



Higher-harmonic radiation loads and wave fields from instantaneous wetted surface modelling: A time-domain Rankine source study of floating wind platforms

Ronja Olsmats Baumeister¹, Joseph Saverin¹, and Christian Oliver Paschereit¹

¹Chair of Fluid Dynamics, Hermann Föttinger Institute, Technische Universität Berlin, Berlin, Germany

Correspondence: Ronja Olsmats Baumeister (r.baumeister@campus.tu-berlin.de)

Abstract. This study investigates how the instantaneous wetted surface affects hydrodynamic radiation loads and wave fields of floating offshore wind platforms. A direct time-domain Rankine source boundary element method compares a linear formulation evaluated at the mean body position with a body-exact formulation that updates the wetted body surface and free surface intersection at each time step. The free surface boundary conditions remain linearised about the mean water level in both cases, so differences in their responses relate to the treatment of the instantaneous wetted surface. Radiation problems are considered for a vertical cylinder as a reference geometry, as well as for the OC3-Hywind spar buoy and UMaine VoltturnUS-S semi-submersible in surge, heave, and pitch motion. The unsteady pressure loads contain higher-harmonic contributions absent in the linear formulation, following a symmetry-dependent structure for the axisymmetric cylinder and spar, with a leading second harmonic in heave and leading third harmonics in surge and pitch motion. These scale with the square and the cube of the motion amplitude, respectively, and the unsteady pressure contribution to the second harmonic in heave of the spar buoy reaches 99–126 % of the linear fundamental at the largest motion amplitude for the investigated wave numbers. Including the quadratic term in Bernoulli's equation reduces the total second harmonic to 56–73 % of the fundamental for the same cases. For the spar, the radiated wave field shows corresponding higher-harmonic content. For the non-axisymmetric VoltturnUS-S, the unsteady pressure second harmonic reaches 3.7 % of the fundamental in surge, 18 % in heave, and 19 % in pitch. For the axisymmetric geometries, the second-harmonic contributions of the quadratic term vanish in surge and pitch due to symmetry. The quadratic term in Bernoulli's equation differs only slightly between the linear and body-exact formulations but is not negligible, as it acts nearly out of phase with the unsteady pressure second harmonic. The results show that the instantaneous wetted geometry with linearised free surface boundary conditions introduces symmetry-dependent higher-harmonic radiation loads. The body-exact formulation provides a basis for further development of accelerated weak-scatterer simulations coupled with flexible structural models for the hydroelastic analysis of floating offshore wind platforms.

1 Introduction

Floating offshore wind (FOW) is expected to expand significantly over the next decade (Williams et al., 2026). To reduce the levelised cost of electricity (LCOE), increasingly large wind turbines are being developed together with larger floating support structures (Abdelmoteleb et al., 2022; Ran et al., 2023). Platform optimisation aims to reduce material use and structural



mass (Abdelmoteleb et al., 2022; Ran et al., 2026). These developments can lead to more flexible floating structures, making hydroelastic effects increasingly important for the analysis and design of floating offshore wind turbine (FOWT) platforms (Ran et al., 2023; Abdelmoteleb et al., 2027). High-fidelity numerical approaches, such as computational fluid dynamics (CFD) and fully nonlinear potential flow solvers, can describe the resulting fluid–structure interactions in greater detail. However, their computational cost limits their use in routine design and optimisation studies (Ran et al., 2026). This motivates the development of efficient engineering models that can capture important hydrodynamic effects while remaining suitable for system-level analysis and design.

System-level models for FOWT platforms, used for evaluating a large number of design variations, typically use simplified hydrodynamic representations based on potential flow theory, Morison’s equation, or a hybrid of both (Gao et al., 2023; Ran et al., 2026). Morison’s equation suits slender structural members, while potential flow methods are preferred for large-volume bodies where wave diffraction and radiation are dominant (Faltinsen, 1990; Kvittem et al., 2012). In practice, both are often combined, with potential flow coefficients describing radiation and diffraction and Morison drag terms accounting for viscous loads (Kvittem et al., 2012; Souza and Bachynski-Polić, 2022; Wang et al., 2022). In conventional potential flow applications, radiation, diffraction, and wave-excitation coefficients are calculated using frequency-domain boundary element method (BEM) solvers for a fixed reference geometry and boundary conditions linearised about the mean free surface level (Kvittem et al., 2012; Ran et al., 2026). Frequency-domain models are commonly used in design optimisation, as they evaluate many design iterations more efficiently than time-domain simulations (Ran et al., 2026). In time-domain simulations, the coefficients are converted into a time-domain representation using the Cummins equation (Cummins, 1962; National Renewable Energy Laboratory, 2026). Structural flexibility can also be represented through distributed structural models, in which the hydrodynamic and hydrostatic loads are distributed over the structure rather than applied at a single platform reference point, for example through modal or multi-body approaches (Borg et al., 2017; Ran et al., 2026; Bergua et al., 2026; Abdelmoteleb et al., 2027). However, the hydrodynamic model is still based on a linearised geometry, assuming that platform motion or deformation is small, so that the geometry is not recomputed as the body moves or deforms (Borg et al., 2017; Teng et al., 2018; Abdelmoteleb et al., 2027). Thus, while these approaches can often effectively represent the overall system response, they typically do not account for changes in the hydrodynamic problem associated with the instantaneous body configuration (Kvittem et al., 2012; Abdelmoteleb et al., 2027; Bergua et al., 2026).

OpenFAST (Jonkman, 2013) uses potential flow and Morison-based hydrodynamic models in its HydroDyn module (National Renewable Energy Laboratory, 2026). Similar hydrodynamic modelling approaches are used in tools such as HAWC2 (Larsen and Hansen, 2023; DTU Wind Energy, 2026). Frequency-domain BEM solvers such as WAMIT (WAMIT, Inc., 2026), OrcaWave (Orcina Ltd., 2026), ANSYS AQWA (ANSYS, Inc., 2025), and NEMOH (Babarit and Delhommeau, 2015) are commonly used to calculate hydrodynamic coefficients for floating bodies.

