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# **Development of coupling module between BHawC aeroelastic** software and OrcaFlex for coupled dynamic analysis of floating wind turbines

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Abstract. Floating Offshore Wind Turbines (FOWTs) dynamic analysis can be quite challenging as it requires to model within the same calculation aerodynamics, hydrodynamics, controller, moorings and structure behaviour. Mooring and anchor design are strongly affecting FOWTs dynamic behaviour. Also, floater structural behaviour can be complex to model in a decoupled finite element analysis software. To do so, Innosea and Siemens Gamesa Renewable Energy developed a coupling between BHawC software and OrcaFlex software. BHawC is a nonlinear aeroelastic tool performing dynamic analysis of wind turbines. OrcaFlex is a generalist offshore marine engineering software that can perform the dynamic analysis of floaters and their mooring system. This paper describes the method and the mathematical background that is used to perform detailed time-domain simulations of a floating wind turbine coupling BHawC and OrcaFlex. The coupling is verified comparing time domain simulations on several load cases for rigid floaters coupled to a turbine with a rigid RNA. This shows a good agreement which confirms the correctness of the coupling.

# **1. Introduction**

With the emerging floating wind market, the need to model complex floating foundations and to perform coupled dynamic analysis of floating wind turbine systems is arising. This type of analysis requires accurate modeling of the coupled wind turbine structural dynamics, control algorithms, aerodynamics, floater hydrodynamics, floater structural dynamics and mooring system. Several wind turbine suppliers use internal, in-house aeroelastic software tools for the modelling and design of their platforms. These tools have been primarily developed for onshore and bottom-fixed offshore turbines. Adapting these tools for floating wind turbines would be a significant development effort, with the need to implement features such as amongst others multibody potential flow hydrodynamic theory, mooring line dynamics. Another strategy is to couple these aeroelastic tools with offshore software tools already having the relevant features.

Siemens Gamesa Renewable Energy (SGRE) and Innosea have addressed the issue by developing a software solution in the form of a Dynamic Link Library (DLL) that connects BHawC software and OrcaFlex software:

Siemens Gamesa Renewable Energy performs time domain analyses for offshore wind turbines for design and structural integrity checks of the Rotor Nacelle Assembly (RNA),

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tower and foundation with their in-house code BHawC. This is a non-linear aeroelastic tool for dynamic analysis of wind turbines.

- OrcaFlex developed by Orcina is the world's leading commercial software for the dynamic analysis of offshore marine systems. OrcaFlex has the capability to be used as a library, allowing a host of automation possibilities and ready integration into 3<sup>rd</sup> party software.

This paper describes the method, mathematical background and the implementation that is proposed to perform detailed time-domain simulations of a floating wind turbine using BHawC and OrcaFlex. It is based on domain decomposition, using multi-step time integration with a staggered scheme. Several key challenges inherent to such coupling have been tackled. Amongst others: FOWT model split between the two software, handling the different simulation phases, coupling the dynamics, convergence of the coupled system, different coordinate frames and the synchronisation of time steps. The coupling is verified comparing time domain simulations on several load cases for rigid floaters coupled to a turbine with a rigid RNA.

#### 2. Description of the numerical framework of the coupling

The coupling methodology is based on a Dynamic Link Library (DLL) that connects BHawC and OrcaFlex software. The five actors of the coupling are identified on Figure 1:

- BHawC: BHawC is SGREs aero-servo-elastic software. Tower elements above interface flange and RNA are modelled and dynamically analysed by BHawC;
- BHawCLink: This module has been developed by SGRE to perform coupled dynamic simulations with BHawC and an external software. This linker is only designed to do the communication with BHawC;
- The DLL: the DLL connects the BHawCLink and the OrcaFlex API;
- OrcaFlex API: This is the OrcaFlex interface used to communicate with OrcaFlex. The API is developed by Orcina;
- OrcaFlex: Selected software responsible for the hydrodynamic and structural dynamic simulations of the floater. The floater and mooring lines are modelled and dynamically analysed by OrcaFlex. It is developed by Orcina.

