Offshore Wind Turbine Hydrodynamics Modeling in SIMPACK

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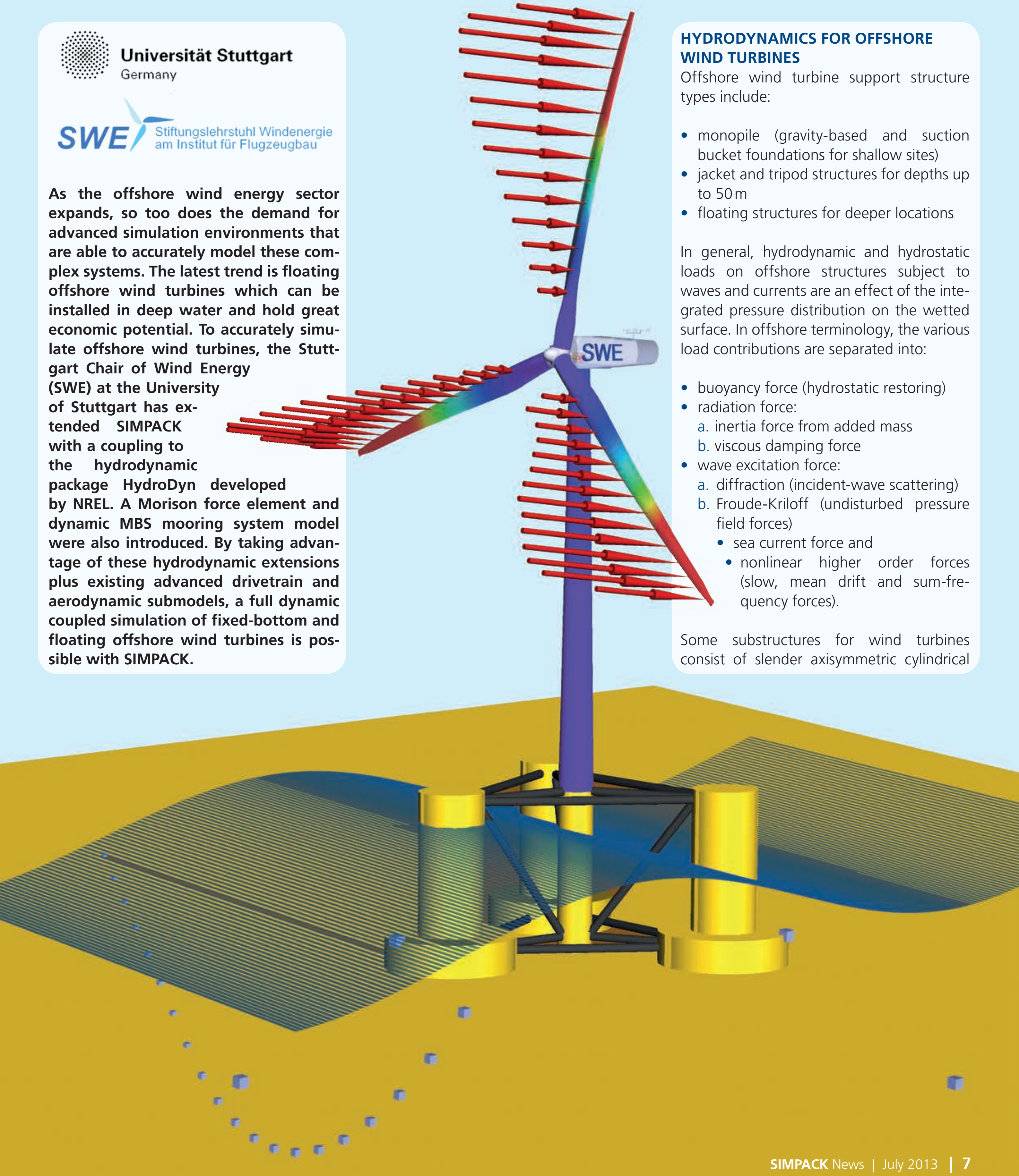
As the offshore wind energy sector expands, so too does the demand for advanced simulation environments that are able to accurately model these complex systems. The latest trend is floating offshore wind turbines which can be installed in deep water and hold great economic potential. To accurately simulate offshore wind turbines, the Stuttgart Chair of Wind Energy (SWE) at the University of Stuttgart has extended SIMPACK with a coupling to the hydrodynamic package HydroDyn developed by NREL. A Morison force element and dynamic MBS mooring system model were also introduced. By taking advantage of these hydrodynamic extensions plus existing advanced drivetrain and aerodynamic submodels, a full dynamic coupled simulation of fixed-bottom and floating offshore wind turbines is possible with SIMPACK.



