Verification of interface between an aeroelastic code and a time domain Rankine solver for completing structural analysis of floating wind turbine foundation design

Ali Bakhshandehrostami*, Kai-Jia Han, Steven Parkinson, Laurens Alblas, William Collier, Flora C.W. Sun

DNV – Digital Solutions

*Corresponding author, email: ali.bakhshandeh@dnv.com

Abstract

The aim of this study is to verify a new interface between an aeroelastic code, Bladed, and a 3D potential flow solver, Sesam’s Wasim. The interface is developed to transfer floater kinematics and sea state from a fully-coupled time domain simulation of a floating wind turbine into a 3D time domain potential flow solver to compute a time history of the pressure distribution on the foundation, and at the same time transfer the loads of wind turbine and mooring forces calculated in the coupled analysis. The pressure distribution, together with the other loads, can then be used for performing the structural analysis and post-processing of the floater. The functionality of the interface has been verified with various test cases. The verification study shows that the interface works properly.

1 Introduction

Awareness about the potential of floating offshore wind turbines (FOWT) in harnessing the energy from an extensive source of ocean and sea wind has progressively been increased in the recent decade. Having powerful and efficient tools for the design and analysis of such turbines is highly demanded by related industries nowadays.

It is standard practice to require coupled loads analysis for floating wind foundation design using an aero-hydro-servo-elastic code and time domain simulations [1]. In a coupled analysis approach, the equations of motion of the whole model of a floating turbine, composed of a foundation, mooring lines and a wind turbine (tower and rotor), are solved simultaneously when wind and wave loads are applied on the turbine. It can capture interactions between all parts, which is important in the design of a FOWT.

In the coupled analysis, the hydrodynamics of the foundation are frequently modelled as a combination of the Morison equation and the boundary element method (BEM) theory, where the latter is necessary for the analysis of large bodies that radiate and diffract waves. The benefit of using a Morison approach is the implicit calculation of internal loads along the different elements of the structure. This is not the case when using a BEM hydrodynamic theory, as all the hydrodynamic loading is applied at a single point for the foundation. Translating this single hydrodynamic load output into a range of internal foundation loads is not obvious. Moreover, use of only internal sectional loads may not be sufficient for structural assessment of certain parts of the foundation, where the time and spatial varying hydrodynamic pressure may contribute significantly to localised stress ranges across the foundation surface.
To overcome the aforementioned challenge, an interface has been developed to transfer outputs of a fully-coupled time domain simulation of a floating wind turbine into a 3D time domain potential flow solver to compute a time history of the pressure distribution on the foundation and at the same time transfer the loads of wind turbine and mooring forces calculated in the coupled analysis. The pressure distribution, together with the other loads, can then be used for performing the structural analysis and post-processing of the floater. The objective of this paper is to perform a verification study on this interface.

2 Methods

This paper studies the coupling between DNV’s aeroelastic code, Bladed, and DNV’s 3D time domain potential flow solver, Sesam’s Wasim. A simple model of a floating vertical cylinder was defined, as well as different environmental conditions including wind and waves.

2.1 Software

Sesam is a software package used for strength assessment of fixed and floating offshore structures. One of the modules in Sesam to generate hydrodynamic loading is Wasim. Wasim 6.1-08 is a 3D time domain potential flow solver for computing global responses and local loading on offshore foundations, including floating wind turbine foundations. Wasim solves the fully three-dimensional radiation/diffraction problem by a Rankine panel method on a grid representing the surface of the structure and the free surface. One of the outputs from Wasim is the calculated pressure distribution from the hydrodynamic panels mapped to the structural mesh, as well as the accelerations and loads on Morison elements. This is input to the structural analysis.

Bladed 4.11 is a multibody aero-elastic code used for fully-coupled analysis of a floating wind turbine. This tool includes a Boundary Element Method for computing hydrodynamic loads on a large radiating-diffracting foundation. The BEM approach requires hydrodynamic coefficients from a frequency domain potential flow solver (such as Sesam’s Wadam). The coefficients describe the hydrodynamic load response to the incident wave field and foundation motions. The approach assumes that the hydrodynamic loads can be applied to the foundation at a series of discrete points representing each BEM body. This allows global motions of the turbine to be accurately captured. However, the stresses on the foundation are not calculated.

2.2 Workflow and Interface

An example Bladed and Sesam workflow for floating wind turbine analysis is presented in Figure 1. It involves the combined use of Bladed and Sesam software tools to carry out modelling, determining hydrodynamic coefficients of the floater for use in the fully-coupled analysis, hydrodynamic load generation, structural analysis and post-processing on a floating wind turbine. An interface, shown in Figure 2, has been developed to pass output from Bladed to Wasim. The interface enables users to perform a fully-coupled time domain simulation of a floating wind turbine in Bladed, and then use the wave state, structural kinematics, and loads from mooring and tower base to reproduce the loads on the floating foundation model using Sesam’s Wasim, including a time history of the hydrodynamic pressure distribution on the floater.