The DLL communicates with BHawCLink and the OrcaFlex API. The DLL facilitates coupled dynamic simulation in which the response of each of the subsystems (tower and RNA in BHawC on the one hand; foundation in OrcaFlex on the other hand) is updated during the iterative 'enhanced' explicit scheme. BHawC is the master of the coupling, meaning that BHawC initiates and finalizes the coupled simulations.



Figure 1 Coupling stakeholders.

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#### 3. Mathematical background

In this solution, tower and floating foundation will be treated and solved as two separate substructures, which are connected at a certain height along the tower. This connection point is also referred to as the (numeric) interface; it represents the interface between the aero-elastic simulation performed in BHawC and the solution for the floating foundation in OrcaFlex. The following sections are mostly based on [4], [5] and [6].

#### 3.1 Decoupling equations of motion

In Figure 2, a graphical representation is given of the two decoupled substructures, and the interface forces and motions.



Figure 2 Graphical representation of decoupled foundation and wind turbine

The equations of motion of the uncoupled wind turbine can be described as:  $\boldsymbol{M}^{(W)}(\boldsymbol{u}^{(W)})\boldsymbol{\ddot{u}}^{(W)} + \boldsymbol{p}^{(W)}(\boldsymbol{\dot{u}}^{(W)}, \boldsymbol{u}^{(W)}) = \boldsymbol{f}^{(W)}(\boldsymbol{\dot{u}}^{(W)}, \boldsymbol{u}^{(W)}) + \boldsymbol{g}^{(W)}$ (1)

In this equation,  $\mathbf{M}^{(W)}$  is the configuration dependent mass matrix,  $\mathbf{p}^{(W)}(\dot{\mathbf{u}}^{(W)}, \mathbf{u}^{(W)})$  is a vector expressing internal (non-linear) elastic and damping forces,  $f^{(W)}(\dot{\mathbf{u}}^{(W)}, \mathbf{u}^{(W)})$  represents the external forces on the wind turbine and  $\mathbf{g}^{(W)}$  represents the interface force vector, containing forces due to the coupling with the foundation substructure. Note that the time dependency is not explicitly written out in this equation. The equations of motion for the foundation can be written in a similar way.

Two signed Boolean matrices  $B^{(W)}$  and  $B^{(F)}$  are introduced which locate the relevant boundary degrees of freedom of both substructures. These Boolean matrices are used to rewrite the imposed continuity of displacements at the interface in terms of the full degrees of freedom of the substructure:  $u^{(W)} = u^{(F)} - B^{(W)}u^{(W)} + B^{(F)}u^{(F)} = 0$ (2)

$$\boldsymbol{u}_{b}^{(W)} - \boldsymbol{u}_{b}^{(F)} = \boldsymbol{B}^{(W)} \boldsymbol{u}^{(W)} + \boldsymbol{B}^{(F)} \boldsymbol{u}^{(F)} = \boldsymbol{0}$$
(2)

The equations of motion of the turbine and the foundation can be coupled using dual assembly. Lagrange multipliers are used to impose compatibility and equilibrium at the interface between the structures. When it is assumed that equilibrium at the interface is satisfied by the Lagrange multipliers  $\lambda$ , the interface force  $g^{(s)}$  of substructure (s) can be replaced with  $B^{(s)^T} \lambda$ . Thereby the coupled set of equations of motions to solve becomes:

 $\begin{cases} M\ddot{u} + p + B^T\lambda = f\\ Bu = 0 \end{cases},$ (3)

with:

$$\boldsymbol{M} = \begin{bmatrix} \boldsymbol{M}^{(W)} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{M}^{(F)} \end{bmatrix}, \boldsymbol{p} = \begin{bmatrix} \boldsymbol{p}^{(W)} \\ \boldsymbol{p}^{(F)} \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} \boldsymbol{B}^{(W)} & \boldsymbol{B}^{(F)} \end{bmatrix}, \boldsymbol{f} = \begin{bmatrix} \boldsymbol{f}^{(W)} \\ \boldsymbol{f}^{(F)} \end{bmatrix}, \boldsymbol{u} = \begin{bmatrix} \boldsymbol{u}^{(W)} \\ \boldsymbol{u}^{(F)} \end{bmatrix}$$

