted for in the proposed coupled aeroelastic and hydrodynamic formulation.

The implementation of aerodynamic loads is based on the Blade Element Momentum theory where wind turbine specific corrections for tip and hub losses, wake effects and the impact of the tower shadow are accounted. Hydrodynamic loads are composed of drag loads and of inertial loads and account for the relative velocity and acceleration fields between the fluid and the moving and/or vibrating offshore structure.

Two different applications of dynamic analysis of offshore wind turbines are presented. The wind turbine models are discretized by more than 3,000 Degrees of Freedom (DOF) and account for all the abovementioned coupled effects.

**Coupled Aero-elastic, Hydro-dynamic, Structural FEM & MBS Analysis**

The applied mathematical approach is based on a non-linear Finite Element formalism, which accounts simultaneously for flexible Multi-Body-System functionalities [1][2][3][4], control devices, aerodynamics in terms of the Blade Element Momentum theory [1][2][4][5][6][7], hydrostatic buoyancy loads and finally hydrodynamic loads in terms of the Morison equation [2][5][10][11][12][13][14].

**Mathematical background**

In the context of an “Augmented Lagrangian Approach” and the “one-step time integration method of Newmark” [1][3], the incremental form of the equations of motion in the presence of constraints is given in equation (1). According to the definition of the residual vector of equation (1), the vector \( \bar{\mathbf{g}} \) assembles the sum of elasto-visco-plastic internal forces \( \bar{\mathbf{g}}_{\text{int}} \), complementary inertial forces where centrifugal and gyroscopic effects are included, external forces \( \bar{\mathbf{g}}_{\text{Ext}} \), the aero-dynamic forces \( \bar{\mathbf{g}}_{\text{Aero}} \) and finally the hydro-dynamic and hydrostatic loads \( \bar{\mathbf{g}}_{\text{Hydro}} \). The vector \( \bar{\mathbf{g}} \) introduces additional equations of the generalized solution \( \bar{\mathbf{q}}, \bar{\mathbf{z}} \) which are used to include general Multi-Body-System/MBS functionalities for the modelling of the power train, pitch and yaw drives and finally further DOF which are related to controller state variables for blade pitch, yaw orientation and generator modelling.

The non-linear set of equations (1) is solved iteratively and further details on the time integration procedure, error estimators and solution strategies can be found in the SAMCEF-Mecano user manual [1].

**Aero-dynamic and structural coupling**

Blades are modeled in the S4WT software [1][2] through a non-linear FEM formalism adapted to large transformations and large rotations. For computational efficiency, the structural blade model is presented either in terms of Super Elements [1][3], or in terms of non-linear beam elements. The elemental aerodynamic forces are computed according to the Blade Element Momentum/BEM theory including specific corrections and additional models for the tip and hub losses, turbulent wake state, tower shadow effect, dynamic inflow and dynamic stall [1][2][5][6][7][8][9].

The structural/aerodynamic coupling is performed implicitly at the blade section nodes of the structural blade model through the connection of “Aerodynamic Blade Section Elements” which contribute in terms of elemental aerodynamic forces to the global equilibrium equation (1). The discretisation of the aerodynamic loads corresponds to the FEM discretisation of the structural blade model and the nodes for the aero-elastic coupling are generally located at the ¼ chord length positions of typically about 15 to 20 blade sections distributed along the blade span. Taking into account that the aerodynamic loads \( F_{\text{Lift}}, F_{\text{Drag}}, M_{\text{Pitch}} \) presented in equation (2) are included in the residual vector of equation (1), once the iterative solution of equation (1) to (8) is found, the induced velocities, angles of attack, Prandtl loss coefficients, hydrodynamic forces and the global structural dynamic response are consistent.

It is emphasized that this methodology features a “strong coupling”, i.e. all equations associated either with aerodynamics, hydrodynamics, structures, mechanisms, or control loops are solved simultaneously. A major advantage of a “strong coupling” is that blade vibrations induced by aerodynamic forces and/or hydrodynamic loads, implicitly affect the structural response of the global dynamic wind turbine model. Accordingly, the relative speeds \( \dot{\mathbf{v}}_{\text{rel}} \) that enter in the aerodynamic load computation, account implicitly for the aerodynamically induced speeds \( \dot{\mathbf{v}}_{\text{ind}} \) and the resulting speeds \( \dot{\mathbf{v}}_{\text{B}} \) of the structural Blade Section nodes. Where \( a \) and \( a' \) are respectively the axial and tangential induction factors. Details on the procedure applied in order to compute the induced speed vector \( \dot{\mathbf{v}}_{\text{ind}} \) in terms of the aerodynamic inductions are given in references [1][2][5].

