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Performance of the Open-Source Potential Flow Solver HAMS in Estimating the Hydrodynamic Properties of a Floating Wind Turbine

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ABSTRACT: This work evaluates the use of an open-source potential flow solver in the hydrodynamic analysis of floating wind turbine dynamics. The platform in question is a free-float capable TLP design. It performs as barge in the towing condition, and it is a TLP when installed. In the barge mode, it has moon-pool type openings that improve towing dynamics, leading to a complex geometry. The hydrodynamic properties are evaluated in both conditions (i.e., installed and transport) using WAMIT and HAMS. Added mass, potential damping, and wave exciting forces are compared in the frequency domain. Then, the dynamics of the platform in the installed condition is evaluated in time domain, using FAST. The time domain evaluation clarifies whether the differences between solvers affect the estimation of coupled motions resulting from the hydrodynamic and aerodynamic loads.

1 INTRODUCTION

While wind energy has its roots onshore, its offshore usage also has an established presence since Vindeby 1991. Consequently, it has slowly moved towards deeper waters requiring fixed bottom support structures to be replaced with floaters. There is continued progress in this direction as further developments are within the renewable energy plans worldwide. (e.g., Wind Europe 2016). Hence, developing efficient platforms is of interest to both the scientific community and the industry.

When assessing the coupled motion dynamics of floating wind turbines, the two prevalent loads are hydrodynamics and aerodynamics. The aerodynamic loads primarily relate to the turbine. The dynamics of the floater are a function of its interaction with the waves. In both cases, several numerical solutions can be adapted to obtain the forces. For instance, the blade element momentum theory is an option for the aerodynamic loads. Similarly, there are several alternatives for hydrodynamics.

If the floater is small enough to allow undisturbed wave passage, the forces it encounters may be estimated empirically using the Morison equation. However, given the size of recent turbines and floaters, this approach fails to deliver reliable results (Uzunoglu and Guedes Soares 2018a). Accordingly, there are effectively two options: a potential flow solver or the use of computational fluid dynamics (CFD).

CFD software can deliver reliable results in emulating both hydrodynamics and aerodynamics. However, they are computationally expensive methods. They cannot be used in the design stages of platforms where hundreds of alternative hull forms, hull sizes, and environmental conditions may need to be tested, as in Uzunoglu and Guedes Soares (2019). On the other hand, using a potential flow solver for the same purpose has been possible for more than a decade (Lee *et al.* 2007).

When it comes to availability, CFD software has an advantage. There are trusted open-source options, such as OpenFOAM (Islam *et al.* 2019, Rezanejad *et al.* 2019). Conversely, for the potential flow solutions, WAMIT (Lee and Newman 2005) has provided the hydrodynamic data for a significant number of projects (Sclavounos *et al.* 2007, Robertson *et al.* 2014, 2017). However, this software is not open to community development as in the OpenFOAM example. The primary potential flow solver alternatives that adapt an open-source approach are NEMOH (Babarit and Delhommeau 2015) and HAMS (Liu 2019). Capytaine (Ancellin and Dias 2019) can also be added to this list; however, it is primarily a Python adaptation of NEMOH.

Out of the options above, WAMIT has a long list of validation studies, and it has established itself as a reference in the field (Sclavounos *et al.* 2007, Lee and Lim 2008, Datta *et al.* 2011, Uzunoglu and Guedes Soares 2018b). It has also provenp itself to deliver reliable results when simulating wind turbines (Coulling *et al.* 2013, Oguz *et al.* 2018). When it comes to NEMOH and HAMS, these studies are not available. Comparisons are limited mainly to the hydrodynamic coefficients (Sheng *et al.* 2022). However, to what level this difference reflects in estimating the coupled motion dynamics of a floating wind turbine is unclear.