#### 3.2 Time integration

In BHawC the generalized- $\alpha$  method [5] is implemented to discretize the system for numeric integration. The Newton-Raphson scheme is used to minimize the residual. In this scheme, the effective stiffness matrix S of a nonlinear function is used to determine the correction of an initial solution. As the interface forces are also unknowns, the system to solve for a next Newton-Raphson step is [6]:

$$\begin{bmatrix} \boldsymbol{S}^{(W)} & \boldsymbol{0} & \boldsymbol{B}^{(W)}^{T} \\ \boldsymbol{0} & \boldsymbol{S}^{(F)} & \boldsymbol{B}^{(F)}^{T} \\ \boldsymbol{B}^{(W)} & \boldsymbol{B}^{(F)} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{u}_{n}^{(W)} \\ \Delta \boldsymbol{u}_{n}^{(F)} \\ (1 - \alpha_{f}) \Delta \boldsymbol{\lambda}_{n} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{r}_{n}^{(W)} \\ -\boldsymbol{r}_{n}^{(F)} \\ \boldsymbol{0} \end{bmatrix}.$$
 (4)

Where the Jacobian S for support structure (s) can be written as:

$$\boldsymbol{S}^{(s)} = (1 - \alpha_m) \left( \frac{\partial \boldsymbol{M}^{(s)}}{\partial \boldsymbol{u}^{(s)}} \ddot{\boldsymbol{u}}^{(s)} + \boldsymbol{M}^{(s)} \frac{1}{\beta h^2} \right) + (1 - \alpha_f) \left( \frac{\gamma}{\beta h} \boldsymbol{C}_t^{(s)} + \boldsymbol{K}_t^{(s)} \right),$$
(5)

with

$$\boldsymbol{C}_{t}^{(s)} = \frac{\partial \boldsymbol{p}^{(s)}}{\partial \dot{\boldsymbol{u}}^{(s)}} - \frac{\partial \boldsymbol{f}^{(s)}}{\partial \dot{\boldsymbol{u}}^{(s)}}$$

and

$$\boldsymbol{K}_{t}^{(s)} = \frac{\partial \boldsymbol{p}^{(s)}}{\partial \boldsymbol{u}^{(s)}} - \frac{\partial \boldsymbol{f}^{(s)}}{\partial \boldsymbol{u}^{(s)}}$$

being respectively the tangent stiffness and tangent damping matrices and  $\alpha_m$ ,  $\alpha_f$ ,  $\beta$ ,  $\gamma$  and h the integration parameters related to the generalized- $\alpha$  method. Note that  $C_t^{(s)}$  and  $K_t^{(s)}$  are assumed to be known as separate entities in the equations of motions of both structures.

#### 3.3 Coupling

Both substructures perform an individual time integration, while during this integration the solution is coupled at the interface. This means that during the iterations performed to solve the non-linear equations within a timestep in one of the substructures, the response of the complementary substructure is accounted for and updated per iteration.

Van der Valk [6] has derived that during the iteration, the problem can be solved as two uncoupled systems. This can be done by substituting the expression for the interface force change due to a change in displacements in the residual equation of the wind turbine. As such the only unknowns in the residual equation of the wind turbine are the displacements. To find these displacements, an update on them can be done by solving a Newton-Raphson iteration step:

$$\Delta \boldsymbol{u}_{n}^{(W)} = -\widehat{\boldsymbol{S}}^{(W)^{-1}} \left( \boldsymbol{r}_{n}^{(W)} + \boldsymbol{B}^{(W)^{T}} \left( (1 - \alpha_{f}) \boldsymbol{B}^{(F)} \boldsymbol{S}^{(F)^{-1}} \boldsymbol{B}^{(F)} \right)^{-1} \boldsymbol{B}^{(F)} \Delta \widehat{\boldsymbol{u}}^{(F)} \right), \tag{6}$$

where  $\hat{S}^{(W)}$  is the actual effective stiffness of the turbine, extended with the effective interface stiffness (condensed onto the interface degrees of freedom) of the foundation model:

$$\widehat{\boldsymbol{S}}^{(W)} = \boldsymbol{S}^{(W)} + \boldsymbol{B}^{(W)^{T}} \left( \boldsymbol{B}^{(F)} \boldsymbol{S}^{(F)^{-1}} \boldsymbol{B}^{(F)^{T}} \right)^{-1} \boldsymbol{B}^{(W)}.$$
(7)

After the displacements of the wind turbine are found, they can be substituted back into the equations for the interface force and the displacement of the foundations, to find their corresponding solutions.