HYDRODYNAMICS FOR OFFSHORE WIND TURBINES

Offshore wind turbine support structure types include:

- monopile (gravity-based and suction bucket foundations for shallow sites)
- jacket and tripod structures for depths up to 50 m
- floating structures for deeper locations

In general, hydrodynamic and hydrostatic loads on offshore structures subject to waves and currents are an effect of the integrated pressure distribution on the wetted surface. In offshore terminology, the various load contributions are separated into:

- buoyancy force (hydrostatic restoring)
- radiation force:
  a. inertia force from added mass
  b. viscous damping force
- wave excitation force:
  a. diffraction (incident-wave scattering)
  b. Froude-Kriloff (undisturbed pressure field forces)
    - sea current force and
    - nonlinear higher order forces (slow, mean drift and sum-frequency forces).

Some substructures for wind turbines consist of slender axisymmetric cylindrical elements. This enables the use of the simple and efficient semi-empirical Morison Equation which is valid if the flow acceleration can be assumed uniform at the location of the cylinder thus simplifying the diffraction problem. This requires that the diameter of the cylinder D be much smaller than the wavelength L — typically D/L values of less than 0.15–0.2. It is also assumed that relative motions are small so that viscous drag dominates the damping; radiation damping can be neglected; and that off-diagonal added-mass terms are negligible, as in the case of axisymmetric structures. Since the equation contains empirical coefficients for added mass, inertia and drag (which depend on the Keulegan-Carpenter number, Reynolds number and surface roughness), careful attention to these is required to obtain viable results.

For structures with larger diameters and larger motions—typically tripods or floating structures—effects from hydrodynamic radiation and diffraction (not considered by Morison's Equation) become important. For such structures, linear hydrodynamic theory is currently most commonly used. It is based on potential theory, and includes effects from linear hydrostatic restoring, added mass and damping contributions from linear wave radiation (including free-surface memory effects), and incident wave excitation from linear diffraction. Typically, nonlinear viscous drag contributions are