The objective of the interface is two-fold. The first objective is the time domain reconstruction of hydrodynamic loads in Wasim, based on kinematics calculated by Bladed in coupled analysis and sea state information as used by Bladed. The second is to ensure that
mooring line and tower interface loads can be transferred to Wasim. Wasim can then output both the hydrodynamic, mooring line and tower interface loads to a structural mesh so that these can be used for structural analysis of the floater in Sesam [2]. The intended use cases of the Bladed-Wasim interface are summarised below:

1. **Hydrodynamic load reconstruction**: Here FOWT foundation kinematics calculated by Bladed and sea state information used by Bladed are transferred to Wasim to compute the pressure distribution on the foundation.

2. **Completing the structural analysis workflow of the foundation of a FOWT**: In addition to use case 1, the Bladed-Wasim interface allows mooring line and tower interface loads computed by Bladed to be transferred to Wasim. For structural analysis, Wasim allows mapping of the calculated pressure distribution from the hydrodynamic panels to the structural mesh. Wasim can also use the input mooring line and tower interface loads and transfer these to the closest beam nodes in the structural mesh.

Combination of both use cases enables the total stresses in the floating wind turbine foundation model to be obtained in a structural analysis in Sesam [2], so that post-processing (such as a fatigue analysis) can be performed on the foundation.

![Figure 1](image1.png) **Figure 1**: Floating OWT workflow using Bladed and Sesam. The red box shows Bladed, Wasim and the interface between them which is studied in this report.

![Figure 2](image2.png) **Figure 2**: Bladed-Wasim interface diagram. Outputs from Bladed are transferred into Wasim (here, SEA file contains wave characteristics like the wave height, the wave period, etc.)
2.3 Models

To verify the interface, a model of a floating vertical cylinder (as a representative substructure of a floating wind turbine foundation and being a suitable model for the verification) was constructed in both Sesam and Bladed. The model and its general characteristics are shown in Figure 3. In this study, the mass of RNA (Rotors Nacelle Assembly) including rotor, nacelle and associated members were set to zero in Bladed to make the comparison with Wasim simple. This way Bladed & Wasim only needed to represent the mass of the vertical cylinder to carry out the verification study. The origin of the global coordinate system is placed at free surface. The mid-section of the cylinder is placed on the origin of the global coordinate system, so the height of cylinder extends from -20m to 20m in the Z direction. Added mass and hydrostatic stiffness coefficients matrices were calculated by Sesam’s Wadam and imported into Wasim and Bladed.

![Figure 3: Model and general characteristics of floating vertical cylinder.](image)

2.4 Test cases

A series of test cases were simulated to check the setup of the models and the functionality of the coupling interface. The target of each test case is explained in the following:

- To check that the mass, inertia, hydrostatic restoring and radiation damping setup of the models is in good agreement, free decay test cases (test 1 in Table 1) were run. In this test, each tool is run independently and then results are compared.
- To check that the excitation forces due to incident waves on the structure match in both software tools, a test with a stationary structure in regular waves (test 2 in Table 1) was run.
- To demonstrate that the mooring and tower interface loads prescribed by Bladed can be transferred to Wasim and used for structural analysis in Sesam, the interface loads, hydrodynamic load components and the structure kinematics of both tools are compared. To check this functionality, mooring loads are checked through forced decay tests (test 4 in Table 1) and tower interface loads are checked (test 5 in Table 1).
- To test if the hydrodynamic loads can be reconstructed in Wasim using prescribed motions calculated by Bladed and the input SEA file (which contains information to generate a sea state) a floating structure in irregular wave conditions (test 3 in Table 1) was used.
The combination of the above described tests verifies the interfaces required for the intended use cases that were described in Section 2.2.

Table 1: Definition of test cases for verification study

| Test No. | Test name                  | Mooring line definition | Sea surface conditions   | Prescribed files | Use of interface |
|----------|----------------------------|-------------------------|--------------------------|-----------------|------------------|
| 1        | Free decay (heave & pitch) | No mooring lines        | Calm water               | -               | -                |
| 2        | Fixed cylinder             | Rigid Structure         | Regular wave H=2 m, T=8s | -               | Y                |
| 3        | Structure in irregular wave| Fore-aft moorings       | JONSWAP, Hs=2m, Tp=8s   | Y               | Y                |
| 4        | Forced decay (Surge)       | Single mooring line     | Calm water               | -               | Y                |
| 5        | Tower load due to Thrust / | Fore-aft moorings       | Calm water               | -               | Y                |

3 Theory

In this section the formulation of the equations of motion in Bladed and Wasim is discussed in detail. To determine the compatibility of the calculated hydrodynamic loads on a structure by both software, different terms of the equation are compared.