Instead of solving this equation directly, one can now solve the equations as an uncoupled system, while still accounting for the effect of the foundation substructure on the wind turbine. Using the updates on the displacement and the Lagrange multipliers, the new residual can be computed.

#### 3.4 Coupling with OrcaFlex

As OrcaFlex only allows limited extraction of data on the boundary nodes, which is explained in Section 4, an alternative formulation is developed. Under the assumption that the dynamics of the floater structure are slower than the dynamics of the turbine, the most important dynamic properties of the floating foundation can be condensed on the interface node with BHawC. The condensed form of the equation of motion for the floater can be written as:

$$M_{eqv}^{(F)}(u^{(F)})\ddot{u}_{int}^{(F)} + p_{eqv}^{(F)}(\dot{u}^{(F)}, u^{(F)}) + B^{T}\lambda = f_{eqv}^{(F)}(\dot{u}^{(F)}, u^{(F)})$$
(8)

Note that this equation is very similar to those presented in Equation 3, except that we are now using equivalent matrices and the 6 interface DOF solely. The condensation of the interface force  $\lambda$  is equal to its original due to the Boolean operator  $B^T$ .

Due to the nonlinear dynamics of the floater, it is not possible to derive a condensed shape of this equation which is valid throughout the full simulation time. Instead, the matrices and loads relevant for the equilibrium can be derived each timestep.

Following the same argumentation as before, the Jacobian becomes dependent on the equivalent matrices:

$$\boldsymbol{S}_{\text{eqv}}^{(F)} = (1 - \alpha_m) \left( \frac{\partial \boldsymbol{M}_{\text{eqv}}^{(F)}}{\partial \boldsymbol{u}_{\text{int}}^{(F)}} \ddot{\boldsymbol{u}}_{\text{int}}^{(F)} + \boldsymbol{M}_{\text{eqv}}^{(F)} \frac{1}{\beta h^2} \right) + (1 - \alpha_f) \left( \frac{\gamma}{\beta h} \boldsymbol{C}_{t,\text{eqv}}^{(F)} + \boldsymbol{K}_{t,\text{eqv}}^{(F)} \right)$$
(9)

with

$$\boldsymbol{C}_{t,\text{eqv}}^{(F)} = \frac{\partial \boldsymbol{p}_{\text{int}}^{(F)}}{\partial \dot{\boldsymbol{u}}_{\text{int}}^{(F)}} - \frac{\partial \boldsymbol{f}_{\text{int}}^{(F)}}{\partial \dot{\boldsymbol{u}}_{\text{int}}^{(F)}}$$

and

$$\boldsymbol{K}_{t,\text{eqv}}^{(F)} = \frac{\partial \boldsymbol{p}_{\text{int}}^{(F)}}{\partial \boldsymbol{u}_{\text{int}}^{(F)}} - \frac{\partial \boldsymbol{f}_{\text{int}}^{(F)}}{\partial \boldsymbol{u}_{\text{int}}^{(F)}}.$$

In Equation 8 and 9,  $M_{eqv}^{(F)}$ ,  $C_{t,eqv}^{(F)}$  and  $K_{t,eqv}^{(F)}$  are approximations of the mass, damping and stiffness of the full floating substructure felt by the 6 degrees of freedom at the interface. The derivation of these are explained in Section 4.

Combining equation 5 to 9 results in:

$$\Delta \boldsymbol{u}_{n}^{(W)} \approx -\widehat{\boldsymbol{S}}^{(W)^{-1}} \left( \boldsymbol{r}_{n}^{(W)} + \boldsymbol{B}^{(W)^{T}} \frac{1}{(1-\alpha_{f})} \boldsymbol{S}_{\text{eqv}}^{(F)} \Delta \widehat{\boldsymbol{u}}_{\text{int}}^{(F)} \right), \tag{10}$$

where

$$\widehat{\boldsymbol{S}}^{(W)} = \boldsymbol{S}^{(W)} + \boldsymbol{B}^{(W)T} \left(\boldsymbol{S}_{eqv}^{(F)}\right)^{-1} \boldsymbol{B}^{(W)}.$$

In contradiction with Equation 7, the condensation of foundation structure is not the Schur complement anymore, instead the equivalent interface properties are directly used. Comparing Equation 6 and Equation 10, one can see that internal dynamics of the floater are partially neglected during the BHawC iterations within one timestep.