The limitations of engineering-level hydrodynamic models have been investigated in a series of international benchmark studies. The OC3 and OC4 projects established reference configurations (Jonkman, 2010; Robertson et al., 2014a) and compared responses obtained with different simulation tools (Jonkman and Musial, 2010; Robertson et al., 2014b). The subsequent OC5 project systematically compared simulations with physical experiments and identified discrepancies in predicting



low-frequency responses of the DeepCwind semi-submersible (Robertson et al., 2017). During Phase I of the OC6 project, Robertson et al. (2020) investigated these discrepancies and reported persistent underprediction of low-frequency surge and pitch responses. Wang et al. (2022) subsequently improved OpenFAST’s predictions of this global response through modifications to the modelling of viscous drag forces, achieving good agreement with the OC6 experimental measurements. This approach has since been adopted in QBlade-Ocean (Behrens de Luna et al., 2024). More recently, OC7 has extended the comparison to flexible floating structures and member-level loads. For the UMaine VoltturnUS-S semi-submersible platform, Bergua et al. (2026) reported that platform motions and mooring line tensions were accurately reproduced, with member-level loads showing reasonable overall accuracy. Discrepancies in the predicted pontoon torque were attributed to potential flow models neglecting higher-order effects of the instantaneous wetted surface. This motivates hydrodynamic models that directly resolve the instantaneous wetted surface.

Direct time-domain potential flow methods provide a viable framework for addressing this limitation, resolving local pressure and motion nonlinearities associated with the instantaneous body configuration. While convolution-based time-domain methods transform precomputed frequency-domain coefficients to the time domain, direct time-domain methods solve the hydrodynamic boundary value problem at each time step (Watai et al., 2016; Teng et al., 2018). Crucially, solving in the time domain enables body-exact formulations that explicitly evaluate the boundary conditions and resolve the spatially distributed hydrodynamic pressure field on the instantaneous wetted surface. Compared to fully nonlinear BEM, the weak-scatterer formulation provides a more efficient alternative by linearising the fluid perturbation induced by the structure around the incident wave field. Related Rankine source approaches have been applied to seakeeping problems using solvers such as SWAN-4 (Huang, 1997), LAMP-4 (Shin et al., 2003), and WISH-3 (Kim et al., 2011). Furthermore, the WS_CN solver developed at École Centrale Nantes has demonstrated the weak-scatterer formulation for wave energy converters (Letournel, 2015), interacting bodies (Wuillaume, 2019), and the hydroelastic response of a bottom-fixed offshore wind turbine (Leroy et al., 2021).

For floating wind applications, a major challenge is the computational cost of repeatedly solving the time-domain BEM problem as the body configuration changes. The fast multipole method and other accelerated BEM techniques provide a possible means of reducing this computational cost. The time-domain Rankine source solver BEMUseRS (Olsnats Baumeister et al., 2026) has been developed to provide a computationally efficient hydrodynamic framework for floating offshore wind. Its long-term objective is to incorporate a weak-scatterer formulation for incident-wave interactions and, subsequently, coupling to flexible structural models for hydroelastic analysis. Establishing a body-exact time-domain formulation is a crucial step towards this objective. In the present work, the instantaneous wetted body surface and waterline intersection are updated during prescribed body motion, allowing evaluation of the hydrodynamic boundary-value problem and pressure distribution on the moving geometry. The resulting higher-harmonic radiation loads and wave fields are investigated to characterise the effects of the instantaneous wetted surface before extending the formulation to incident waves and structural deformation.

BEMUseRS was cross-verified against frequency-domain results by Olsnats Baumeister et al. (2026). Building on that verification, this work quantifies the higher-harmonic radiation loads and wave fields arising from the instantaneous wetted surface in the body-exact formulation, relative to the corresponding linear solution, for motion amplitudes and frequencies representative of floating offshore wind platforms. Radiation problems are considered for a vertical cylinder, the OC3-Hywind



95 spar buoy, and the UMaine VoltturnUS-S semi-submersible, in surge, heave, and pitch motion. Mesh sensitivity is assessed
 for the free surface and body discretisations. For the cylinder, motion amplitudes and radiation wavelengths are varied to
 investigate the effects of the instantaneous wetted geometry. The platform cases extend this analysis to representative floating
 wind geometries over a range of frequencies and motion amplitudes. The higher-harmonic content in the radiated wave field
 and hydrodynamic loads is quantified against the corresponding fixed-geometry linear solution and related to the amplitude
 100 and symmetry of the prescribed motion.

2 Methodology

2.1 Hydrodynamic boundary value problem

This study employs a BEM based on potential flow theory, assuming an inviscid, incompressible, and irrotational ideal fluid.
 A Rankine source formulation represents the perturbation velocity potential and its normal derivative as source and dipole
 105 distributions over the wetted body and free surfaces. The source and dipole strengths are determined by solving a linear
 boundary value problem (BVP) for the perturbed velocity potential, ϕ_p . Boundary conditions are enforced on the mean free
 surface, S_{FS} ($z = 0$), and the wetted body surface, $S_B(t)$. The body boundary condition ensures non-penetration flow, while
 the free surface conditions derive from the linearised kinematic and dynamic fluid constraints, expressed as

$$\begin{cases} \frac{\partial \phi_p}{\partial t} = -g\eta_p, & \text{on } S_{FS} : z = 0, \\ \frac{\partial \eta_p}{\partial t} = \frac{\partial \phi_p}{\partial z} & \text{on } S_{FS} : z = 0, \\ \frac{\partial \phi_p}{\partial n} = \mathbf{U} \cdot \mathbf{n}, & \text{on } S_B, \end{cases} \quad (1)$$

110 where η_p is the perturbed free surface elevation, and g is the gravitational acceleration. Here, $\mathbf{U}$ denotes the prescribed body
 velocity, which corresponds to rigid-body motion in the present study, and $\mathbf{n}$ is the unit normal vector on S_B , pointing out of
 the body into the fluid. To satisfy the radiation condition at the domain boundary, an artificial absorbing beach (Huang, 1997)
 is applied in an outer domain of the free surface by adding damping terms to the kinematic condition,

$$\frac{\partial \eta_p}{\partial t} = \frac{\partial \phi_p}{\partial z} - 2\nu(r)\eta_p + \frac{\nu(r)^2}{g}\phi_p, \quad (2)$$

115 where the damping coefficient $\nu(r)$ is zero in the inner region and increases from the inner edge of the beach to the outer
 boundary.