There are two ways of looking at this problem. One part is the direct comparison of the hydrodynamic coefficients mentioned above, as in Parisella and Gourlay (2016) and Sheng *et al.* (2022). Then, it needs to be understood that the hydrodynamic coefficients are only a part of the equation in estimating a wind platform's coupled responses. The coupled system response is affected by other factors such as the inertial terms and the mooring stiffness. Accordingly, the overall response of the platform needs to be studied after considering all loads. What may seem to be a considerable difference in added mass estimations may become negligible concerning the overall system response and vice versa. Hence, it is required to evaluate the structure in combined wind and wave loading using different solvers. This approach clarifies to which degree the coupled responses are affected by the panel method solver (e.g., WAMIT, HAMS, NEMOH).

This paper provides a study of this type using the CENTEC-TLP (Uzunoglu and Guedes Soares 2020). The platform has a hull with moon-pool type openings in its transport mode, and its motions are experimentally validated (Mas-Soler, *et al.* 2021). In the published solution, WAMIT was utilized; therefore, it is known that its RAO estimations in the frequency domain are reliable. In operation, the structure performs as a TLP (Uzunoglu and Guedes Soares 2021).

The work starts with a description of the solvers and the platform. Consequently, it evaluates the hydrodynamic coefficients and the wave exciting forces. The RAOs in the frequency domain are also included in the transport condition. Then, the time-domain simulations are presented in the turbine's rated operational condition. The simulations in operational condition identify whether the differences stemming from the BEM solvers will carry over to the coupled responses.

2 ESTIMATION OF PLATFORM RESPONSES

The solution to estimating the system responses can be given in two parts. Combining the wave exciting forces, hydrodynamic coefficients (i.e., the added mass and potential damping) can deliver the RAOs in the frequency domain. These variables can also be used in the time domain solution to estimate the coupled responses of the floating structure. Both WAMIT and HAMS can provide frequency-domain solutions. FAST takes the added mass, potential damping, and wave exciting force as input and solves the problem in the time domain considering the coupled dynamics. Information on both the frequency-and time-domain parts is provided below.

2.1.1 *WAMIT*

WAMIT ('Wave Analysis MIT') (Lee and Newman 2005) has a long history since its first release by MIT in 1987. Since then, it has gained been used in numerous studies involving offshore structures and other floaters. Based on the linear and second-order potential flow theory, WAMIT can solve boundary integral equations using the constant panel method (Liang *et al.* 2018) or a higher-order B-spline method. In WAMIT, polynomial approximations are applied to calculate the free-surface Green function (Newman 1985), and an extended boundary integral equation method (Lee *et al.* 1996) is applied to remove irregular frequencies. It can use parallelization to speed up computations starting with Version 7. In this work, version 6.4 is used. Therefore, this parallel computation capability is not evaluated. Being a commercial-purpose software, WAMIT is not suitable for community involvement regarding its development.

2.1.2 *HAMS*

HAMS ('Hydrodynamic Analysis of Marine Structures') is an open-source code aiming to compute wave loads and motions of offshore platforms and ocean energy converters in waves. The first version of HAMS was released in 2020 on GitHub. Since its release, it has been used for several comparison studies (Ucar *et al.* 2021, Sheng *et al.* 2022). The code's recency signifies that more validation studies can help to establish HAMS in this field. The current version is based on the linear potential flow theory and the constant panel method. Polynomial approximation (Wu *et al.* 2017, Liang *et al.* 2018) and series expansions (Liu *et al.* 2018) are applied to calculate the free-surface Green function. An overdetermined integral equation method (Liu 2021a) is applied to remove irregular frequencies. The HAMS code offers OpenMP parallelization to speed up the computations. It is free and open-source software released under the Apache License. Therefore, community involvement in its development is possible. It is publicly available on GitHub (Liu 2021b).