Note that OrcaFlex has its own method for calculating and solving the dynamic simulations that are performed. These simulations use the resulting motion of the interface, which is calculated in BHawC, as externally applied boundary conditions. It is important to realize that this, in combination with the force approximation that is described in the next section, gives opportunities for different time-steps in the two different domains.

#### *3.5 Time integration with OrcaFlex*

Since it is not possible to have multiple calls of OrcaFlex within a time step of a dynamic simulation, an explicit formulation is used for this coupling.

The communication between BHawCLink and the DLL are shown in Figure 3. The solution implemented is based on the following approach:

- At the beginning of time step t, BHawC determines a first guess for  $\ddot{u}_n$ ,  $\dot{u}_n$  and  $\hat{u}_n$ , where  $\ddot{u}_n$ ,  $\dot{u}_n$  and  $\hat{u}_n$  are respectively the acceleration, the velocity and the position of the origin of the instantaneous interface frame at instant t;
- $\ddot{\boldsymbol{u}}_{[b],1}^{(F)}$ ,  $\dot{\boldsymbol{u}}_{[b],1}^{(F)}$  and  $\hat{\boldsymbol{u}}_{[b],1}^{(F)}$  are imposed in OrcaFlex dynamic simulation via the DLL;
- The DLL returns the total force at the interface  $g_n^{(F)}$ , the mass matrix of the floater  $M_{eqv}^{(F)}$ , tangent stiffness  $K_{t,eqv}^{(F)}$  and damping matrices  $C_{t,eqv}^{(F)}$  of the foundation extracted from OrcaFlex.
- Using these matrices, BHawC updates  $\ddot{\boldsymbol{u}}_n$ ,  $\dot{\boldsymbol{u}}_n$  and  $\boldsymbol{u}_n$  solving the equations of motion under a residual form. At each Newton-Raphson iteration, the new interface force  $\boldsymbol{g}^{(W)}$  is approximated by BHawC using BHawCLink without calling OrcaFlex but using the tangent stiffness and damping matrices  $\boldsymbol{K}_{t,eqv}^{(F)}$  and  $\boldsymbol{C}_{t,eqv}^{(F)}$ :

$$\boldsymbol{g}_{n-1}^{(W)} = \boldsymbol{g}_{n}^{(W)} - \boldsymbol{C}_{t,eqv}^{(F)} \left( \dot{\boldsymbol{u}}_{n}^{(F)} - \dot{\boldsymbol{u}}_{n-1}^{(F)} \right) - \boldsymbol{K}_{t,eqv}^{(F)} \left( \boldsymbol{u}_{n}^{(F)} - \boldsymbol{u}_{n-1}^{(F)} \right)$$
(11)

- When the convergence is reached, BHawC moves to the next time step.



Figure 3 Partitioned time integration method, Explicit coupling.

#### 4. Data exchange during Newton-Raphson iteration

The content of each matrix (mass, damping and stiffness) and load vector exchanged at each time step of the coupling are listed respectively in Table 1. All the contributions are directly extracted from OrcaFlex.

Table 1 Mass, stiffness and damping matrix and load vector transmitted by the DLL at each time step.

Matrix / Vector	Part modelled	Contribution	
	Flooton	Mass	
$\mathbf{M}_{\text{org}}(\mathbf{M}^{(F)})$	Floater	Hydrodynamic added mass	
Mass (M <sub>eqv</sub> )	Mooring lines	Mass	
		Hydrodynamic added mass	
$\mathbf{G}$	Elector	Hydrostatic stiffness	
	Floater	Structural stiffness	
Summess $(\mathbf{A}_{t,eqv})$	Mooring lines	Mooring stiffness	
		Hydrostatic stiffness	