Two nondimensional parameters are used to assess the limitations of the underlying modelling assumptions. The Keulegan–
 Carpenter (KC) number, which for a pure radiation problem, where the relative flow velocity is the body velocity, reduces to
 $KC = 2\pi A/D$, where A is the motion amplitude and D the characteristic body dimension, measures the motion amplitude
 120 relative to the body size. For KC values of order unity or larger, depending on geometry and flow conditions, flow separation
 becomes increasingly important (Faltinsen, 1990). Here, KC is therefore used as an indicator of potential theory limitations
 rather than a strict applicability threshold. For rotational motion, the displacement increases with distance from the rotation



centre, so KC is evaluated with the local lever arm. Since the kinematic and dynamic free surface boundary conditions are linearised about $z = 0$, their applicability depends on the radiated wave steepness $k\eta$, where η denotes the radiated free surface elevation amplitude. Larger values suggest that neglected nonlinear free surface effects may become relevant, regardless of KC .

The free surface and body boundary, $S = S_{FS} \cup S_B$, are discretised into flat triangular panels. The velocity potential, ϕ_p , and its normal derivative, $\sigma_p \equiv \partial\phi_p/\partial n$, are approximated on the elements with a linear distribution, ensuring continuity between elements. A collocation scheme enforces the boundary integral equation at each node, resulting in the linear system $\mathbf{H}\phi = \mathbf{G}\sigma$.

The source and dipole kernels for the influence coefficient matrices $\mathbf{G}$ and $\mathbf{H}$ are evaluated analytically using the linear-strength flat triangular panel formulation by Newman (1986). When a receiver node coincides with a source panel, the $1/r$ singularity in the single-layer integral is resolved using a Duffy-type polar coordinate transformation, while the double-layer contribution vanishes for all coplanar receivers. The diagonal self-influence coefficient of $\mathbf{H}$, representing the solid angle enclosed by the fluid domain at each collocation point, is calculated from the dihedral angles between the panels at the node using the Gauss–Bonnet relation for a spherical polygon (Mantič, 1993). The continuity of the velocity potential at sharp body edges with double or triple nodes is ensured by enforcing equivalency in the linear systems for the influence coefficient matrices. At the waterline interface where the body meets the free surface, the boundary integral row of the body node n_1 is replaced with the direct constraint $\phi_p(n_1) = \phi_p(n_2)$, enforcing equality with the known free surface potential at the coincident free surface node n_2 .

To solve the system, a Neumann condition ($\partial\phi/\partial n = \mathbf{U} \cdot \mathbf{n}$) is enforced on the body boundary, and a Dirichlet condition from the previous time step is applied to the free surface. Rearranging the known quantities yields a mixed linear system. As the influence coefficients depend on geometry, their matrices are updated whenever geometries change. Free surface quantities are integrated over time using a two-step Adams–Bashforth (AB2) scheme, initialised with an explicit forward-Euler step. A smooth ramp function is applied to the body displacement, velocity, and acceleration over the first three oscillation periods to avoid initial numerical transients.

To evaluate the hydrodynamic pressure on the body, the time derivative of the perturbation potential ($\partial\phi_p/\partial t$) is obtained by solving an acceleration BVP (Letournel, 2015; Wuillaume, 2019). Influence coefficient matrices from the above described potential BVP are reused. The spatial gradient $\nabla\phi_p$ is evaluated using B-spline interpolation of the velocity potential. Pressures are calculated using the unsteady Bernoulli equation,

$$P(t) = P_u + P_q = -\rho \frac{\partial\phi_p}{\partial t} - \frac{\rho}{2} |\nabla\phi_p|^2, \quad (3)$$

and integrated over the wetted surface to yield the hydrodynamic force

$$\mathbf{F}(t) = - \iint_{S_B(t)} P \mathbf{n} dS. \quad (4)$$

The unsteady and quadratic-velocity pressure contributions, P_u and P_q , are evaluated separately to isolate the effect of the instantaneous wetted surface on each. The loads obtained by integrating P_u and P_q are referred to as the P_u and P_q loads.

Hydrostatic pressure is excluded, so the results are purely hydrodynamic.



2.2 Linear and body-exact formulation

Two variants of the time-domain solver BEMUseRS are implemented, both assuming rigid-body motion for the study conducted here. The linear formulation calculates the hydrodynamic influence coefficient matrices once at the mean body position. In contrast, the body-exact formulation solves the BVP on the instantaneous wetted surface, requiring updates to the body mesh, the body-free-surface intersection, and therefore the influence coefficient matrices at each time step. The kinematic and dynamic free surface boundary conditions remain linearised about the mean water level, $z = 0$, in both the linear and the body-exact approach. Thus, the linear formulation provides a reference that excludes the instantaneous wetted geometry effects present in the body-exact formulation. Higher-harmonic components absent from the linear reference quantify the nonlinear response associated with the instantaneous wetted surface treatment.

The free surface is discretised using a conformal mesh. For the body-exact formulation, the conformal free surface mesh around the body is updated at each time step to follow the moving waterline. Waterline nodes are repositioned to the current body-free-surface intersection, identified by a bisection search along the body contour. The conformal mesh nodes are redistributed between the moving waterline and the fixed outer boundary, allowing the mesh to follow body motion. Only the constrained Delaunay region of the VoltturnUS-S mesh (Sect. 3) remains fixed. Free surface quantities such as wave elevation, velocity potential, and previous time derivatives for time integration are interpolated onto the updated node positions using a radial basis function interpolation scheme with the thin-plate-spline kernel $\varphi(r) = r^2 \log r$. The kernel is augmented with a quadratic polynomial, and interpolation is local, using each node and its first- and second-order mesh neighbours.

