A comparative study on BEM solvers for Wave Energy Converters

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ABSTRACT: Wave Energy Converters (WECs) are expected to significantly contribute to the energy transition; however, this depends on their interactions with the resource. Calculating the power generated by WECs depends heavily on the accurate modelling of wave-structure interactions. The Boundary Element Method (BEM) based on the potential flow theory has yielded accurate results at low computational costs when compared to complex Computational Fluid Dynamics (CFD) methods. Hydrodynamic Analysis of Marine Structures (HAMS), a recently developed open-source BEM frequency domain solver, originally was created for large marine structures. To date it has only been applied to single WECs with spherical/cylindrical geometries. HAMS offers unique advantages through its efficient removal of irregular frequencies and lower computational costs. This paper aims to compare hydrodynamic coefficients, exciting forces, Response Amplitude Operators (RAOs) and computational costs between HAMS, WAMIT, and NEMOH for a cylindrical point absorber and an oscillating surge WEC, extending the currently limited WECs application in HAMS.

1 INTRODUCTION

Ocean wave energy has immense potential and can provide twice as much electricity as globally produced, due to its high energy density (UPCC 2019, Balitsky 2019). Apart from the vastness of the resource, waves are more predictable, and available throughout the year when compared with other forms of renewable energy. In order to rapidly develop the wave energy industry to meet our renewable energy targets, it is essential that we advance numerical techniques that can simulate the behavior of WECs. These would offer the advantage of employing significantly less expenses as compared to performing physical tests on scaled models using wave tank testing.

In order for numerical models to predict the motion of, forces acting on and the power produced by WECs, it is essential to understand their wave-structure interaction (Penalba et al. 2017). BEM is perhaps the most common method for this in the field of wave energy with those employing the potential flow theory being the most popular. There are well established commercial codes such as WAMIT (Lee 1995) and ANSYS AQWA (2012) as well as open-source codes such as NEMOH (Babarit & Delhommeau 2015), Aquadyn and Aquaplus (Delhommeau 1993) with WAMIT and NEMOH being the most popular. Capytain (Ancellin & Dias 2019) and HAMS (Liu et al. 2018) are two recently developed open-source solvers, which are still being established within the field. Open-source solvers for modelling wave-structure interaction could provide valuable options to meet the numerical challenges within the field of ocean engineering, particularly the possibility of low computational effort with good accuracy.

This research makes some comparisons between the open-source solver HAMS with the commercial solver WAMIT and another open-source solver NEMOH for two different types of WECs: a semi-immersed cylindrical Point Absorber (PA) and a semi-immersed Oscillating Surge Wave Energy Converter (OSWEC). The compared parameters include hydrodynamic coefficients, exciting forces, RAOs and computational efficiency.

Although the Cylindrical PA has been widely studied with WAMIT, NEMOH and HAMS (Penalba et al. 2017, Liu et al. 2018, Liu 2019, Sheng et al. 2022), it has been chosen here to show an example of the capability of HAMS to efficiently remove the so-called ‘irregular’ frequencies, which is also possible on the commercial solver WAMIT. Additionally, the case of OSWEC is demonstrated as this has only been analyzed previously with WAMIT and NEMOH.

2 BACKGROUND OF THE BEM SOLVERS

The BEM solvers WAMIT, NEMOH and HAMS employ panel methods based on the linear potential flow theory, which employs the Green's function and solves the diffraction/radiation problem of source distribution on the surface on the body. The key is to establish boundary integral equations using specific Green's function that satisfy the free surface condition and wave radiation condition at infinity.

WAMIT and HAMS employ similar algorithms for solving the free surface Green's function which are based on Newman's approximation methods, while NEMOH uses interpolation based on a look-up table to solve for the wave part of the Green's function, thus avoiding some calculations/approximations as seen in WAMIT and HAMS (Sheng et al. 2022). While NEMOH has been shown to provide good solutions for many problems in wave-structure interaction, it is still susceptible to 'irregular frequencies', which are purely numerical and arise from ill-conditioning in the boundary integral problems, sometimes resulting in large underestimation or overestimation of hydrodynamic parameters at certain frequencies (Kelly et al. 2021). These coincide with the eigenfrequencies of the hypothetical sloshing modes (flow filling the interior of the structure), which are obtained from the internal Dirichlet problem (Marburg et al.) and numerically caused by the interaction of the water-plane section of the floating bodies intersecting with the free-water surface (Liu 2019). WAMIT and HAMS are both capable of tackling this by discretizing the free surface within the body and solving an extended boundary integral equation problem (Lee et al. 1996, Liu 2019).