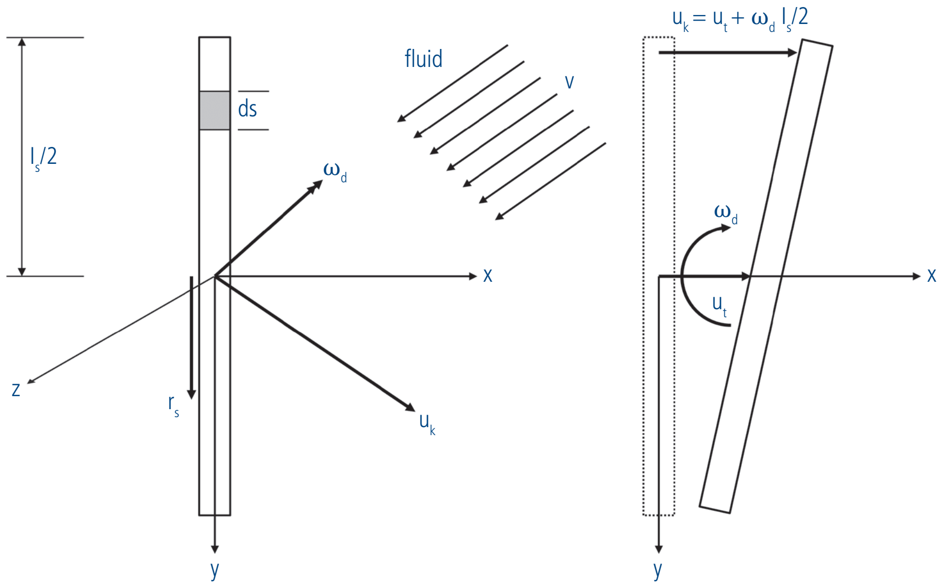


Fig 1: Calculation of Morison forces on mooring line segment

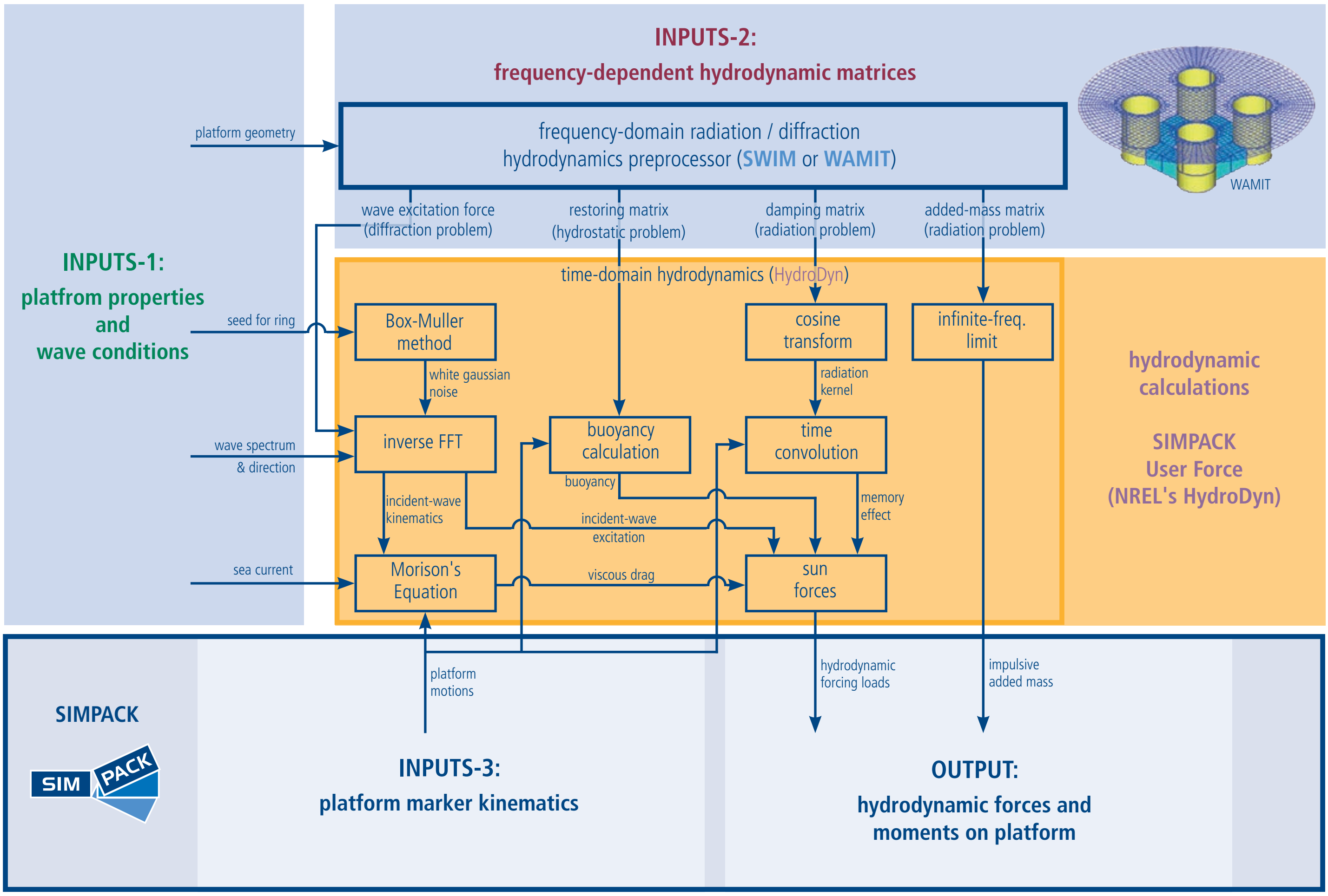


Fig 2: HydroDyn calculation procedure and interface to SIMPACK (image source: NREL)