3.1 Computation of hydrodynamic loads in Bladed

Assuming that the Boundary Element Method (BEM) is used to describe the hydrodynamic loads acting on a body, then for a rigid body with a 6x6 mass matrix \( m \) that is free to move in the water in all six degrees of freedom the equation of motion in Bladed is formulated as follows:

\[
(m + m_{\infty})\ddot{x}(t) + F_R^B(t) + F_K^B(t) = F_E^B(t). \tag{1}
\]

where \( x(t) \) represents the translational and rotational degrees of freedom of the body and the acceleration of the body is denoted by \( \ddot{x}(t) \), \( m_{\infty} \) is the hydrodynamic mass (added mass), and \( F_R^B \), \( F_K^B \), and \( F_E^B \) represent the radiation force, the hydrostatic restoring force, and the excitation force, respectively.

In equation 1, the radiation force is calculated by

\[
F_R^B = \int_{-\infty}^{\infty} k(t-\tau)\dot{x}(\tau) \, d\tau
\]

where \( k(t) = \frac{2}{\pi} \int_{0}^{\infty} B_r(\omega) \cos(\omega t) \, d\omega \) is radiation impulse response functions and \( B_r(\omega) \) is the radiation damping coefficient (see section 8.13 of Bladed theory manual [3] for more details).

Moreover, the restoring force is calculated as

\[
F_K^B = K_{hs}x(t)
\]

where \( K_{hs} \) is the hydrostatic stiffness matrix.

Further, the excitation force is defined as

\[
F_E^B = \sum_n A_n F_n \cos(\omega_n t + \phi_{wn} + \phi_{dn})
\]

where \( A_n \) is the wave amplitude and \( \Gamma_n \) is the excitation amplitude. The phase of the wave excitation is denoted \( \phi_{wn} \) and phase changes due to drift is denoted by \( \phi_{dn} \). The phase drift is omitted for this study as the platform is relatively constrained in surge and sway motions.
3.2 Computation of hydrodynamic loads in Wasim

Wasim solves the fully three-dimensional radiation/diffraction problem by a Rankine panel method. The equations of motion in Wasim are written for a structure with mass matrix $M_{ij}$ and with six degrees of freedom that are represented by $\xi_i(t)$ as follows:

$$
(M_{ij} + A_{ij})\ddot{\xi}_i(t) + c_{ij}\dot{\xi}_i(t) = F^W_{FK}(t) + F^W_M(t) + F^W_{Ext}(t)
$$

(2)

where $c_{ij}$ is the restoring matrix due to hydrostatics and gravity, $A_{ij}$ is added mass from the local flow, $F^W_{FK}$ and $F^W_M$ represent the Froude Krylov, and memory force, respectively, and $F^W_{Ext}$ includes the external forces such as spring and auxiliary forces applied on the structure [4]. The prescribed force from Bladed into Wasim is passed on by $F^W_{Ext}$. It is noted that for this specific case of floating cylinder, the damping matrix is zero.

3.3 Compatibility of hydrodynamic loads in Bladed and Wasim

To compare hydrodynamic loads between Bladed and Wasim, the load terms that contribute to the total hydrodynamic applied loads were examined. The load components, including hydrostatic, added mass, excitation, radiation, and mooring applied load, between Bladed and Wasim were paired and these are reported in Table 2. This table shows that the equations of motion in Bladed and Wasim are compatible.

| Name of pair          | Wasim               | Bladed          |
|----------------------|---------------------|-----------------|
| Excitation and Radiation | $F^W_{FK} + F^W_M$ | $F^B_R - F^B_R$ |
| Added mass            | $A_{ij} \ddot{\xi}(t)$ | $m_{rwo} \ddot{x}(t)$ |
| Hydrostatic           | $c_{ij} \xi(t)$     | $K_{bs}x(t)$    |
| Mooring               | $F^W_{Ext}(t)$      | $F^B_E(t)$      |

4 Results and Discussion

Figure 4 demonstrates the comparison of motion amplitude and radiation force calculated by Bladed and Wasim in the free decay test (test 1 in Table 1). Decay tests were run using each software to check that the modelling of the structural, geometric, and hydrodynamic properties has been set up correctly in both systems. These runs were carried out independently and did not include the use of the coupling interface. It was found that the kinematics of the structure in heave, pitch, and surge are in very good agreement, which fundamentally demonstrates that the hydrostatic and radiation forces acting on the floating cylinder are in good agreement and the model setup is consistent in Bladed and Wasim.