**Hydrostatic buoyancy & hydrodynamic wave loads**

In the present work, offshore loads are presented by hydrostatic buoyancy loads and by hydrodynamic forces which approximate wave loads. The hydrostatic buoyancy loads are composed of a buoyancy force vector \( \mathbf{F}_{\text{Buoy}}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \) and of a buoyancy restoring moment \( \mathbf{M}_{\text{Buoy}}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \). The hydrodynamic wave loads \( \mathbf{F}_{\text{Morison}}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}, t) \) are approximated through Morison’s equation in terms of a drag and an inertia term [10][11][12].

Analogously to the aero-elastic coupling through the connection of “Aerodynamic Blade Section Elements” to the FEM model of the rotor blades, the coupling of hydrodynamic loads to the offshore structure is realized through “Hydrodynamic Load Elements/HLE”. In the context of a non-linear FEM formalism, the “Hydrodynamic Load Elements” are to be considered as “1-noded elements” connected to the nodes of the FEM mesh of the offshore structure. Accordingly, each node of the FEM model of the offshore structure is loaded by a six-dimensional vector \( \mathbf{F}_{\text{Hydro}}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}, t) \) according to equation (3).

**Large transformations & fluid kinematics**

In particular in the case of floating offshore wind turbines, the entire wind turbine, or sub-components like for example the mooring lines, might be subjected to large oscillations which produce eventually large rotations. In order to account properly for large displacements, large rotations
\[
\begin{align*}
\begin{bmatrix} [M] & [0] \\
[0] & [0] \\
\end{bmatrix} \begin{bmatrix} \Delta \dot{q} \\
\Delta \lambda \\
\end{bmatrix} + \begin{bmatrix} [C] & [0] \\
[0] & [0] \\
\end{bmatrix} \begin{bmatrix} \Delta q \\
\Delta \lambda \\
\end{bmatrix} = \begin{bmatrix} [K] & [B^T] \\
[B] & [0] \\
\end{bmatrix} \begin{bmatrix} \Delta \dot{q} \\
\Delta \lambda \\
\end{bmatrix} = \begin{bmatrix} \dot{R}(\bar{q},\bar{\lambda},t) \\
\dot{\phi}(\bar{q},\bar{\lambda},t) \\
\end{bmatrix} + \rho(\Delta^2)
\end{align*}
\]  

\(\ddot{q}\): Position vector, \(\dot{\ddot{q}}\): Acceleration vector, \(\lambda\): Vector of Lagrange Multipliers  

\(K\): Stiffness matrix, \(C\): Damping matrix, \(M\): Mass & Inertia matrix  

\(\dot{\phi}\): Constraint vector, \([B]\) = \[\begin{bmatrix} \partial \phi/\partial q \end{bmatrix}\]: Constraint Jacobian matrix, \(p\): Penalty factor  

Residual vector: \(\ddot{R}(\bar{q},\bar{\lambda},t) = -\dddot{g}_{\text{Int.}} + \dddot{F}_{\text{Aero}} + \dddot{F}_{\text{Hydro}} - g_{\text{Ext.}} - \begin{bmatrix} M \end{bmatrix} \dddot{q} - [B^T](\dddot{\lambda} + p \dddot{\phi})\)  

with Internal Forces \(g_{\text{Int.}}(\bar{q},\bar{\lambda},\bar{\lambda},t)\), External Forces \(g_{\text{Ext.}}(\bar{q},\bar{\lambda},\bar{\lambda},t)\)  

\(\dddot{F}_{\text{Aero}}(\bar{q},\bar{\lambda},\bar{\lambda},t) = \begin{bmatrix} \dddot{F}_{\text{Lift}} & \dddot{F}_{\text{Drag}} \end{bmatrix} \begin{bmatrix} M \end{bmatrix} \dddot{q}(\bar{q},\bar{\lambda},\bar{\lambda},t) \)  

\(\dddot{F}_{\text{Hydro}}(\bar{q},\bar{\lambda},\bar{\lambda},t) = \begin{bmatrix} \dddot{F}_{\text{Buoy}} & \dddot{F}_{\text{Morison}} \end{bmatrix} \begin{bmatrix} M \end{bmatrix} \dddot{q}(\bar{q},\bar{\lambda},\bar{\lambda},t) \)  