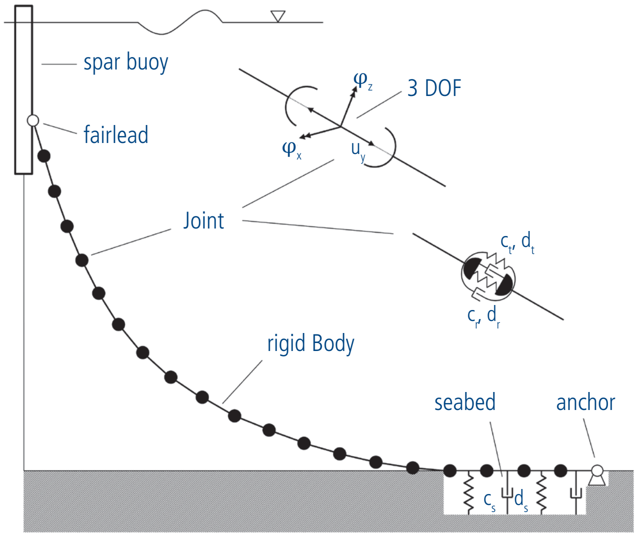


Fig 3: Topology of dynamic nonlinear MBS mooring system

added from Morison's equation. However, nonlinear steep and/or breaking waves, vortex-induced vibrations, second-order effects of mean-drift, slow-drift and sum-frequency excitation, and any other higher order effects, are neglected within HydroDyn. To overcome this limitation, a coupling between SIMPACK and the Computational Fluid Dynamics (CFD) tool ANSYS CFX is currently being developed at SWE (Beyer, Arnold & Cheng, 2013). The incorporation of second-order hydrodynamic effects is planned for future releases of HydroDyn.
To enable modeling of offshore wind turbines in SIMPACK, the two hydrodynamic modeling methodologies described have been implemented. Currently, most other commercial codes only apply Morison's equation and are, therefore, limited to aforementioned slender structures where radiation damping and off-diagonal added-mass terms are negligible.

"For cylindrical fixed-bottom structures and mooring systems, a SIMorison user Force Element was implemented at SWE into SIMPACK 9."

MORISON FORCE ELEMENT

For cylindrical fixed-bottom structures and mooring systems, a SIMorison user Force Element was implemented at SWE into SIMPACK 9. It uses the relative formulation of the Morison equation according to Östergaard and Schellin, and also includes an option to directly account for buoyancy if the body is always completely submerged. Due to the relative simplicity of the Morison Equation, the user only needs to supply values for the two empirical coefficients: inertia C_m and drag C_D. A Reynolds dependency of these coefficients can be added. Water density, kinematic viscosity, effective cylindrical diameter (to determine the cross sectional area) and length of the body where the Force Element is applied also need to be defined. The desired discretization of a mooring system can be achieved by using multiple Morison Force Elements along cylindrical structures with different diameters and lengths (Fig. 1).
Since the Morison equation in its relative formulation features an added mass term depending on the relative fluid acceleration, the routine requires the structure to accelerate at each time step. In MBS, the acceleration is usually not solved during integration, thus making the implementation of Morison's Equation complex. Here, SIMPACK's ability to use algebraic states (q-states) is utilized, "anticipating" acceleration results of the Right-Hand Side, i.e., making them available before they are actually calculated.