In addition to its capability of efficiently removing 'irregular frequencies', HAMS also employs open multi-processing parallelization techniques to reduce computational effort on multiple-core systems.

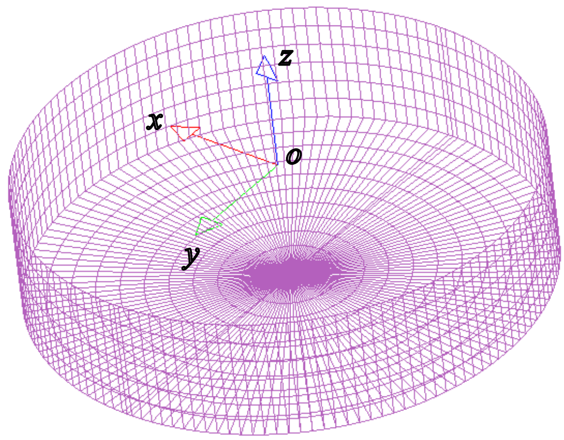
3 HYDRODYNAMIC ANALYSIS OF WEC DEVICES

In this section, the geometries of the examined two types of WECs are initially introduced. This is followed by the comparison of the hydrodynamic coefficients, exciting forces and RAOs.

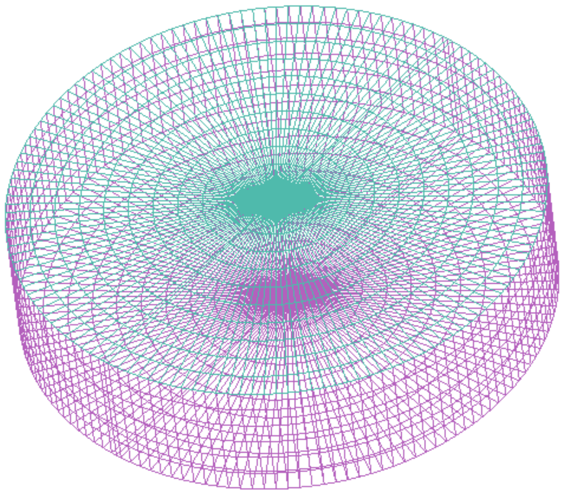
3.1 *Semi-immersed cylindrical point absorber*

A cylindrical PA of height 3.0 m and radius, *R*, 3.0 m radius is considered. Its draft is 1.5 m; hence, it is modelled as a truncated cylinder. The center of gravity coincides with the origin of the global coordinate systems o*xyz* located at the Mean Water Level (MWL), while the center of buoyancy is 0.75 m below the MWL. For the PA, deep water conditions are taken into account.

In order to remove the irregular frequencies in HAMS, an additional water plane mesh needs to be provided as input when running the simulation. Hence, two cases are considered here: **Case (a) – Only hull**, where, just the hull of the structure is modelled and **Case (b) – Hull and water plane**, where both the hull and the interior water plane are modelled to enable the removal of irregular frequencies. The interior water plane is modeled with an additional mesh applied at the level of the water surface within the circumference of the cylindrical PA. The meshes for the two cases are shown in Figure 1. The mesh in 1(a) is used for the hull in WAMIT, NEMOH and HAMS. The mesh in 1(b) is used for irregular frequencies for WAMIT and HAMS.



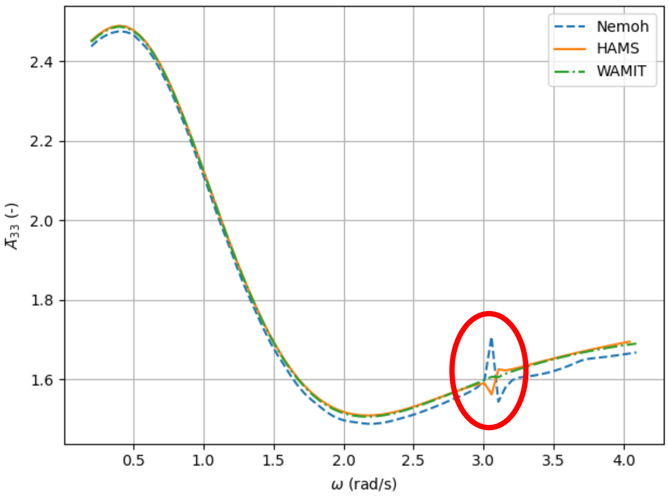
(a)