\(\dddot{F}_{\text{Inertia}}(\bar{q},\bar{\lambda},\bar{\lambda},t) = \begin{bmatrix} \dddot{F}_{\text{Buoy}} & \dddot{F}_{\text{Morison}} \end{bmatrix} \begin{bmatrix} M \end{bmatrix} \dddot{q}(\bar{q},\bar{\lambda},\bar{\lambda},t) \)  

\(\dddot{g}\): gravity vector, \(\rho\): fluid density, \(E\): depth w.r.t. FWL, \(\dddot{\lambda}\): restoring moment lever  

\(S(\bar{q},\bar{\lambda},\bar{\lambda},t):\) envelope surface of submerged body, \(\dddot{n}(\bar{q},\bar{\lambda},\bar{\lambda},t):\) normal to surface at point \(\dddot{q}\)
and/or deformations of the offshore wind turbine, the kinematical variables which are involved in the hydrostatic & hydrodynamic formulation of equations (3) to (8) are formulated implicitly as a function of the solution of the respective time integration step of the global equilibrium equation (1). According to Fig. 1 and Fig. 2, the effectively submerged depth $\mathbf{E}_{\text{eff}}(\mathbf{q},t)$ is measured w.r.t. a time variable Free Water Level/FWL defined by the wave height $\mathbf{W}(\mathbf{q},t)$. It is noted that a span length vector $\mathbf{L}_{\text{Span}}(\mathbf{q},t)$ and the associated envelope surface $\mathbf{S}(\mathbf{q},t)$ are attached to each node of the FEM mesh of the offshore. The surface normal vector $\hat{n}(\mathbf{q},t)$ of equation (5) is to be interpreted as the outward normal for any point of the integral of the envelope surface $\mathbf{S}(\mathbf{q},t)$. Since the span vector $\mathbf{L}_{\text{Span}}(\mathbf{q},t)$ and the envelope surface $\mathbf{S}(\mathbf{q},t)$ are moving and rotating with the associated structural node of the FEM mesh, the fluid depth $\mathbf{E}_{\text{eff}}(\mathbf{q},t)$ depends implicitly on the solution vector $\mathbf{q}(t)$ of the respective time integration step. As a consequence, the buoyancy, drag and inertial loads of equations (5) to (8) account implicitly for the solution-dependent effectively submerged span length $L_{\text{eff}}(\mathbf{q},t)$ and for the effectively submerged volume $V_{\text{eff}}(\mathbf{q},t)$.

**Hydrostatic buoyancy force and restoring moment**

Hydrodynamic loads are introduced through 1-noded Hydrodynamic Load Elements/HLE attached to each node of the FEM mesh of the offshore component. According to equation (5), the buoyancy force $\mathbf{F}_{\text{Buoy}}(\mathbf{q},t)$ and the restoring moment $\mathbf{M}_{\text{Buoy}}(\mathbf{q},t)$ are obtained from the integration of the pressure distribution that acts on the envelope surface of the submerged offshore components. In case of cylindrical geometries, the integrals of equation (5) are obtained analytically. According to the first integral term of equation (5), the direction of the buoyancy force $\mathbf{F}_{\text{Buoy}}(\mathbf{q},t)$ is opposed to the gravity vector and function of the integral of the pressure acting on the submerged envelope surface. The restoring moment $\mathbf{M}_{\text{Buoy}}(\mathbf{q},t)$ is determined by the second integral term of equation (5) where the lever vector $\mathbf{l}(\mathbf{q},t)$ points from the origin of the local coordinate system of the Hydrodynamic Load Element to the respective integration point of the envelope surface $\mathbf{S}(\mathbf{q},t)$ with the normal vector $\hat{n}(\mathbf{q},t)$. The orientation of the local axis of the restoring moment $\mathbf{M}_{\text{Buoy}}(\mathbf{q},t)$ results from the integral solution of the second term of equation (5) which is function of the inclination of the offshore component w.r.t. to the gravity vector.

**Hydrodynamic wave loads according to Morison’s equation**

Morison’s formula was originally applied to the computation of uncoupled hydrodynamic forces on vertical, fixed piles with shallow water wave loading. It has since been extended to a three-dimensional formulation for arbitrarily oriented moving structures, with both wave and current loadings [10][11][12]. As stated in equations (6) to (8), the coupled Morison equation presents an empirical formulation that describes the hydro-dynamic loads as a superposition of a fluid drag $\mathbf{F}_{\text{Drag}}$ and an inertial term $\mathbf{F}_{\text{Inertia}}$ that accounts for the added fluid mass accelerated due to the fluid-structure interaction.