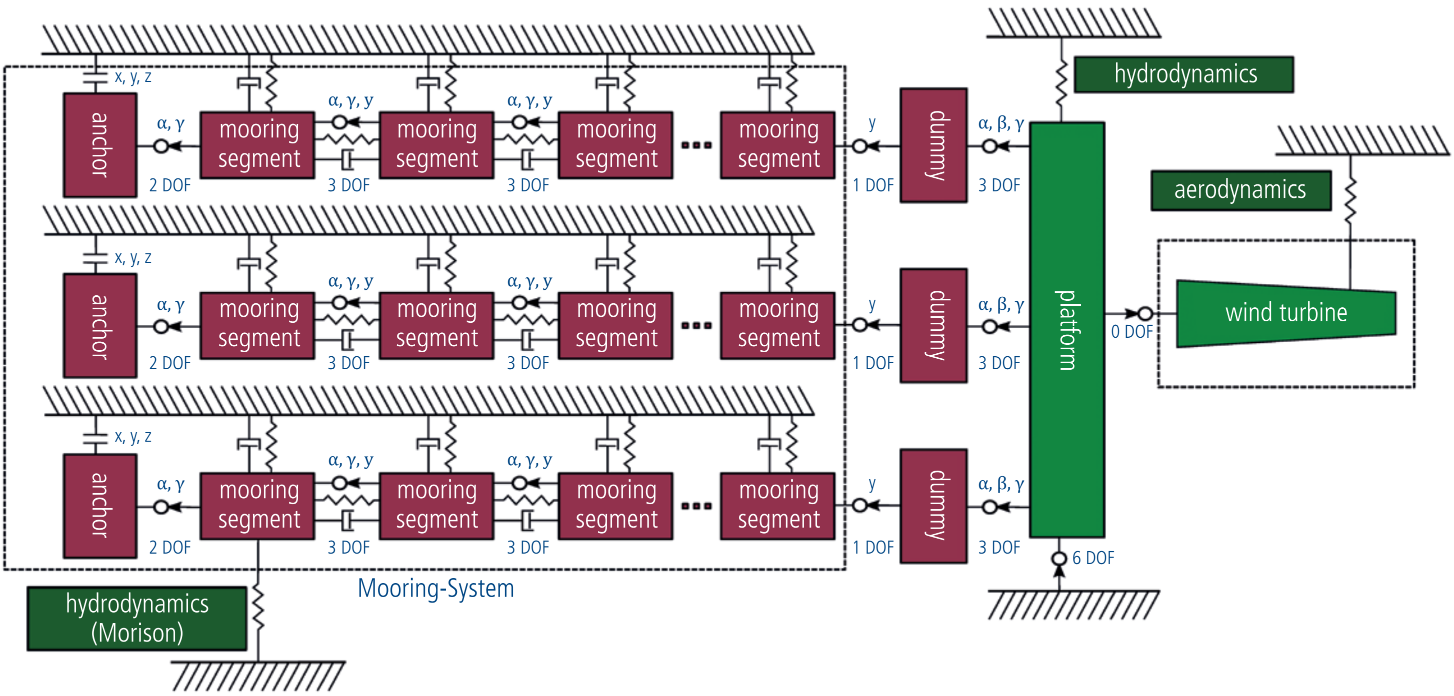


Fig 4: Topology of floating offshore wind turbine

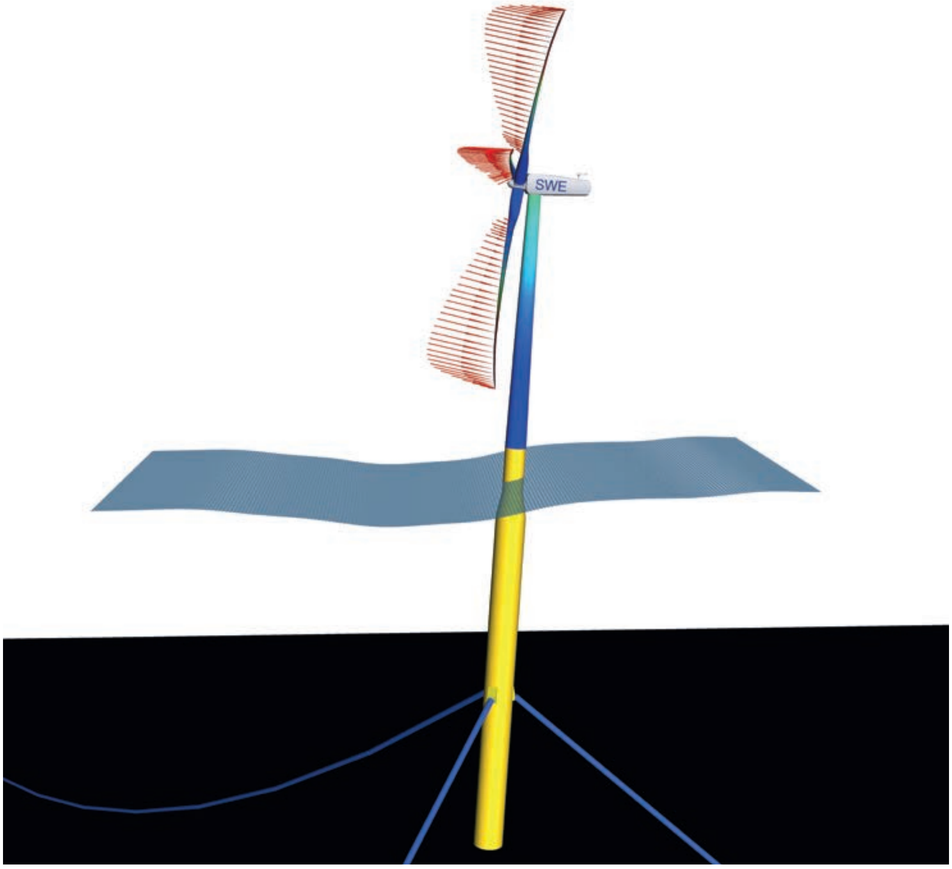


Fig 5: OC3 spar-buoy floating wind turbine model with MBS mooring system

At SWE, the SIMorison Force Element is primarily used and validated by modeling the hydrodynamic loads on mooring lines. The regular or irregular Airy wave kinematics used by this element are computed by the SIMHydro element which is described next.

SIMHYDRO — COUPLING TO NREL'S HYDRODYN

The SIMHydro Force Element couples NREL's HydroDyn module with SIMPACK (Fig. 2). HydroDyn was developed by Jason Jonkman at NREL (Jonkman, 2007) and has since been used to model monopiles and various floating structures. The current release of HydroDyn offers four important features:

- a wave generator for periodic and regular/irregular Airy waves (JONSWAP, PM spectra) including stretching
- the Morison equation module for hydrodynamic load calculation
- a linear hydrodynamics module for load calculation on non-slender (floating) bodies
- a quasi-static mooring line module for mooring system load calculation of floating platforms

"At SWE, a dynamic nonlinear mooring line model has been developed within SIMPACK to overcome the drawbacks of the quasi-static approach."

The wave generator can generate either periodic waves or random irregular Airy waves with user-defined significant wave height and peak spectral period based on a defined wave spectrum (the JONSWAP and Pierson-Moskovitz spectra are predefined). Kinematic stretching (Vertical, Extrapolation, Wheeler) is also implemented to provide predictions of wave kinematics above the mean water level; an option used only for Morison calculations since it is inconsistent with linear hydrodynamic theory.