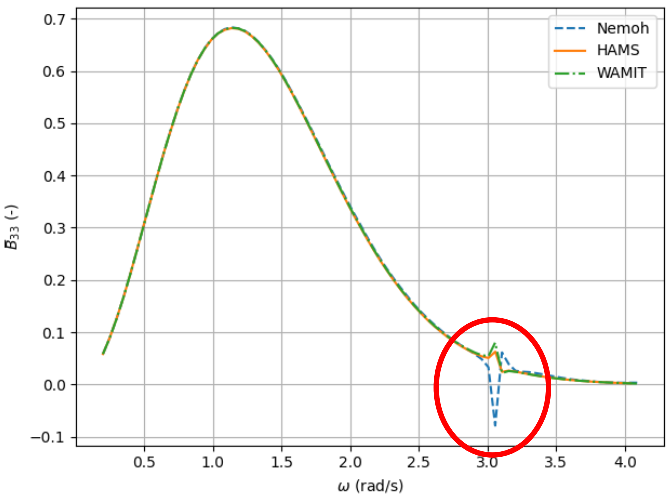
(b)

Figure 1(a). Mesh for the hull (purple) of the cylindrical PA as modelled in HAMS, NEMOH and WAMIT, (b) Mesh for the hull (purple) and water plane (cyan) for the cylindrical PA as modelled in HAMS and WAMIT. The global *ox* (red) o*y* (green) *oz* (blue) axes are shown in (a). The same are used in (b).

The hydrodynamic coefficients, exciting forces and RAOs for Case (a) are shown in Figures 2, 3 and Figure 4 respectively. The corresponding results for Case (b) are shown in Figures 5, 6 and 7 respectively. All 6 Degrees Of Freedom (DOFs) were considered here. For brevity, results are only shown for heave. Exciting forces, F_3, are normalized by $\rho g A \pi R^2$, while added mass, A_{33}, and radiation damping, B_{33}, coefficients by ρR^3 and $\rho\omega R^3$ respectively, where ρ=1025 kg/m^3 is the water density, g the acceleration due to gravity, ω the frequency, and A is the unit wave amplitude.



(a)



(b)

Figure 2(a). Heave added mass and (b) heave radiation damping for Case (a) of the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)

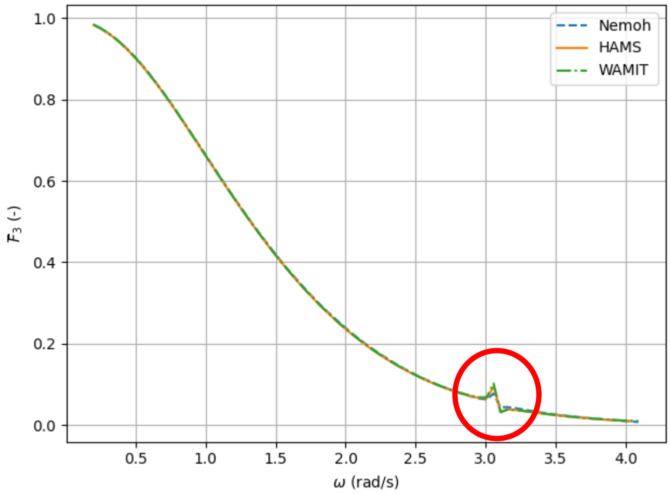


Figure 3 Heave exciting force for Case (a) for the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)