2.3 Solver implementation and strategy

BEMUseRS is implemented in C++. Linear algebra operations use the Eigen library (Guennebaud et al., 2010). To avoid evaluating costly transcendental functions across all panel pairs, the influence coefficient matrices are assembled using a hybrid integration scheme. Far-field interactions are computed with low-order numerical quadrature, while near-field and singular interactions use the analytical formulations described above. The influence coefficient matrices are assembled in parallel using OpenMP (Dagum and Menon, 1998).

The choice of matrix solver depends on the formulation. For the linear formulation the system matrix is constant throughout the simulation, so it is factorised once and reused at every time step. For the body-exact formulation the matrix is reassembled at every time step and is solved by LU decomposition with partial pivoting.

The time-domain solver BEMUseRS is implemented in the open-source library BEMUse (Saverin and Grüter, 2022; Uçar et al., 2025), developed by the Numerical Fluid Mechanics Group at the Institute for Fluid Dynamics and Technical Acoustics, Technische Universität Berlin, which also provides a frequency-domain BEM solver based on a free surface Green's function formulation. BEMUseRS shares geometry handling, surface discretisation, and numerical integration with the frequency-domain solver and was cross-verified against it in Olsmats Baumeister et al. (2026). All body-exact results below are compared to this cross-verified linear solution.



3 Numerical setup and reference cases

To systematically evaluate the body-exact formulation, three geometries are considered: a vertical cylinder with a radius of 1 m and a draft of 5 m, the OC3-Hywind spar buoy, and the UMaine VoltturnUS-S semi-submersible (Jonkman, 2010; Allen et al., 2020). The cylinder serves as a reference geometry for studying the numerical behaviour of the body-exact formulation, while the two platform geometries provide benchmark cases. Figure 1 compares the body discretisation of the linear and body-exact formulations for the VoltturnUS-S at maximum pitch. In the linear formulation, the discretisation is fixed at the mean position, while in the body-exact formulation, the hull follows the prescribed rotation as the discretisation is adapted at each time step.



Figure 1. UMaine VoltturnUS-S geometry for the linear and body-exact formulations at a pitch motion of $\theta_0 = 6^\circ$.

For the cylinder and OC3-Hywind spar, the free surface is discretised using a conformal mesh. For the VoltturnUS-S semi-submersible, conformal meshes are used around the surface-piercing columns and connected through a constrained Delaunay triangulation (CDT). The CDT consists of an inner region for wave propagation and a coarser outer region corresponding to the absorbing beach, where numerical damping is applied.

Radiation is investigated in surge, heave, and pitch. For the cylinder, translational motion amplitudes of $A = 0.1, 0.2$, and 0.4 m and pitch amplitudes of $\theta_0 = 3^\circ, 6^\circ$, and 12° are considered at wave numbers $k = 1.5$ and 3.0 m^{-1} using the deep-water dispersion relation. These cases vary motion amplitude and radiation wavelength systematically. For the spar, translational amplitudes of $A = 0.4, 1.6$, and 3.2 m and pitch amplitudes of $\theta_0 = 3^\circ, 6^\circ$, and 12° are considered at wave numbers $k = 0.02, 0.05$, and 0.10 m^{-1} . For the semi-submersible, the same wave numbers and translational amplitudes are used, while the pitch amplitudes are limited to $\theta_0 = 2^\circ, 4^\circ$, and 6° . The platform wave numbers correspond to periods of 6.3 to 14.2 s through $k = \omega^2/g$, covering the moderate to severe periodic sea states defined for the OC3-Hywind spar (Jonkman, 2010). For the cylinder, higher wave numbers are selected to test the numerical formulation at shorter radiation wavelengths relative to the body dimensions. All studied wave numbers, along with their corresponding angular frequencies and periods, are summarised in Table 1.



Table 1. Oscillation frequencies used in this study, with the radiated wavelength from the deep-water dispersion relation $\omega^2 = gk$.

k [m^{-1}]	ω [rad s^{-1}]	T [s]	λ [m]	Geometry
0.02	0.44	14.19	314.20	Platforms
0.05	0.70	8.97	125.70	Platforms
0.10	0.99	6.34	62.80	Platforms
1.50	3.84	1.64	4.19	Cylinder
3.00	5.43	1.16	2.09	Cylinder

For the VoltturnUS-S, the translational cases correspond to $0.2 \leq KC \leq 1.6$, while pitch yields larger local values at the
 210 outer columns, up to $KC \approx 2.7$, due to their distance from the rotation axis. For the OC3-Hywind spar, the translational cases
 yield $0.3 \leq KC \leq 2.1$, while the 120 m draft results in larger local values during pitch motion due to the long lever arm, up
 to $KC \approx 17$ at the platform base. These pitch amplitudes test the body-exact formulation and exceed the motion a moored
 spar would reach at these frequencies. The radiated steepness $k\eta$ remains below 0.14 for the OC3-Hywind spar and reaches
 0.28 for the VoltturnUS-S in surge at the highest wave number and motion amplitude. The cylinder cases also reach relatively
 215 large radiated wave steepness and, for pitch, $KC \approx 3.3$ at the base. These values suggest that viscous separation and neglected
 nonlinear free surface effects may become relevant for some investigated conditions. Throughout this study, the reported
 loads represent inviscid potential flow radiation responses and do not account for viscous separation or nonlinear free surface
 boundary conditions.