DEWI offers an independent service for periodic technical inspections on wind turbines and wind farms during the project life cycle. The services provided by DEWI allow project developers, wind farm owners or investors to combine technical safety with a reliable and profitable management within the long-term operation of the wind farm.

As one of the leading international consultants in the field of wind energy, DEWI offers all kinds of wind energy related measurement services, energy analyses and studies, further education, technological, economical and political consultancy for industry, wind farm developers, banks, governments and public administrations. DEWI is accredited to EN ISO/IEC 17025 and MEASNET for certain measurements and is recognised as an independent institution in various measurement and expertise fields.

DEWI offers an independent service for periodic technical inspections on wind turbines and wind farms during the project life cycle. The services provided by DEWI allow project developers, wind farm owners or investors to combine technical safety with a reliable and profitable management within the long-term operation of the wind farm.

As one of the leading international consultants in the field of wind energy, DEWI offers all kinds of wind energy related measurement services, energy analyses and studies, further education, technological, economical and political consultancy for industry, wind farm developers, banks, governments and public administrations. DEWI is accredited to EN ISO/IEC 17025 and MEASNET for certain measurements and is recognised as an independent institution in various measurement and expertise fields.

www.dewi.de
The fluid drag vector formulated in equation (7) and the fluid inertial load vector formulated in equation (8) are both contained in the plane perpendicular to the span direction, but show generally different directions, i.e. the “angle of attack of the drag forces” and the “angle of attack of the inertia forces” do not generally coincide.

A coupled formulation of Morison’s approach is exposed in references [11][12] in a form analogous to equation (8) where the direction of the Morison inertia load vector is determined by 2 distinct contributions with a-priori 2 different vector orientations. The first term of the Morison equation (8),

\[
\rho \frac{\partial \mathbf{V}}{\partial t} (\mathbf{q}, t) \frac{\partial \mathbf{u}}{\partial t},
\]

contributes to the Morison inertia forces, if the unperturbed fluid flow is accelerated. The direction of that vector component corresponds to the direction of the unperturbed fluid direction, but projected into the plane which is perpendicular to the span direction of the offshore component. The second term of the Morison equation (8) contributes to the inertia forces through the relative fluid-structure acceleration

\[
\left( \frac{\partial \mathbf{u}}{\partial t}, \frac{\partial \mathbf{V}}{\partial t} \right)
\]

which results from the unperturbed fluid flow acceleration and from the dynamic response of the offshore structure. It should be noted that both vector components of equation (8) are projected onto the same plane which is perpendicular to the span wise direction, but the respective vector orientations of these two terms are not necessarily aligned if the structure vibrates and/or floats.

It is conjectured that the inclusion of the uncoupled inertia term of the Morison equation (8) might not be straightforward for a formulation dedicated to the simulation of coupled hydrodynamic and structural dynamic phenomena.

It is stipulated that the basic Morison equation as stated in references [10][11][12] might lead to an overestimation of hydrodynamic drag and/or inertia loads, because hydrodynamic inductions and/or wave dispersion are not accounted for in that formulation.

**Added Mass & Eigen-Modes**

The inertia term \( \mathbf{F}_{\text{Inertia}} \) of the Morison equation (8) modifies the total mass associated to the submerged offshore...
structure and as a consequence the Eigen-Modes of the offshore wind turbine are affected. As outlined, the implemented algorithm for the hydrodynamic loads accounts implicitly for the kinematics induced by a heavily moving offshore wind turbine and transient wave height. The total mass taken into account in the Eigen-mode computation of the offshore structure is complemented through the derivative of the inertia term of the Morison equation (8) with respect to the relative accelerations in between the fluid and the vibrating and/or floating offshore structure. Equations (9, 10) define the added mass term in terms of the derivative of the Morison inertia force with respect to the structural accelerations of the respective node of the FEM model. As stated in equation (10) in tensorial form using the Einstein summation convention, the “added fluid mass” is obtained through the derivative of the Morison inertia term and can be presented in terms of two contributions. The first contribution is determined by the added mass $aC_{sub}V\rho$ multiplied by the dyadic product of the acceleration unit vector $\ddot{a}\odot\ddot{a}$. It is emphasized that the unit vector $\ddot{a}$ is contained in the plane perpendicular to the span wise direction of the respective component and might be interpreted as the vector defining the direction of the inertia loads. The second term of equation (10) depends not only on the vector $\ddot{a}$, but as well on the structural acceleration of the respective FEM node $\ddot{q}$ and on the derivative of the acceleration unit vector $\ddot{a}$. As a consequence the additional fluid mass included in the global mass and inertia matrix of equation (1) becomes time dependent and also dependent on the instantaneous spatial direction of the relative acceleration which occurs in between the fluid and the submerged offshore structure. Therefore, not only do the Eigen-Frequencies of the offshore wind turbine become time dependent, but also the Eigen-Shapes are affected by the added fluid mass, because the added mass is directional.