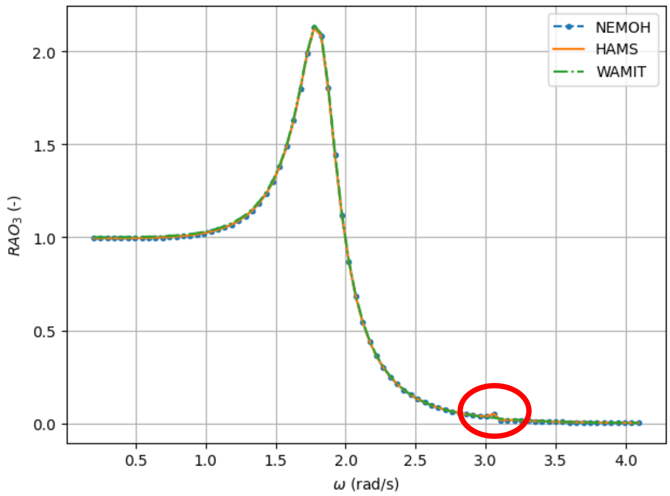
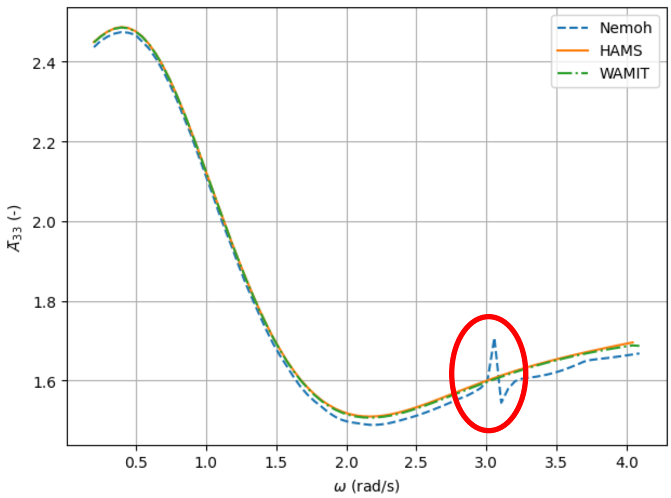
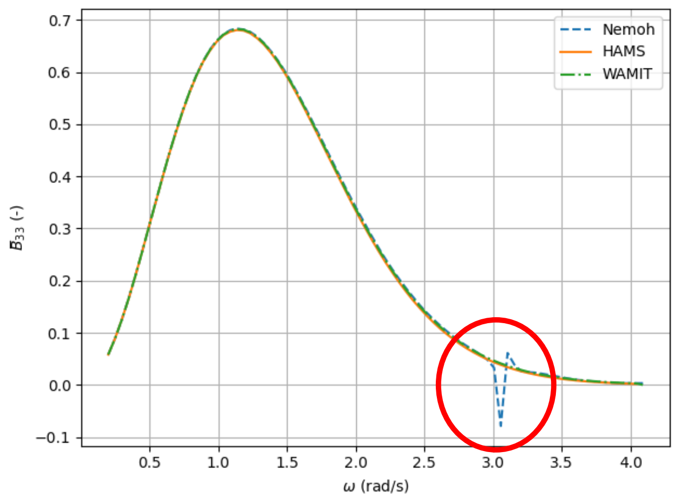


Figure 4 *RAO*$_3$ for Case (a) for the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)



(a)



(b)

Figure 5(a). Heave added mass and (b) heave radiation damping for Case (b) for the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)

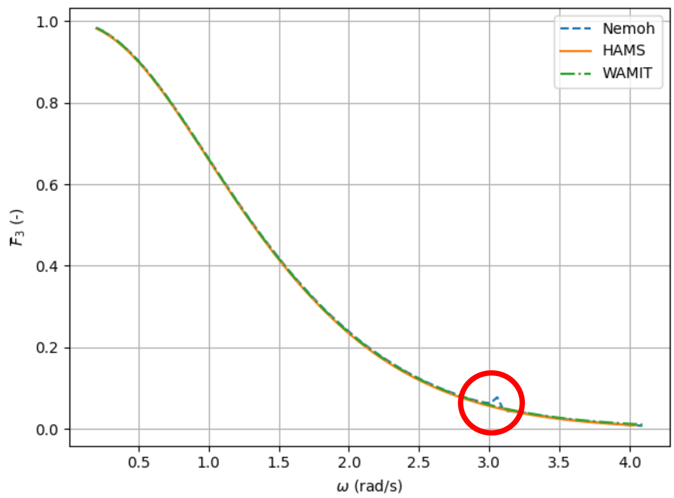


Figure 6 Heave exciting force for Case (b) for the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)