The hydrodynamic response is evaluated using radiated free surface elevations, hydrodynamic forces, and moments. Fourier
 220 analysis is used to investigate the higher-harmonic components generated by the body-exact formulation. A separate evaluation
 shows that the P_q load differs only slightly between the linear and body-exact formulations. The analysis therefore focuses on
 the P_u load to assess the influence of the instantaneous wetted geometry, and the effect of P_q on the total load is summarised at
 the end of each platform section. Spectral analysis is performed over the final five oscillation periods. The mean is subtracted
 from each signal, followed by a discrete Fourier transform using a rectangular window. The resulting spectrum is converted to a
 225 single-sided amplitude spectrum, and the amplitude of the n th harmonic is taken from the discrete frequency bin closest to $n f_1$,
 where f_1 denotes the frequency of the prescribed body motion. For the free surface elevation, the frequency content is derived
 from a spatial average of the Fourier spectra across all probe positions along the positive x -axis, extending from the body to
 two fundamental wavelengths, $2\lambda_1$. Spatial averaging is used because the harmonic amplitudes vary with position, so the result
 does not depend on a single probe location. The spectrum at each probe position is computed from the mean-centred signal
 230 using the described procedure. The spatially averaged spectrum is formed as the mean of the individual spectral magnitudes
 across all probe positions in this range. The spatial averaging reduces the influence of individual probe locations but removes
 information about the spatial distribution of the harmonic amplitudes.



The integrated loads computed from P_u in the linear formulation include only the fundamental frequency f_1 . Any spectral content at higher harmonics is therefore treated as numerical background. The linear spectral level serves as a reference for assessing the higher-harmonic response of the body-exact formulation. The linear spectral level is removed from the body-exact amplitude, denoted BDEExact in figures and tables, by power subtraction,

$$|\hat{q}_{\text{corr}}(nf_1)| = \sqrt{|\hat{q}_{\text{BDEExact}}(nf_1)|^2 - |\hat{q}_{\text{Linear}}(nf_1)|^2} \quad (5)$$

where q denotes a force, moment, or free surface elevation. This assumes that the background and the harmonic are uncorrelated, and it is applied only where the body-exact amplitude exceeds the linear one.

Under the deep-water dispersion relation, a freely propagating component at nf_1 has the wave number $k_n = n^2 k_1$ and the wavelength $\lambda_n = \lambda_1/n^2$, and is therefore resolved with progressively fewer points per wavelength than the fundamental. This limitation is quantified in Sect. 4.

4 Mesh sensitivity study

Spatial convergence is assessed by refining the free surface and body discretisations. Free surface resolution is parameterised by the number of points per wavelength (PPW), where the reference wavelength is that of the radiated wave at the oscillation frequency, $\lambda_1 = 2\pi g/\omega^2$. For the cylinder and OC3-Hywind spar, increasing PPW refines both the free surface and body meshes simultaneously. For the VoltturnUS-S, free surface and body discretisations are controlled separately, with the body mesh defined by a target panel size, Δ_B . The body mesh remains fixed during the free surface refinement study and is then refined separately at the selected free surface resolution.

In each mesh study, the wave number and motion amplitude are fixed while varying the spatial resolution. Translational motion is prescribed with amplitude A and pitch with amplitude θ_0 , using the linear formulation. Wave elevation profiles are shown as η_{peak}/A , and force and moment amplitudes are normalised by the finest-mesh result, assessed over the final five periods. The OC3-Hywind spar in heave motion illustrates wave elevation convergence in Fig. 2. The surge, heave, and pitch profiles show no significant differences from $\text{PPW} = 25$ onward, which was adopted for subsequent simulations.

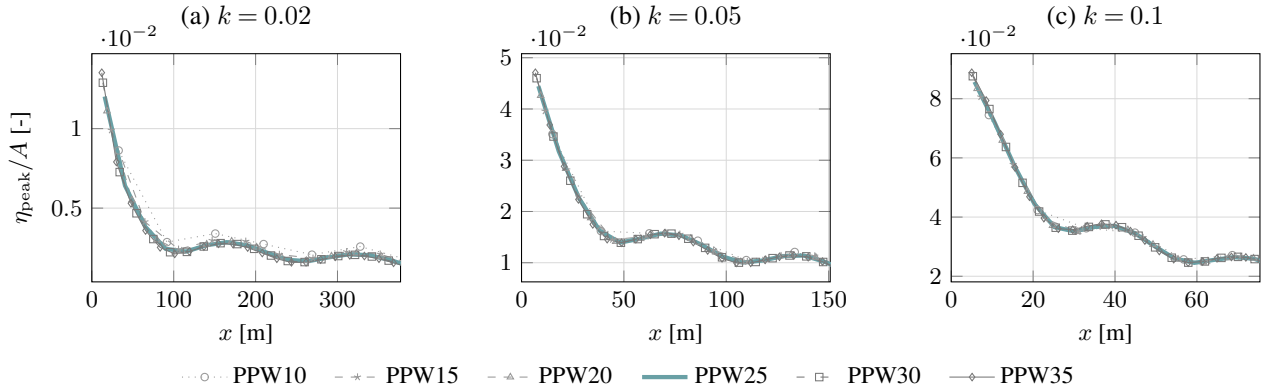


Figure 2. Peak wave elevation along the positive x -axis radiated by the OC3-Hywind spar buoy under heave motion at (a) $k = 0.02 \text{ m}^{-1}$, (b) $k = 0.05 \text{ m}^{-1}$, and (c) $k = 0.10 \text{ m}^{-1}$, for free surface resolutions PPW10–PPW35. The selected resolution PPW25 is highlighted. Results are obtained with the linear formulation and normalised by the motion amplitude.

255 Figure 3 shows the convergence of surge force F_x , heave force F_z , and pitch moment M_y , with the number of radial node rows on the bottom surface, N_R , replacing PPW as the horizontal axis for heave. At PPW = 25, surge and pitch loads are within 0.4% of the finest-mesh result. The smaller heave force, governed by pressure integration over the flat bottom surface, is more sensitive to body discretisation, so the bottom surface is refined separately, and $N_R = 10$ is selected, within 1% of the finest bottom discretisation ($N_R = 16$).