2.2 *Time-domain solutions*

FAST provides the time-domain solutions in this study. It is a code initially developed and maintained at NREL (Jonkman and Buhl Jr 2007). The modelling process of CENTEC-TLP for FAST is explained in (Uzunoglu and Guedes Soares 2020, 2021). Here, the numerical model is identical to those described in the referred works. The only dif-

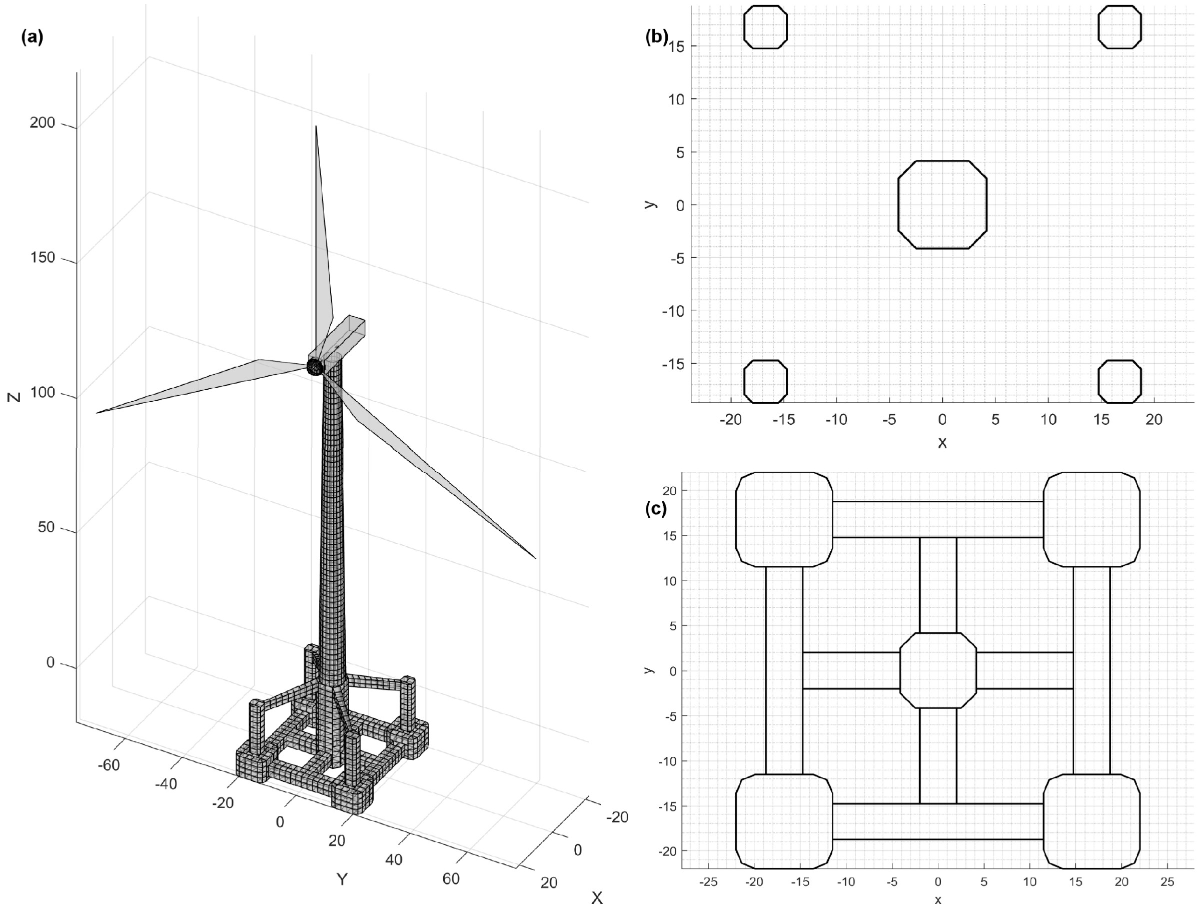

Figure 1: CENTEC-TLP, (a) complete model, (b) waterplane area in installed condition with a 20 m draft, (c) waterplane area in transport

ference is that the hydrodynamic coefficients (i.e., added mass and potential damping), hydrostatic restoring matrix, and exciting forces are calculated by HAMS in addition to WAMIT. Then, the outputs are compared in their respective results sections.