The Morison Equation implementation of HydroDyn is equivalent to the previously described Morison Force Element. It accounts for the current fraction of wetted surface dependent on instantaneous wave elevation. Currently, it is applicable for monopile structures, and the upcoming HydroDyn version 2 (already available in an alpha version) will then be able to simulate multi-member fixed-bottom and floating substructures such as jackets or semi-submersibles with the Morison Equation.

The third feature of HydroDyn is its linear hydrodynamic model. It computes loading contributions from:

- linear hydrostatic restoring
- nonlinear viscous drag contributions from Morison's Equation
- added mass and damping contributions from linear wave radiation (including free-surface memory effects)
- incident wave excitation from linear diffraction

The linear hydrodynamic option in HydroDyn requires the user to enter frequency-dependent hydrodynamic vectors and matrices. These must be pre-calculated by external offshore panel-based codes such as WAMIT® or ANSYS® AQWA™, which solve the linearized radiation and diffraction problems in the frequency domain. Full details of HydroDyn's theory are given in Jonkman (Jonkman, 2007). The upcoming HydroDyn version 2 release will also feature the possibility of Morison elements with linear hydrodynamics which can be used to model the hydrodynamic forces on the main pontoons of a semi-submersible with linear theory and on the braces with Morison's.

The fourth module within HydroDyn provides a quasi-static mooring line model to efficiently calculate mooring line loads on floating platforms. At SWE, a dynamic nonlinear mooring line model has been developed within SIMPACK to overcome the drawbacks of the quasi-static approach (Fig. 3, 4). More details on this MBS mooring line model are given by Matha (Matha, Fechter, Kühn, Cheng, 2011).