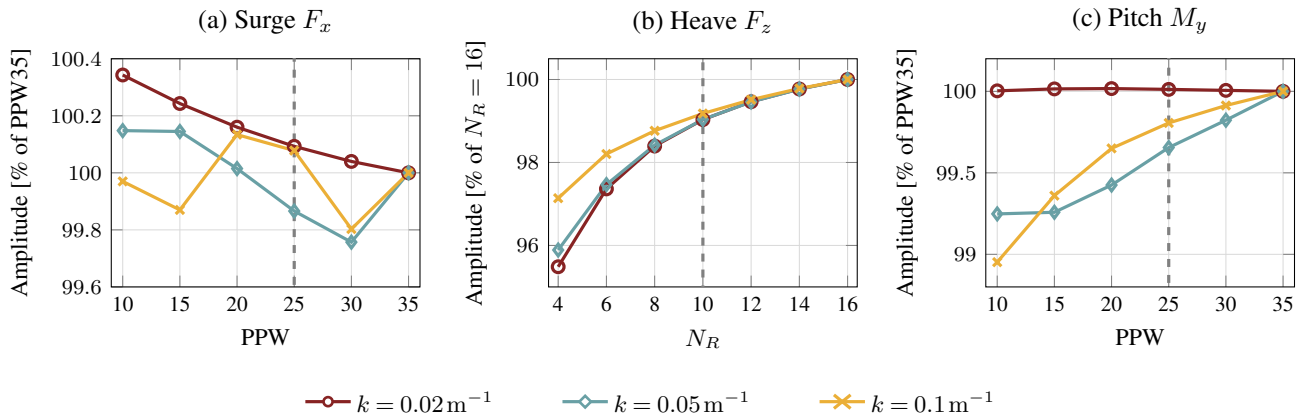


Figure 3. Mesh convergence of radiation loads for the OC3-Hywind spar buoy at $k = 0.02, 0.05$, and 0.10 m^{-1} : (a) surge force F_x with varying PPW, (b) heave force F_z with varying number of radial node rows on the bottom surface, N_R , and (c) pitch moment M_y with varying PPW. Results are obtained with the linear formulation and normalised by the finest-mesh result.

260 The adopted PPW = 25 is based on the fundamental radiation wavelength λ_1 , and the effective resolution decreases for the higher harmonics, giving 6.25 and 2.78 points per wavelength at $2f_1$ and $3f_1$, respectively. The third harmonic is therefore



close to the Nyquist limit of two points per wavelength, and the wave-field analysis is restricted to $2f_1$. Linear calculations at the $2f_1$ wave number confirm that the wave elevation profiles remain unchanged from $PPW = 25$ onward. At the $2f_1$ and $3f_1$ wave numbers, the integrated loads change by less than 1% between $PPW = 20$ and 30, and $N_R = 10$ is within 1% of $N_R = 16$ at $2f_1$. These calculations do not establish convergence of the nonlinear harmonic amplitudes.

For the VoltturnUS-S, the free surface mesh sensitivity is shown in Fig. 4 for heave excitation. A resolution of $PPW = 10$ was selected, as further refinement led to minor changes while significantly increasing computational costs. The body mesh was then refined from $\Delta_B = 6$ to 2 m (Fig. 5), and $\Delta_B = 3$ m was adopted as a compromise between spatial resolution and computational cost, with integrated loads within 2% of the finest mesh. The loads vary stepwise rather than smoothly with Δ_B , because the number of panels around the column circumference changes only at certain values of Δ_B . At $PPW = 10$, the free surface resolution corresponds to approximately 2.5 and 1.1 points per wavelength at $2f_1$ and $3f_1$, respectively. The higher-harmonic wave components are therefore not sufficiently resolved for quantitative analysis, limiting the VoltturnUS-S assessment to integrated loads.

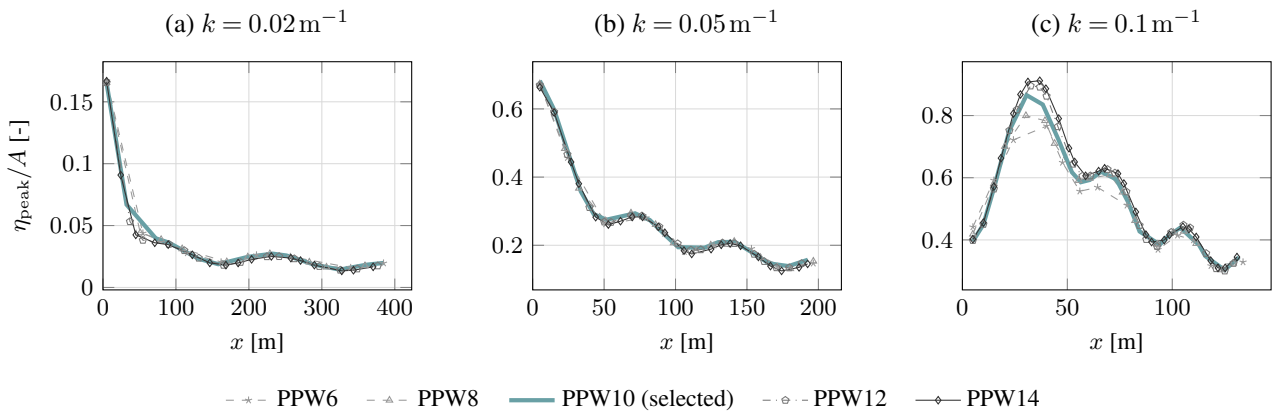


Figure 4. Peak wave elevation along the positive x -axis radiated by the UMaine VoltturnUS-S under heave motion at (a) $k = 0.02 \text{ m}^{-1}$, (b) $k = 0.05 \text{ m}^{-1}$, and (c) $k = 0.10 \text{ m}^{-1}$, for free surface resolutions $PPW6$ – $PPW14$ and a body panel size of $\Delta_B = 3 \text{ m}$. The selected resolution $PPW10$ is highlighted. Results are obtained with the linear formulation and normalised by the motion amplitude.