Airy’s linear wave theory
In the present studies, the unperturbed fluid velocity/acceleration field is modelled according to equation (11) through Airy’s wave theory [13][14] that approximates the transient fluid dynamics of waves as a function of parameters like water depth, wave height and period. The following application examples are based on fluid/water speed distributions according to equation (11) and are generated by the independent program Waveloads of the University of Hannover [13].
Application Examples

Two distinct simulations of offshore wind turbines are presented. Even though the implemented methodology supports the implementation of very complex offshore structures in terms of general FEM models, in the present examples the offshore structures are modelled by non-linear beam elements of circular geometry.

The first application corresponds to an offshore wind turbine supported by a jacket structure that corresponds to the OC4 reference base line model [15]. The second example presents a floating offshore wind turbine whose floater and mooring lines correspond to the OC3 reference model [16].

Offshore wind turbine supported by Jacket structure

Fig. 1 presents the S4WT wind turbine model supported by a jacket structure according to the OC4 reference model [15]. The applied wind turbine model comprises in total 3732 DOFs and includes a detailed gearbox model, pitch and yaw drives and further flexible structural components like the bedplate and nacelle structure in terms of Super Elements. The jacket structure is modelled by non-linear beam elements and loaded by buoyancy and hydrodynamic loads.

The following simulation results correspond to a load case with wind field of a mean speed of 10 [m/s] and a wave definition according to Airy’s linear wave model with the following characteristics:
- Wave Height: 6m, Wave Period: 10s, Water Depth: 50m
- Angle in between wave & wind direction: 0 [deg.]

Note that the spatial fluid speed distribution is obtained from the external software Waveloads [13]. The corresponding acceleration field of the external wave and the relative structural-fluid accelerations of equations (8) are computed in the hydrodynamic element of the solver SAMCEF-Mecano.

Fig. 3 presents the hydrodynamic boundary conditions for the jacket node #40 located closely to the Still Water Level/SWL. The applied wave velocities in longitudinal XGL and vertical ZGL directions refer to the left ordinate of Fig. 3 and the wave height refers to the right ordinate of Fig. 3. The location of the jacket node #40 considered here is depicted in Fig. 1. Fig. 4 presents for node #40 the resulting buoyancy force, the fluid drag and finally the Morison inertia force.

Floating offshore wind turbine

Fig. 5 presents the S4WT model of a floating offshore wind turbine supported by a floating structure according to reference [16]. The wind turbine model comprises in total 3402 DOFs and includes a detailed power train model, pitch and yaw drives and further flexible structural components like the mooring lines.

The simulated load case corresponds to a constant wind field of a mean speed of 16 [m/s] and a wave definition according to equation (11) with the following characteristics:
- Wave Height: 6m, Wave Period: 10s, Water Depth: 320m
- Angle in between wave & wind direction: 45 [deg.]

As depicted in Fig. 5, the floating offshore wind turbine is attached by 3 cables which are separated each by a rotation of 120 [degrees] w.r.t. to the vertical reference axis. The length of each cable is about 700 [m]. In S4WT’s floating
SAMCEF for Wind Turbines European Tour:

- 27th September 2011, Barcelona, Spain
- 16th November 2011, Liège, Belgium

Registration opened on www.samtech.com!

Design tomorrow’s On- & Offshore Wind Turbines!

More information on contact@samtech.com
wind turbine model, the cables are presented either by non-linear cable elements ( neither compression, nor bending stiffness), or respectively by non-linear Beam Elements.

The large oscillations of the floating wind turbine induce large low frequency speed variations in the rotor plane. Fig. 6 clearly shows the low frequency speed and rotor torque variations induced by the global tilt oscillations of the floating turbine. It can be noted that further controller tuning would be required in order to reduce these oscillations induced by the floating wind turbine concept.

Fig. 6 presents the blade pitch, speed and power transients of the presented floating offshore wind turbine. The presented transients of blade pitch angle and the produced power show low frequency oscillations induced by the rotor plane speed variations due to the tilt oscillations of the entire floating wind turbine.