The original input file for HydroDyn has been modified for usage in SIMPACK and allows the user to define the incoming waves, to select between the Morison and linear hydrodynamic module, and define the properties of the mooring system.

VALIDATION WITH OC3 & OC4

The SIMHydro coupling was first validated with results from phase four of the IEA Annex 23 Offshore Code Comparison Collaboration (OC3) project (Fig. 5), and is currently used in phase two of the follow-up OC4 project. Exemplary results from OC4 load cases 1.3, representing free decay tests where the semi-submersible platform (Fig. 6) is released at an initial displacement in still water without wind loads, are shown in Fig. 7 and Fig. 8.

The presented platform surge and pitch displacement show very good agreement between SIMPACK and other participants applying linear hydrodynamic theory like FAST (NREL) and DeepLinesWT (Principia). Compared to codes using Morison's equation for modeling the hydrodynamics — like HAWC2 (DTU) and Bladed (GH) — distinct

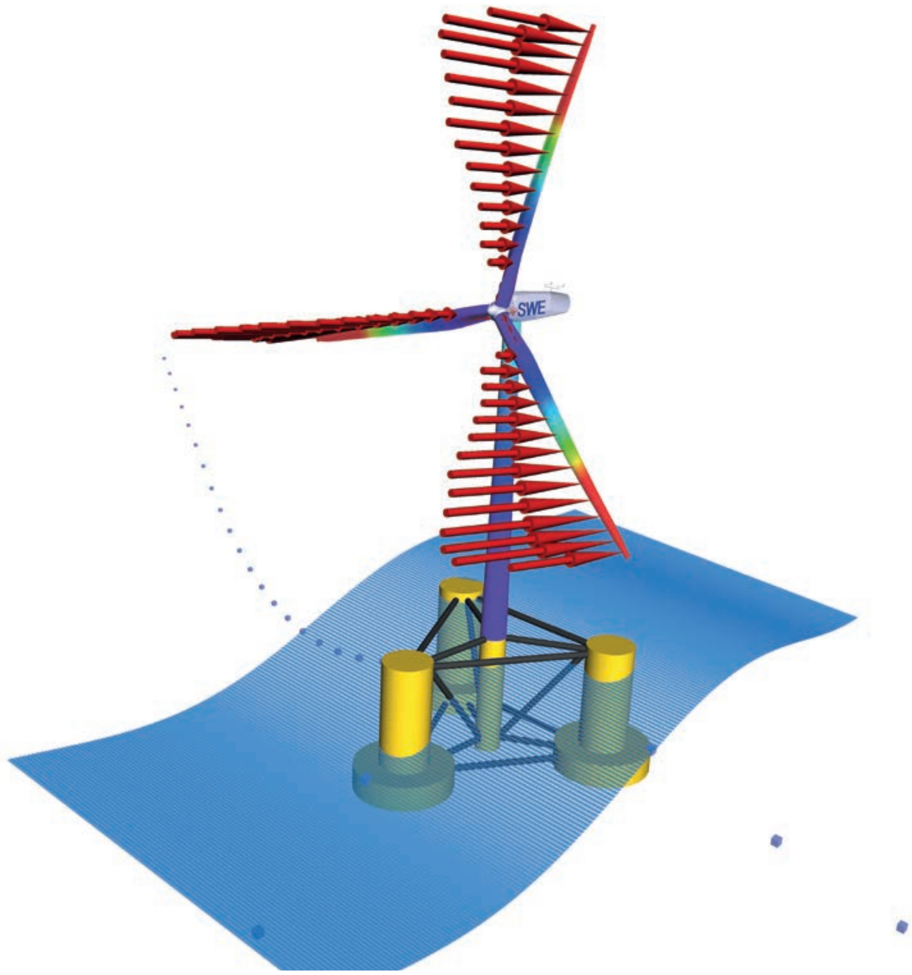


Fig 6: OC4 semi-submersible floating wind turbine with quasi-static mooring system (only nodes displayed)

differences in load and motion predictions are evident depending on the load case. This is due to the differences in the semi-empiric approach of a Morison-only formulation.