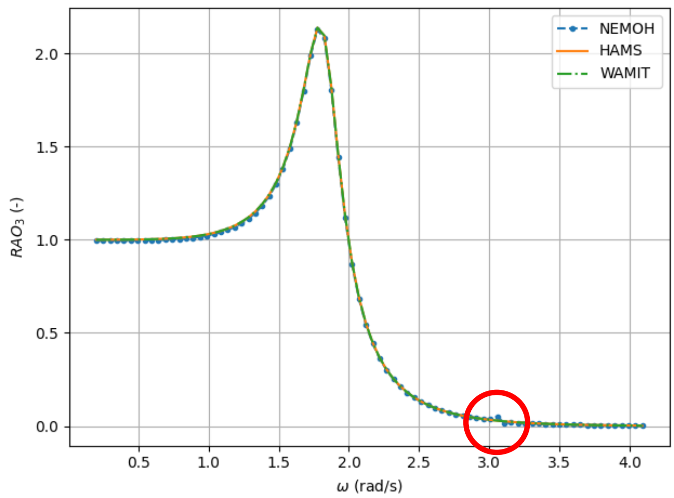


Figure 7 RAO_3 (heave) for Case (b) for the cylindrical PA where only the hull mesh is used for HAMS (irregular frequency highlighted within the red circle)

As seen in Figures 2, 3 and 4, the results of HAMS and NEMOH are very close to WAMIT, particularly RAO_3. Slight deviation is observed for frequencies > 3 rad/s for the A_{33} when comparing NEMOH with WAMIT, yet HAMS leads almost to the same result with WAMIT. Additionally, in Case (a) when not solving for irregular frequencies, a small jump is observed in HAMS and WAMIT. A larger jump for NEMOH is observed at the 'irregular frequency' (close to 3 rad/s) for A_{33} and B_{33} for the same case.

As seen in Figures 5, 6 and 7, the irregular frequency is suppressed in HAMS and WAMIT as compared to NEMOH. In this case a hull and water mesh is given as input for the simulation in HAMS. With WAMIT, the option for the suppression of irregular frequencies, IRR, was used, which also creates a waterplane mesh similar to HAMS automatically. HAMS employs an extended boundary integral equation which assumes that the potentials in the interior of the water plane are zero. This equation is hence used as an additional equation to the input boundary integral equations which are solved on the hull surface (Liu 2019).

3.2 *Semi-immersed oscillating surge WEC*

The dimensions of the OSWEC were taken from Penalba et al. (2017) and correspond to the Oyster device. The height of the device, *h*, is 12.0 m, its length is 20.0 m and its width is 2.0 m. The draft is considered equal to 10.0 m. The OSWEC is bottom hinged. In order to emulate this condition in the analysis, the center of rotation was taken at the bottom (*z* = -10.0 m). The shallow water depth of 10.5 m was considered, to keep the bottom of the OSWEC close to the sea bottom.

The mesh (hull) of the OSWEC model in HAMS is shown in Figure 8.

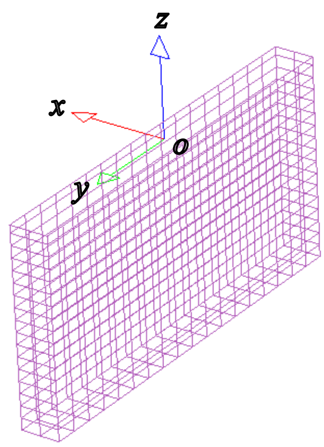
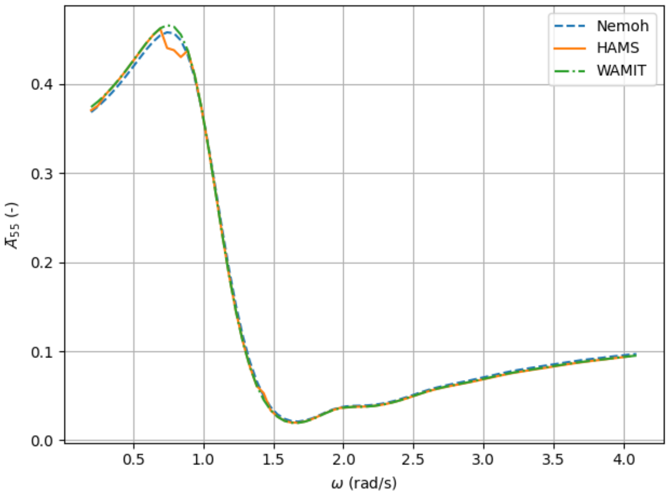
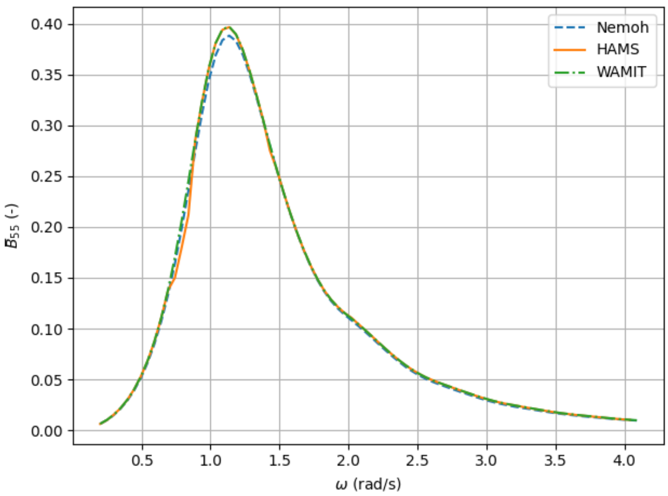