<b>Damping</b> ( $C_{t,eqv}^{(F)}$ )	Floater	Linear & Quadratic damping Hydrodynamic drag Structural damping Radiation damping	
Load ( $\boldsymbol{g}_1^{(W)}$ )	Floater	Excitation loads Weight Hydrostatic stiffness Radiation damping Hydrodynamic drag Structural stiffness Structural damping Linear & Ouadratic damping	
	Mooring lines	Weight Hydrodynamic drag Mooring stiffness	

# 4.1. Load vector

The load vector  $\boldsymbol{g}_1^{(W)}$  is calculated at each time step with the FASTExtractAddedMassAndLoad-OrcaFlex-API-function. It must be noted that the load vector contains the frequency dependent added mass contribution where the infinite frequency contribution is excluded.

# 4.2. Mass matrix

The mass matrix  $\boldsymbol{M}_{eqv}^{(F)}$  is calculated at each time step with FASTExtractAddedMassAndLoad-OrcaFlex-API-function.

The mass matrix contains the mass and added mass contribution of the elements rigidly connected to the main vessel. Only the infinite frequency added mass is accounted for in the mass matrix.

#### 4.3. Stiffness matrix

Stiffness matrix  $\mathbf{K}_{t,eqv}^{(F)}$  is calculated with the following formula:

$$\boldsymbol{K}_{t,\text{eqv}}^{(F)} = \boldsymbol{K}_{mooring} + \boldsymbol{K}_{vessel}$$
(12)

With:

 $K_{mooring}$  the lines stiffness matrix containing mooring stiffness, structural stiffness of the lines and hydrostatic stiffness of mooring buoyancy elements. This matrix is evaluated at each platform position by OrcaFlex with a shadow stiffness model run in parallel. When the shadow stiffness model is run, an OrcaFlex static simulation is performed: it consists in finding the static equilibrium of the system from the imposed position (dynamic) and as a result extracts the linearized stiffness matrix (which is a linearization of the restoring force).

 $K_{vessel}$  the floater hydrostatic stiffness matrix pre-calculated and directly read in OrcaFlex model.

#### 4.4. Damping matrix

The damping matrix  $C_{t,eqv}^{(F)}$  is calculated with a backward finite difference scheme. The damping matrix diagonal terms at time t for the degree of freedom i,  $C_{ii}(t)$ , are calculated with the following formula:

$$C_{ii}(t) = \frac{f_i(t) - f_i(t - \Delta t)}{\dot{x}_i(t) - \dot{x}_i(t - \Delta t)}$$
(13)

With:

- t corresponds to the current time step and  $t \Delta t$  to the previous time step (in seconds);
- The index *i* corresponds to the 6 degrees of freedom (3 translations *x*, *y* and *z* and 3 rotations  $r_x$ ,  $r_y$  and  $r_z$ );

- $f_i(t)$  the damping force or moment for degree of freedom *i* at time step *t* (in Newton). It includes the drag damping and the quadratic damping;
- $\dot{x}_i(t)$ , (in m/s) the translation or angular velocity of degree of freedom *i* at time step *t* (in Newton);

f(t) is evaluated with a parallel dynamic model imposing displacements and velocities calculated by BHawC. The set-up of this model is done automatically by the coupling DLL. The model is set up this way:

- Environment: Wave, current and wind are deactivated in order to neglect excitation loads on damping load evaluation;
- OrcaFlex elements: Mass, added mass and buoyancy are set to be negligible. Only damping contributions are kept (radiation damping).

Total loads on the main vessel are then extracted from this model with the coupling DLL and used to evaluate the damping matrix.

#### 5. Handling of different simulation phases

During a BHawC simulation, several stages can be distinguished. Details on the BHawC simulation phases and the approach to coupled BHawC and OrcaFlex during each phase are given in the following sections.

#### 5.1. Static initialization

A quasi-static initialization phase is applied in BHawC in which gravitational loads, structural internal loads and steady wind loads are ramped up in a certain number of load steps. For each load step, an OrcaFlex static simulation solves the mooring lines static equilibrium for the floater position calculated and imposed by BHawC. BHawC then solves the global equilibrium position accounting for gravitational, structural and mean wind loads computed in BHawC and interface loads and stiffness matrix provided by OrcaFlex. If the convergence is not reached, BHawC returns a new position to OrcaFlex that determines its new static equilibrium with the new position imposed. If the convergence is reached, one can move to the next load step. It should be noted that, depending on the floater type, the gravity constant is also ramped up in the OrcaFlex model such that the gravity and buoyancy are in line with BHawC model at each load step.