3 THE PLATFORM AND THE TURBINE

The CENTEC-TLP is an experimentally validated dual objective (i.e., free-float capable barge in transport, functioning as a TLP in operation) platform. It is made to host the DTU 10 MW turbine and tower (Bak et al. 2013). While a brief description is provided here, the floater's design process and properties are detailed in (Uzunoglu and Guedes Soares 2020, Mas-Soler, et al. 2021).

The two modes of the platform may be referred to as the transport mode and the installed mode. In transport, the platform replicates the principles of a barge and attains a positive GM using the large waterplane area. When installed, it performs as a tension leg platform (TLP). The design removes the necessity to use external towing vessels commonly needed for tension leg platforms (Amate *et al.* 2016) and reduces the installation costs. The structure also has a limited draft under 4 meters so that it can disregard depth limitations in production locations. The installed draft is 20 meters. Figure 1 illustrates the structure, including the waterplane area for both the installed and the transport modes.

The tower and the turbine are identical to the DTU 10 MW. The tower and RNA have a relatively high centre of gravity (CG) at 57.5 meters. When placed on the platform, the CG attains 67.5 meters. The total mass of the tower and the RNA is approximately 1,300 tons. The platform itself is 2,200 tons with a CG of 8 m. As the platform is lighter than alternatives (e.g., overall displacement of the for the same turbine power is reported at 12,000 t in (Yang *et al.* 2021) as opposed to 3,400 tons for the CENTEC-TLP), the hull form is crucial to reducing motions in transport considering the height of the centre of gravity. Accordingly, the RAO estimations in transport mode are a critical design factor as well as proper performance in the installed mode.

4 WAMIT AND HAMS CALCULATIONS IN THE FREQUENCY DOMAIN

The comparisons below provide data for both the installed and the transport modes. A set of chosen hydrodynamic coefficients are discussed in both cases.