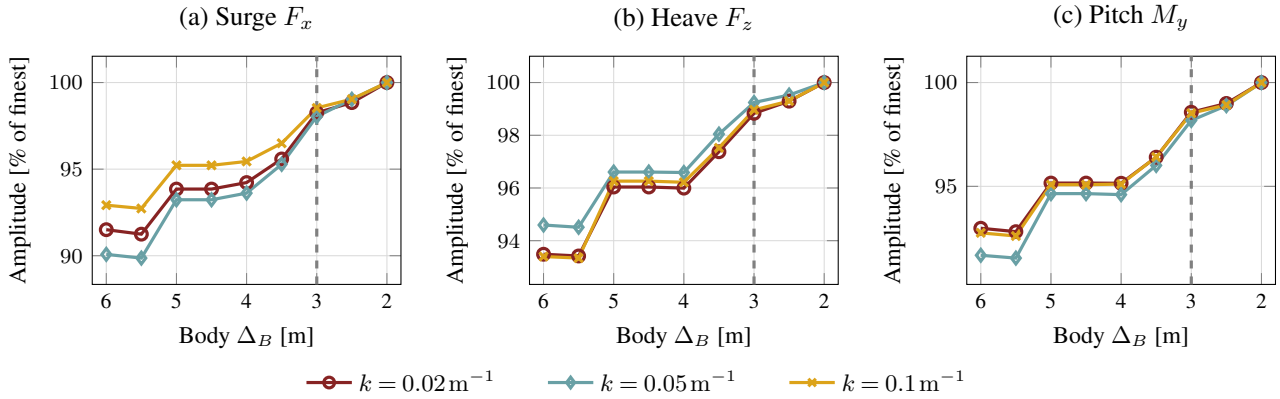


Figure 5. Mesh convergence of radiation loads for the UMaine VoltturnUS-S at PPW = 10: (a) surge force F_x , (b) heave force F_z , and (c) pitch moment M_y , with varying body panel size Δ_B . Results are obtained with the linear formulation and normalised by the finest-mesh result ($\Delta_B = 2 \text{ m}$).

For the cylinder, the convergence study yields PPW = 10 and $N_R = 8$, with the heave force within 1.4% of the finest-mesh result. No separate convergence figures are provided for the cylinder.

5 Higher-harmonic radiation response

5.1 Cylinder

The cylinder results show which harmonics the body-exact formulation produces under systematic variation of motion amplitude and radiation wavelength. Figure 6 shows time series of the surge force, heave force, and pitch moment at $k = 3.0 \text{ m}^{-1}$ for the three motion amplitudes investigated. In surge and pitch, the body-exact response remains symmetric and close to the harmonic linear response, while in heave it becomes increasingly asymmetric as the motion amplitude increases. The corresponding spectra for surge, heave, and pitch are compared in Fig. 7. The linear formulation contains only the fundamental component at f_1 . The body-exact formulation produces additional harmonic components whose magnitude increases with motion amplitude. Heave shows a pronounced component at $2f_1$, while surge and pitch primarily contain odd harmonics at $3f_1$ and $5f_1$. No comparable even-harmonic peaks are resolved above the linear spectral background for surge and pitch.

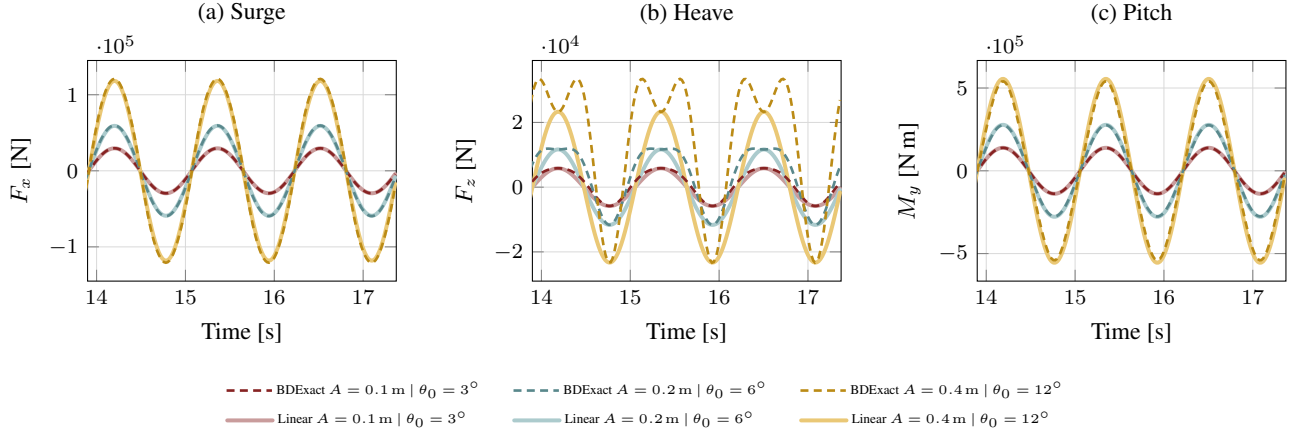


Figure 6. Time series of the hydrodynamic radiation loads for the cylinder at $k = 3.0 \text{ m}^{-1}$: (a) surge force F_x , (b) heave force F_z , and (c) pitch moment M_y . Translation amplitudes are $A = 0.1, 0.2$, and 0.4 m , and pitch amplitudes are $\theta_0 = 3^\circ, 6^\circ$, and 12° . BDExact denotes the body-exact formulation. The last two periods are shown.