## 5.2. Dynamic initialization and dynamic simulation

The aim of the dynamic initialization phase is to start the simulation in a stable way (no transients due to starting the simulation). The dynamic initialization phase is composed of two phases:

- During the first phase, in OrcaFlex, the wave dynamics, vessel motion and optionally the current are built up smoothly from zero to their full level. This gives a gentle start to the simulation which reduces transient responses and thereby the need for long initialization times. On Figure 4, this phase lasts from -200s to -100s.
- When these properties have reached their required level, a certain time is kept ensuring that unfortunate transients are damped out before starting the real dynamic simulation phase. On Figure 4, this phase lasts from -100s to 0s.
- The proper dynamic simulation phase is then started.



Figure 4 Dynamic initialization and dynamic simulation phases

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# 6. Verification of the coupling

The floater used for this verification campaign is the public DeepCWind floater [3], adapted to suit the Siemens-Gamesa 8MW turbine. This floater is modelled in OrcaFlex with a single vessel containing a Hydrodynamic Database, mass, inertias and hydrostatic stiffness of the floater and moored with three catenary lines. Tower and RNA were defined by SGRE.

To verify the coupling DLL, comparisons are done on floater motions between an OrcaFlex only model and an OrcaFlex / BHawC coupled model. The interface loads are not compared has the floater is modelled as rigid. In the OrcaFlex only model, RNA and tower are integrated with 6D buoys rigidly connected to the main vessel, placed at RNA and Tower COGs, containing masses and inertias of the RNA and Tower.

Several types of simulation are performed for the verification:

- Static equilibrium test with and without wind;
- Decay tests with and without wind;
- Regular and irregular waves with and without wind simulations.

The comparisons show very good agreement between OrcaFlex only simulations and BHawC - OrcaFlex coupled simulations for each type of simulation. Examples of comparisons are shown in Table 2, Figure 5, Figure 6, Figure 7 and Figure 8 below. Several peaks are visible on power spectral densities at wave and floater natural frequencies.

Some comparisons were made on a flexible floater model and showed good agreements as well.



Figure 5 Decay test without wind comparison – Pitch



Figure 7 Irregular wave without wind comparison PSD – Heave







Figure 8 Irregular wave without wind comparison PSD – Pitch

DOF	Eigen Perie	Difference	
	BHawC + OrcaFlex	OrcaFlex only	(%)
Surge	112,5 s	111,4 s	1.0%
Sway	112,9 s	112,6 s	0.3%
Heave	17,6 s	17,5 s	0.6%
Roll	27,8 s	27,6 s	0.7%
Pitch	27,5 s	27,6 s	-0.4%
Yaw	80.1 s	80.8 s	-0.9%

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Table	2	Decay	tests	eigen	periods
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## 7. Conclusions

This coupling is very promising as it offers the possibility to perform coupled time domain analysis for wind turbines with several types of floaters and complex mooring systems. This flexibility is offered by the OrcaFlex software and the coupling methodology presented in this paper. All the data exchanged sent by OrcaFlex to BHawC during the Newton Raphson iteration is directly calculated by OrcaFlex to offer the possibility to model a large variety of floater designs.

Several verifications on the rigid floater model are performed. These showed a very good agreement for the different type of simulations that were performed both in time domain and frequency domain. Verifications on a flexible floater (with deformable lines to describe floater slender members) also showed good agreement and are still on-going. OrcaFlex-BHawC simulations on a rigid floater can already address the issue of achieving coupled dynamic analysis of floating wind turbine systems for tower design and for load evaluation of the RNA components.

These results show that during the Newton-Raphson iterations in BHawC, the equivalent formulation and force approximation for the floater can be used. These give a sufficiently accurate approximation of the behavior of the more detailed floater model in OrcaFlex.

Interesting topics for further research could focus on, amongst other, simulation time for detailed models, different timesteps in different domains, improved convergence for flexible floaters and modal analysis possibilities with a coupled model.

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