USAGE OF SIMPACK OFFSHORE

SWE uses SIMPACK to model offshore floating wind turbines in the European research projects OFFWINDTECH, Innwind, AFOSP and FLOATGEN. The latter is currently the largest EU-funded offshore wind energy research project and will deploy two multi-MW floating wind turbine systems in Mediterranean waters over 40 m deep. With this project, the SWE will have the opportunity to compare the SIMPACK floating wind turbine model with measured scale and full-scale prototype data, analyze the differences, validate the predictions and improve the models where required.

SUMMARY

The implementation of SIMorison and SIMHydro Force Elements makes it possible to simulate fixed-bottom and floating wind turbines with SIMPACK. The coupling is validated by OC3 and OC4. SIMPACK offshore wind turbine models have already been successfully applied in a number of research projects, and show excellent potential for future applications.

REFERENCES

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Jonkman, J. (2007). Dynamics Modeling and Loads Analysis of an Offshore Floating Wind Turbine. NREL/TP-500-41958. Golden, US-CO: National Renewable Energy Laboratory.

Matha, D., Fechter, U., Kühn, M., Cheng, P. W. (2011). Non-linear Multi-Body Mooring System Model for Floating Offshore Wind Turbines. University of Stuttgart, OFFSHORE 2011, Amsterdam, Netherlands.

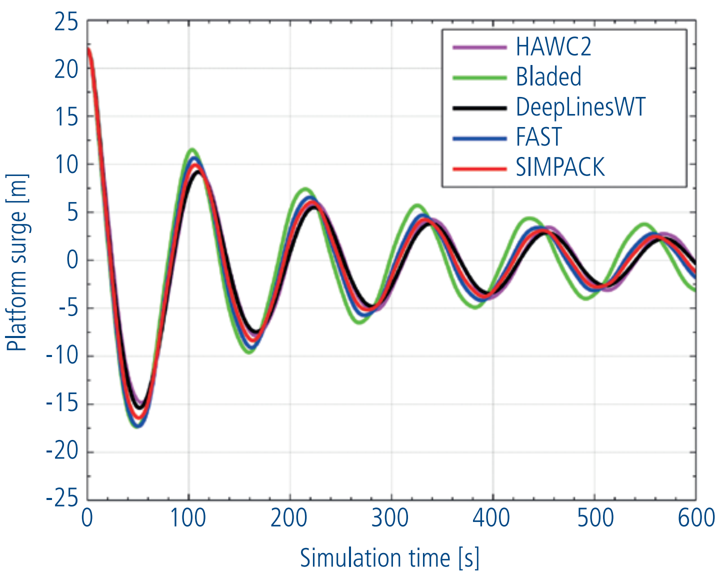

Fig 7: OC4 LC 1.3a: Platform translation in surge direction

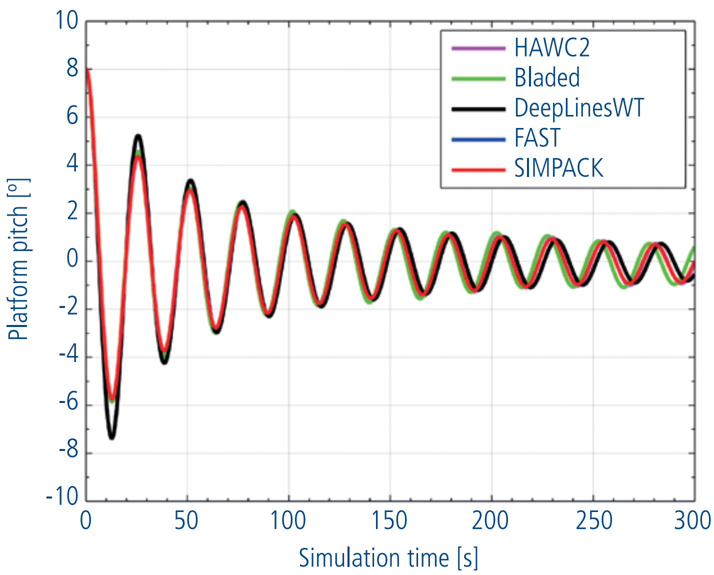

Fig 8: OC4 LC 1.3c: Platform rotation in pitch direction