Figure 8 Mesh for the hull (purple) for the OSWEC as modelled in HAMS. The global *ox* (red) *oy* (green) *oz* (blue) axes are shown.



(a)



(b)

Figure 9(a). Pitch added mass and (b) pitch radiation damping for OSWEC

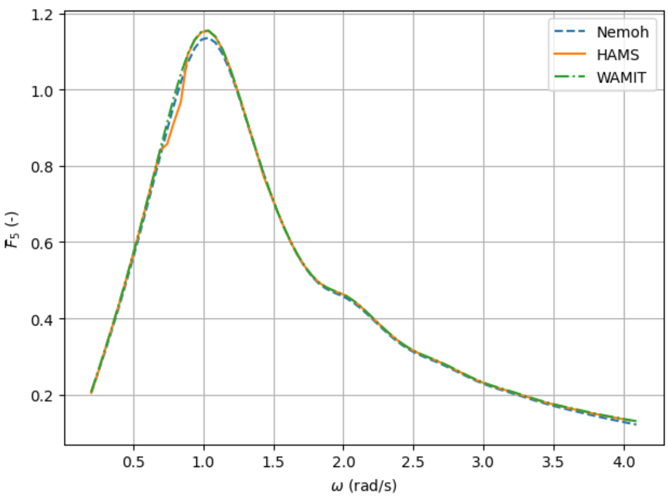


Figure 10 Pitch exciting force for OSWEC

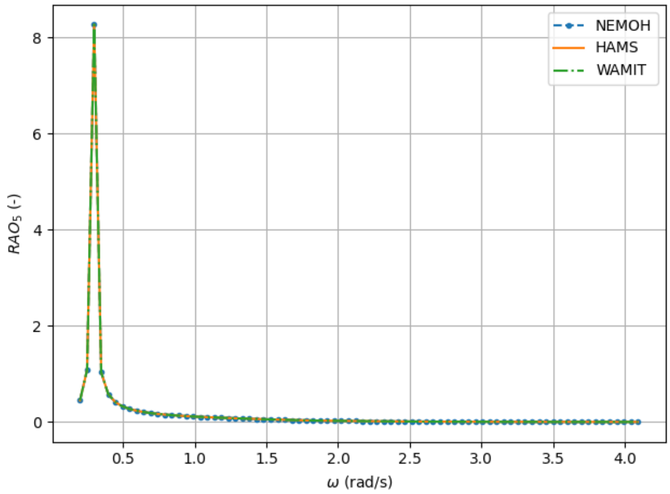


Figure 11 RAO_5 (pitch) for OSWEC

The hydrodynamic coefficients, exciting forces and RAOs for the OSWEC are shown in Figures 9, 10 and Figure 11 respectively. Only pitching DOF was considered here. To calculate the RAO, the pitching moment of inertia and pitching hydrostatic restoring coefficient for a solid rectangular plate were obtained from Tom et al. (2016). Exciting forces, F_5, are normalized by $\rho g A h^3$, while added mass, A_{55}, and radiation damping, B_{55}, coefficients by ρh^5 and $\rho \omega h^5$ respectively.

From Figures 9, 10 and 11, it can be observed that the results for NEMOH and HAMS are close to WAMIT. HAMS slightly under-predicts the pitch added mass, radiation damping and exciting force compared to WAMIT close to 0.75 rad/s. This is much less pronounced for RAO_5.

4 COMPUTATIONAL EFFORT

For making a fair comparison of the three solvers, the simulations were carried out in the same device. The device is a 64-bit laptop with 32 GB RAM, 12 cores and Intel i7-8700 processor of 3.19 GHz CPU.