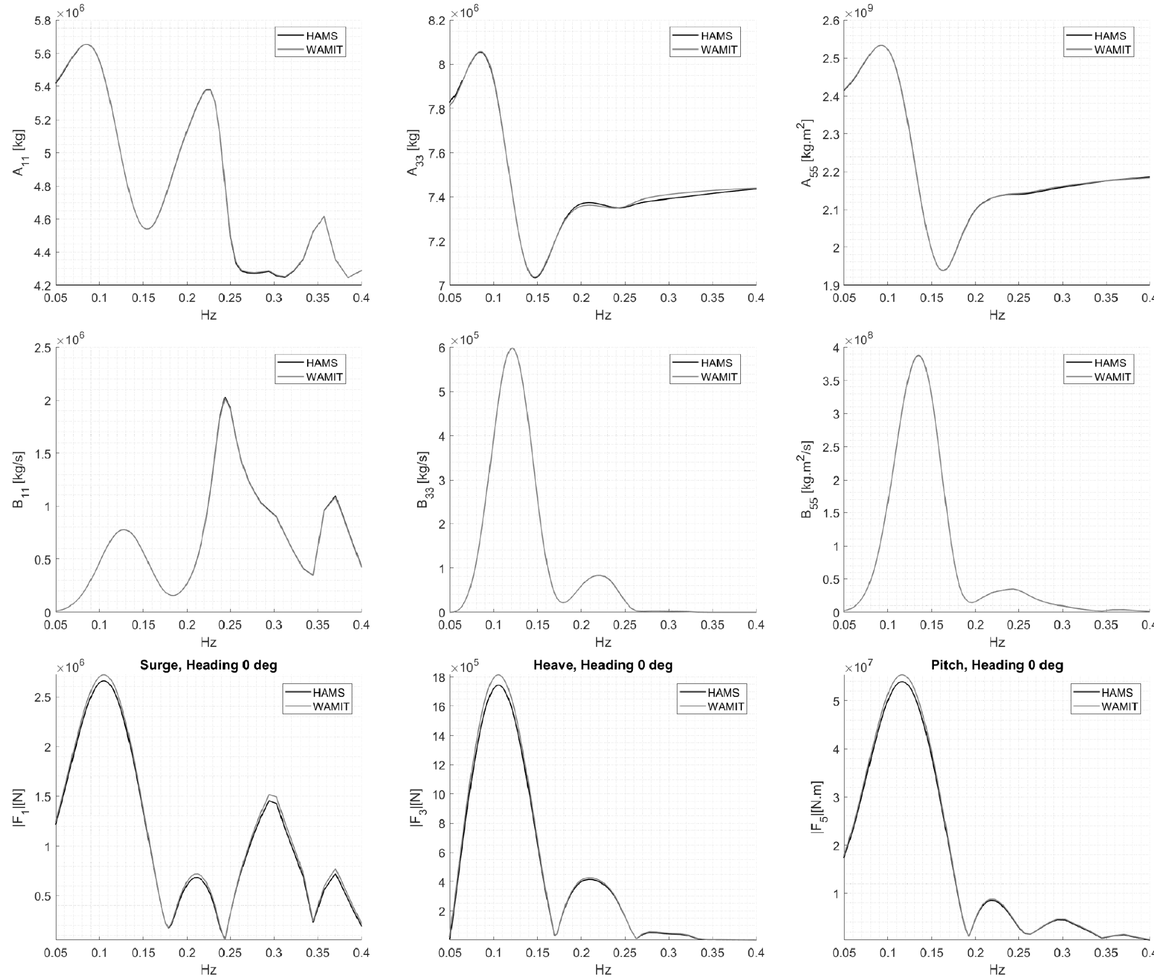

Figure 2: Added mass (A, top row) and potential damping (B, middle row), and wave excitation forces (F, bottom row) in installed mode of CENTEC-TLP as calculated by HAMS and WAMIT

They are evaluated for the installed mode in the time domain. However, RAOs in the frequency domain will be limited to the transport mode.

An identical 2-meter mesh representation of the platform is used for both WAMIT and HAMS to eliminate differences stemming from modelling. While WAMIT delivers RAOs as standard output, HAMS code requires external calculations. The implementation in this work follows Newman (2012).

4.1 *Hydrodynamics coefficients and forces in the installed mode*

The installed mode is at 20 meters of draft, resulting in four stability columns intersecting the waterplane. Additionally, there is the central column that hosts the turbine. The hull is similar to the conventional TLP form (i.e., Hutton TLP).

In this case, Figure 2 shows a favourable comparison between HAMS and WAMIT regarding the added mass and damping in the surge, heave, and pitch modes. When it comes to potential damping, the results overlap entirely. There are slight discrepancies in higher frequencies of the heave and pitch modes in the case of added masses. While these numbers are to be noted, it is helpful to consider them in scale and how they will affect the overall responses of the platform.

The forces do not overlap, as in the case of added mass and damping results. However, they are notably close. WAMIT seems to deliver slightly higher peak values compared to HAMS. However, the trends are similar. While the hydrodynamic coefficients deviate in higher frequencies, the behaviour is identical throughout the entire frequency range when forces are concerned.

Since these values are for the installed mode, it is beneficial to return to them when discussing the time domain data. There, the coupled responses can be evaluated. It is helpful to note that they are a component in a complex system of equations that include aerodynamics, hydrodynamics, and additional factors such as the mooring loads. Therefore, the values presented for this case become input to an extended system of equations. The coupled dynamics in the time domain will include the effects of moor-