Comparison of excitation moment on a cylinder which is fixed to the seabed is shown in Figure 5 (test 2 in Table 1). In this test, the fixed cylinder is exposed to a regular wave with $H=2m$ and $T=8s$. This figure confirms that the wave conditions are recreated exactly in Wasim and that the amplitude and phasing of the loading due to wave excitation is the same in the two tools.
Figure 4: Comparison of time series outputs of amplitude of motion (left) and radiation force (right) in Bladed and Wasim for heave, pitch and surge in free decay test (test 1 in Table 1).

Figure 5: Comparison of time series outputs of excitation moment about y in Bladed and Wasim on a stationary cylinder in a regular wave (H=2 m T=8 s) (test 2 in Table 1).

To verify the coupling interface, an irregular wave case was simulated (test 3 in Table 1). The sea state and motions of the floating foundation as calculated by Bladed were transferred to Wasim. The total forces on the floater were compared to ensure that the motions are interpreted correctly by Wasim and that the sea surface elevation is recreated exactly. Hydrodynamic loads in Bladed and Wasim are output in body-fixed coordinate system. The comparison of results of this test is shown in Figure 6. The figures confirm that the results compare quite well.

In test case 4, the cylinder is perturbed from its equilibrium position and released. Mooring loads calculated by Bladed are imported into Wasim to test that mooring load data is read correctly and applied in the correct coordinate system. Figure 7 shows the comparison of results of motion amplitude, hydrostatic and radiation forces of surge and pitch in the surge decay test. As can be seen, the results show good agreement and it can be concluded that the mooring loads from Bladed are interpreted correctly by Wasim. The results of heave and pitch can be found in a related verification report by DNV [5].
Figure 6: Comparison of time series of wave elevation, mooring force $F_x$, pitch motion amplitude, and applied pitch moment components of hydrostatic, added moment, and “radiation+ excitation”. For Bladed and Wasim in irregular wave. (test 3 in Table 1).

Figure 7: Comparison of time series outputs of motion amplitude, hydrostatic and radiation forces/moments in Bladed and Wasim in surge decay test (test 4 in Table 1).
Test case 5 in Table 1, tower load, aims to check if outputs of Bladed and Wasim are identical when a large load is applied on the tower top. This test is composed of two types of tower load. The first load is a ramping-up thrust load which starts from 0 at the start of the simulation, then ramps up to its maximum value of 100 kN in 20s, and thereafter stays constant until the end of the simulation. The second load is a gravity load equivalent to the mass of the RNA which is 316000 kg. Figure 8 demonstrates the comparison of the results of motion amplitude for this test. The comparison shows good agreement of structural kinematics between Bladed and Wasim and it can be concluded that the Bladed tower load output file is correctly interpreted by Wasim.

![Comparison of time series output of motion amplitude of surge, pitch, and heave in Bladed when a large load is applied on the tower top (test 5 in Table 1). The surge and pitch amplitudes shown (top two plots) are based on a ramp-up thrust load being applied at the tower top, while the heave amplitude shown (bottom plot) is based on applying a gravity load at tower top.](image)

5 Conclusion

An interface has been made between Bladed and Sesam’s Wasim, which allows outputs of a coupled floating wind turbine simulation from Bladed, an aeroelastic time domain code, to be prescribed in Wasim, a 3D time domain potential flow solver. The relevant Bladed outputs include support structure kinematics, wave components, and tower and mooring line loads on the support structure. The purpose of the interface is to be able to recreate the loads on the floating foundation’s structural mesh, including hydrodynamic pressure distribution. The pressure distribution along with other loads, i.e. inertia, mooring line loads, and tower loads, allow for structural analysis of the floating turbine foundation in Sesam. The purpose of this study was to verify the implementation of this Bladed-Wasim interface.

The hydrodynamic equations of motions in both tools have been investigated and equivalent terms compared to check that the hydrodynamic calculations in Bladed and Wasim are compatible.
To verify that the interface works properly, different tests were performed on a floating cylinder, which was chosen as a representative example of a floating wind turbine foundation and a suitable model for the verification. Support structure kinematic results from Bladed and Wasim were found to have close agreement. Similarly, the BEM hydrodynamic point loads calculated by Bladed were found to have close agreement with the total loads calculated in Wasim by integrating the pressure distribution over the support structure. This confirms the correctness of the Bladed-Wasim interface implementation, and that it can be used for floating offshore wind turbine design.

6 References

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