The tower-top trajectory in longitudinal XGL direction (direction of incoming wind) and in the horizontal YGL, is shown on the top-right corner of Fig. 5. The maximum oscillation of the tower-top of the floating wind turbine in the longitudinal direction is evaluated from -1.5 [m] to 9 [m], i.e. a total displacement range of the tower-top of nearly 14[m] in the longitudinal direction. In the case of the simulated wave height of 6 [m], due to the induced buoyancy loads, the wind turbine top oscillates approximately 2[m] in the vertical direction.

On the lower right portion of Fig. 5, the external hydrodynamic fluid loads applied on a specific node of the mooring line FEM model are presented. The location of mooring line node #49 is presented in Fig. 5. It is noted that the Morison inertia force module presents a phase offset with respect to the drag force. The drag and inertial forces are both contained in the same plane perpendicular to the span direction, but the orientation of both force components do not generally coincide.

Conclusions

Morison’s equation was implemented in the solver SAMCEF-Mecano in an extended form proposed in several references such as [11] and [12] in order to account for structural dynamics and hydrodynamics coupling effects. The coupled form of the Morison equation is interpreted as an empirical approximation for the modelling of hydrodynamic currents and/or waves and can be decomposed into two principal contributions. On the one hand, an “uncoupled inertia term” which is only function of the acceleration of the fluid flow, and, on the other hand, a “coupled inertia term” which is function of the relative acceleration in between the offshore structure and the unperturbed fluid flow. It is conjectured that the precision and application range of the coupled form of Morison’s equation might be improved with some further modifications. First, it might be convenient to formulate not only the second term, but as well the first term of the Morison equation (8) implicitly as a function of the dynamic response of the offshore structure. Second, Morison’s model does not account for hydrodynamic inductions on the unperturbed fluid speeds and/or accelerations which would result from the fluid-structure interaction. Analogously, the dispersion of an impacting wave on the offshore structure is not accounted for in Morison’s empirical model. As a consequence, it is stipulated that the application of the Morison equation might tend to an overestimation of hydrodynamic drag and/or fluid inertia loads. It is conjectured that the empirical formulation of Morison might be improved if the added mass coefficient, or respectively the Morison coefficient, is formulated as an empirical decay function of the ratio between the hydraulic diameter and the wavelength, as stated by MacCamy and Fuchs [17]. These empirical decay functions might approximate roughly the effect of fluid-structure inductions and/or wave dispersion, as it has been already reflected in some recommended practices regarding offshore structures [18]. Future implementations will be devoted to automatically modifying the
Morison coefficient taking into account these experimental observations and the corresponding wave dynamics. The fully coupled philosophy of the current code will be kept during this new development, so the effects of the structure kinematics will be considered during hydrodynamic load computation.

Two distinct offshore wind turbines have been analyzed by a fully coupled aerodynamic, hydrodynamic and structural dynamic approach. In the first application example, the OC4 offshore wind turbine model was chosen. The corresponding aero-elastic S4WT wind turbine model is supported by a hydro-dynamically loaded jacket FEM model, includes flexible MBS models of the major mechanisms like the power train including the gearbox, the yaw and the pitch drives, and comprises in total 3732 Degrees of Freedom. The required CPU time for transient analysis on a standard Intel Duo Core 3.2GHz computer, was similar compared to standard "onshore high fidelity wind turbine models" with a CPU time factor of about 45 with respect to real time. It is mentioned that required CPU times depend strongly on the number of Degrees of Freedom and on the excited frequency content of the respective model. In the case of simplified wind turbine models that comprise less than 1000 DOFs, the required CPU is generally less than a factor of 10 with respect to real time.

In the case of the OC3 offshore reference model, the floating wind turbine model is not restrained by fixations as in the case of clamped jacket supports. Instead, the floater is attached to flexible mooring lines attached to the seabed. As a consequence, the dynamic equilibrium of the oscillating floating wind turbine is strongly influenced by coupled buoyancy, hydrodynamic and aero-elastic loads which all strongly mutually interact together with controller actions. In particular the low frequency oscillations of the floating turbine induce large speed variations in the rotor plane. In order to reduce the observed rotor plane speed variations induced by the oscillating floating wind turbine, specific controller tuning for blade pitch and generator torque would be required. Future research will include specific control strategies in order to reduce these oscillations, for instance via the integration of active damping techniques.

References
[15]. F. Vorpahl, W. Popko, D. Kaufer. Description of a basic model of the “Upwind reference jacket” for code comparison in the OC4 project under IEA Wind Annex XXX; Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), 4 February 2011