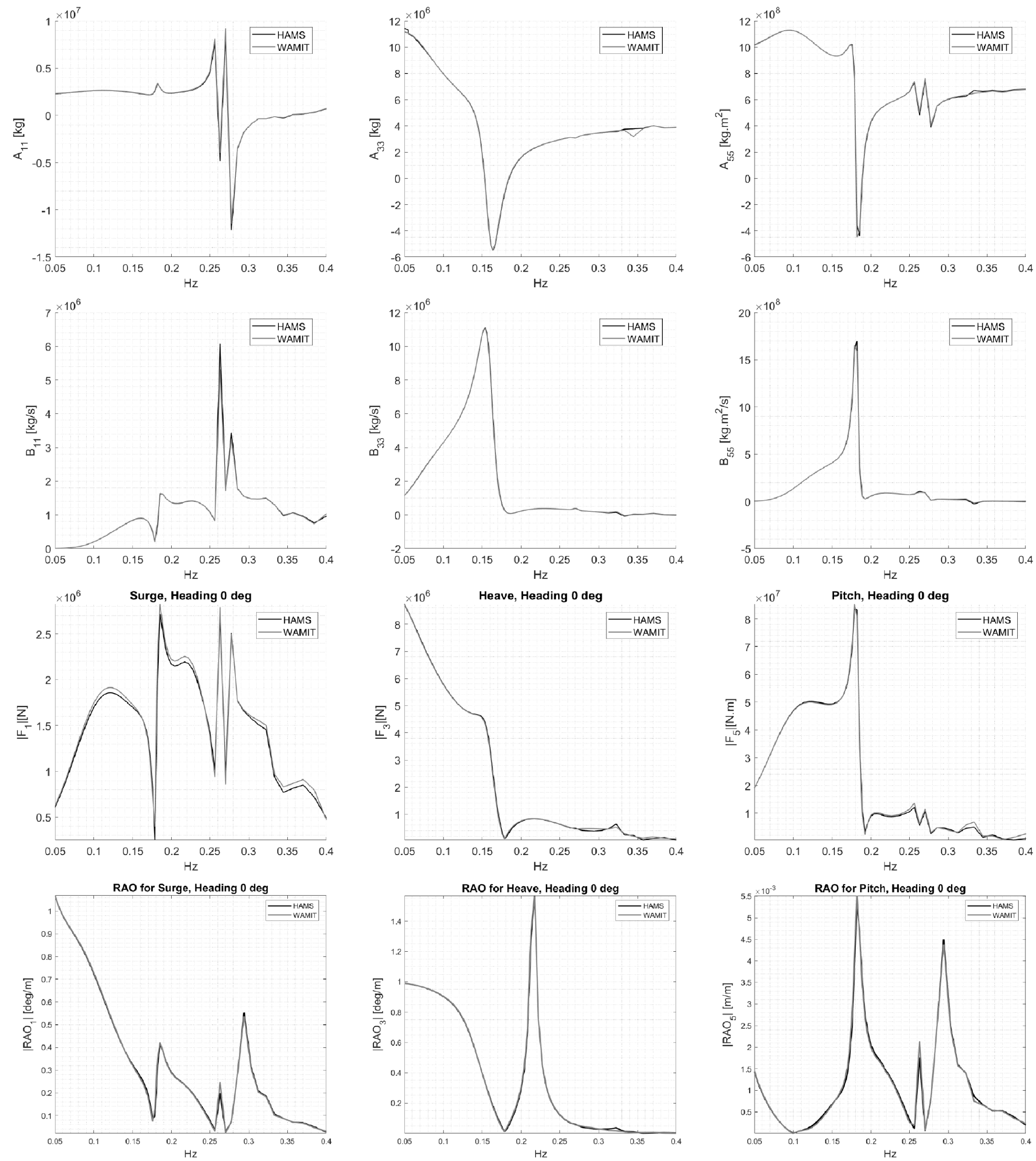

Figure 3: Added mass (A, top row) and potential damping (B, second row), wave excitation forces (F, third row), and response amplitude operators (bottom row) in transport mode of CENTEC-TLP as calculated by HAMS and WAMIT

ing loads, aerodynamics with the controller behaviour, and structural dynamics such as the flexibility of the tower.

4.2 *Hydrodynamic coefficients and responses in transport mode*

The submerged geometry in CENTEC-TLP transport mode has four moonpool-type openings at the waterplane. Accordingly, the resulting geometry is more detailed than the case of cylinders. It presents the possibility of evaluating the potential flow solvers in this scenario and looking for differentiable results.

Under this condition, WAMIT and HAMS deliver the values in Figure 3. Comparing the hydrodynamic coefficients in the first two rows (i.e., added mass and damping) results in conclusions similar to the installed case. The data mostly overlaps, apart from the highest frequency ranges calculated.