The comparison of the computation effort is shown in Table 1. 80 frequencies between 0.2 and 4.2 rad/s were considered for the analysis.

Table 1. Comparison of computation time of the applied BEM solvers

WEC	Solver	No. of panels	DOF	Time (s)
PA(HULL)	WAMIT	2448	6	72
	NEMOH	2448	6	765
	HAMS	2448	6	36
PA(HULL +WATER)	WAMIT	2448 + 1584	6	176
	NEMOH	2448	6	765
	HAMS	2448 + 1584	6	175
OSWEC (HULL)	WAMIT	716	1	39
	NEMOH	716	1	210
	HAMS	716	6*	11

* HAMS always calculates for all 6 DOFs

From Table 1, it can be seen that HAMS is faster than NEMOH (about 21 times for the case of PA with only hull mesh) and WAMIT (2 times for the PA). Similar results were observed for the OSWEC. It should be noted that for the OSWEC case, the diffraction and radiation problem in WAMIT and NEMOH was solved only for pitch, while in the case of HAMS for made all DOFs. When irregular frequency removal is taken into account, WAMIT and HAMS are comparable. It is noted though that in WAMIT the option for removing irregular frequencies was utilized for $\omega > 2.8$ rad/s, corresponding to the frequency range where (for the examined PA and water depth) irregular frequencies are anticipated. As for HAMS, the inclusion of the water mesh in the analysis (Case (b)) made this solver 5 times slower when compared to Case (a). When comparing the results for the PA (Figures 2 to 7), it could be important to check if the water plane mesh is actually required with regard to the range of frequencies that are important to a certain analysis. Furthermore, in this case the water plane mesh is quite fine particularly at its center similar to the bottom surface of the cylindrical PA. This fineness could also be reduced and checked to select an appropriate mesh size for the water plane mesh.

5 CONCLUSIONS

This research makes some comparisons among the open-source solver HAMS with the popular commercial solver WAMIT and another popular open-source solver NEMOH for two different types of WECs: a semi-submerged cylindrical PA and a semi-submerged OSWEC. The compared parameters include the hydrodynamic coefficients, the excitation forces, the response amplitude operators and the computational efficiency.

For the PA, two cases are highlighted here. Case (a) focuses on the simulation where only the hull mesh is used for all the three solvers. Case (b) focuses on the simulation where the water plane mesh is added to the hull mesh for WAMIT and HAMS. The water plane mesh is added particularly to remove irregular frequencies. When comparing the hydrodynamic coefficients, excitation forces and RAOs for Case (a) and Case (b), it can be concluded that the results of HAMS are closer to WAMIT as compared to NEMOH, even at the vicinity of irregular frequencies. Furthermore, when comparing Case(a) and Case(b) for the PA, it can be observed that with Case (b), the irregular frequency is suppressed with HAMS and WAMIT as compared to NEMOH. HAMS and WAMIT employ an extended boundary integral equation which assumes that the potentials in the interior of the water plane are zero. This equation is hence used as an additional equation to the input boundary integral equations which are solved on the hull surface, thus suppressing the irregular frequencies.

In the case of the OSWEC, it is observed that the results from NEMOH and HAMS are very close with the corresponding ones of to WAMIT. HAMS slightly under-predicts the pitch added mass, radiation damping and exciting force compared to WAMIT close to 0.75 rad/s. This is much less pronounced for pitch response.

The last segment of this research compares the computational efficiency of the BEM solvers. HAMS is significantly faster than NEMOH for all the simulations going up to 21 times for the case of the PA and OSWEC with only the hull mesh. Considering the inclusion of the water plane mesh in the case of the PA removing irregular frequencies effects, WAMIT and HAMS are comparable. Comparing the computation time for HAMS with and without the water plane mesh, it can be observed that with the water plane mesh, HAMS is 5 times slower. This is due to the fineness of the water plane mesh. Hence, when considering the water plane mesh, it is important to consider if this is really required, given the frequency of interest. If this holds true, a convergence test to set the limit of the mesh size is suggested to obtain accurate results with less computational effort.

Within the domain of open-source solvers for wave-structure interactions, HAMS offers some unique advantages as compared to NEMOH and is seen to be comparable to the industry standard WAMIT. HAMS has the potential to become one of the more valuable options to meet the numerical challenges within the field of ocean engineering, particularly the possibility of low computational effort with good accuracy.

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