When the exciting forces are considered, the behaviour of the installed mode repeats itself, with WAMIT providing slightly higher values. It may serve to note that the actual values (i.e., experimentally evaluated) are not known for this platform. Hence, it is impossible to identify whether HAMS underestimates the true values or WAMIT overestimates them. The results merely show slight differ-

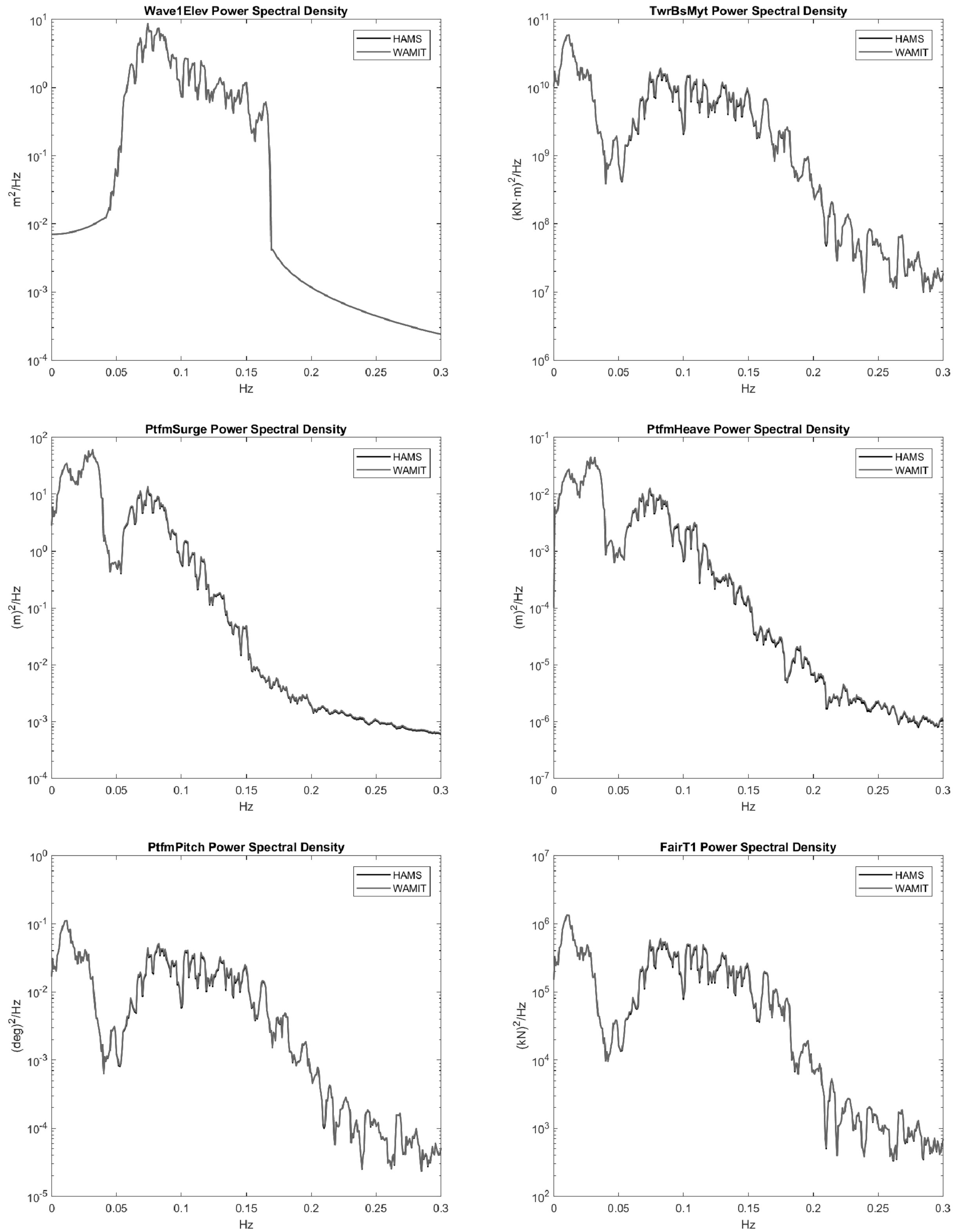

Figure 4: Comparison of time domain simulations in FAST using HAMS and WAMIT for the hydrodynamic components

ences in the estimated values depending on the frequency range.

The RAOs presented in Figure 3 compare WAMIT and HAMS using the hydrodynamic coefficients and forces. However, while WAMIT delivers the RAOs internally, HAMS results were calculated using an external script. The outcome shows that the differences are negligible. In the surge mode, the peaks start showing differences above 0.25 Hz. Similarly, at approximately 0.18 Hz, the peak values are estimated with slight differences. These results likely stem from the force calculation differences at higher frequencies. It may also be helpful to note that 0.2 Hz is where the first-order wave forces start to become less significant, according to DNV (Det Norske Veritas (DNV) 2010). Evaluating the motions and the exciting forces together shows that the exciting forces between 0.05 and 0.2 Hz are indeed higher overall.

WAMIT RAOs are validated experimentally and published for this case (Mas-Soler, *et al.* 2021). Thus, it is possible to state that both potential flow codes deliver reliable results for the TLP's transport condition.

5 COUPLED MOTIONS IN THE TIME DOMAIN

When the coupled motions are calculated in the time domain, a few more factors come into consideration that increases the system complexity. Primarily, there is the aerodynamic component from the wind, including the controller behaviour. Additionally, there is a drag force on the tower. It is also possible to include the mooring responses in the overall calculation of the motions. Finally, the tower elasticity plays a vital role in dictating the platform response. Hence, while the solution is limited to hydrodynamics in frequency-domain calculations above, they become a part of the equation in coupled responses.

This section presents the results from a time-domain simulation under operational conditions for the CENTEC-TLP. The wind speed is assumed to be the rated speed, 11 m/s. In this scenario, the mean turbine thrust is 1500 kN. The wind field is created using the Kaimal spectrum. The significant wave height is 2 meters at a 12.5 second peak period, using the JONSWAP spectrum. These conditions correspond to the characteristics of the installation location of the platform in Ribadeo, Spain (Vittori *et al.* 2021). FAST's finite element mooring model (FEA Mooring) was used to calculate the mooring loads.

It is seen in Figure 4 that the results are identical and overlapping. From this set, it can be said that there is a minimal difference resulting from replacing WAMIT with HAMS in the simulations of CENTEC-TLP. The motions in the surge, heave, and pitch match entirely between the software. This case might have been expected, judging by the previous results. The highest difference could have been in the surge mode, at approximately 0.1 Hz and 0.2 Hz. Indeed, when the curves are examined closely, FAST output using HAMS follows the WAMIT version with negligibly lower values. However, it is hard to state that this difference is physically meaningful.

Overlapping results are also visible when the examination is extended to the mooring lines and the tower base bending moments. The figures show that as the complexity of the system increases to include the elasticity, aerodynamics, and dynamic mooring loads, the differences seen in the hydrodynamic exciting forces lose their significance to a great level.

6 CONCLUSIONS

This work compared HAMS and WAMIT for the CENTEC-TLP hull form. The platform's installed and free-floating (transport) conditions were evaluated in the frequency domain. The hydrodynamic coefficients showed that HAMS and WAMIT delivered almost identical results. There were differences in peak values and higher frequencies. When the wave exciting forces were examined, it was seen that WAMIT delivers slightly higher values depending on the frequency. However, calculating the RAOs in the frequency domain did not result in notable differences.

Extending the study to the time domain adds several components such as mooring line dynamics and tower elasticity to the calculations. Time-domain simulations show that this increase in complexity reduces the importance of deviations in wave exciting force estimations. Hence, almost identical results were obtained whether WAMIT or HAMS is used to get the hydrodynamic coefficients and exciting forces.

This result set shows that HAMS provides promising results in providing the necessary components to simulate CENTEC-TLP. Further studies using other hull forms, platform types, or environmental conditions would clarify where it can be improved.

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