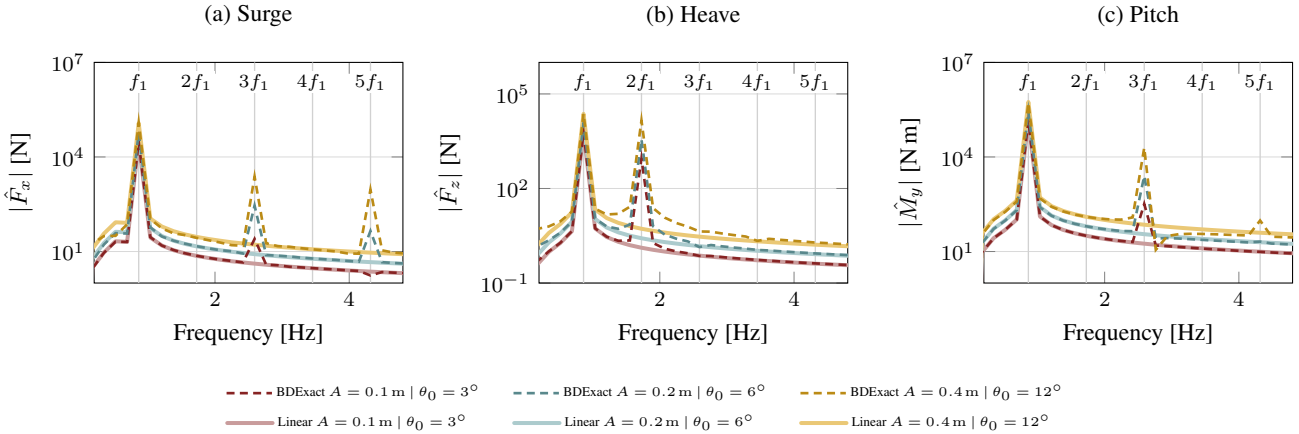


Figure 7. Hydrodynamic load spectra for the cylinder at $k = 3.0 \text{ m}^{-1}$: (a) surge force F_x , (b) heave force F_z , and (c) pitch moment M_y . Translation amplitudes are $A = 0.1, 0.2$, and 0.4 m , and pitch amplitudes are $\theta_0 = 3^\circ, 6^\circ$, and 12° .

The harmonic structure arises from the symmetry of the integrated loads. Surge and pitch change sign under motion reversal, while upward and downward heave motion do not produce equivalent wetted geometries. The cylinder therefore provides a controlled demonstration of the harmonic response introduced by the instantaneous geometry. Additional spectra for $k = 1.5 \text{ m}^{-1}$ are provided in Appendix A. The more systematic dependence on motion amplitude is studied for the OC3-Hywind spar buoy in Sect. 5.2.



5.2 Spar buoy

Representative time-domain responses of the OC3-Hywind spar are shown in Fig. 8. The surge case at $k = 0.10 \text{ m}^{-1}$ remains close to harmonic for all motion amplitudes, and the low-frequency pitch case at $k = 0.02 \text{ m}^{-1}$ deviates only slightly from the linear response. In contrast, the heave case at $k = 0.10 \text{ m}^{-1}$ becomes increasingly asymmetric with motion amplitude and shows the strongest deviation from a purely harmonic response among the investigated load cases.

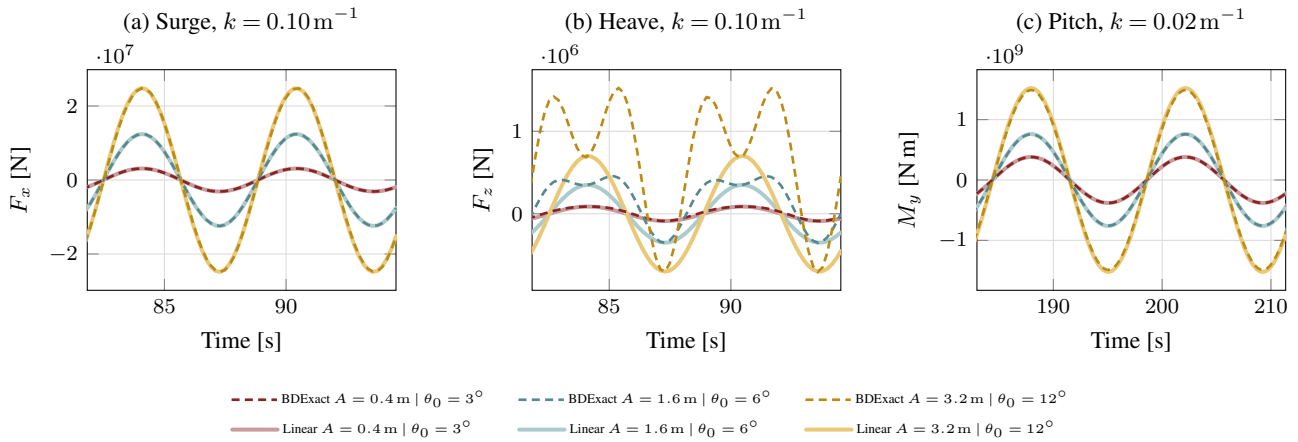


Figure 8. Time series of the unsteady-pressure contribution to the hydrodynamic radiation loads for the OC3-Hywind spar buoy: (a) surge force F_x at $k = 0.10 \text{ m}^{-1}$, (b) heave force F_z at $k = 0.10 \text{ m}^{-1}$, and (c) pitch moment M_y at $k = 0.02 \text{ m}^{-1}$. Translation amplitudes are $A = 0.4, 1.6$, and 3.2 m , and pitch amplitudes are $\theta_0 = 3^\circ, 6^\circ$, and 12° . The final two periods of each plotted time window are shown.

The hydrodynamic load spectra of the spar in surge, heave, and pitch are shown in Fig. 9 for the three wave numbers investigated. The OC3-Hywind spar exhibits the same symmetry-based harmonic structure observed for the cylinder. Heave shows a pronounced contribution at $2f_1$, while surge and pitch contain predominantly odd higher harmonics, with the leading additional contribution at $3f_1$. The harmonic structure is maintained across the investigated wave-number range, while the magnitude of the higher-harmonic components increases with motion amplitude. Consistent with the time series, the higher harmonics are pronounced in heave, whereas in surge and pitch they remain small relative to the fundamental response.

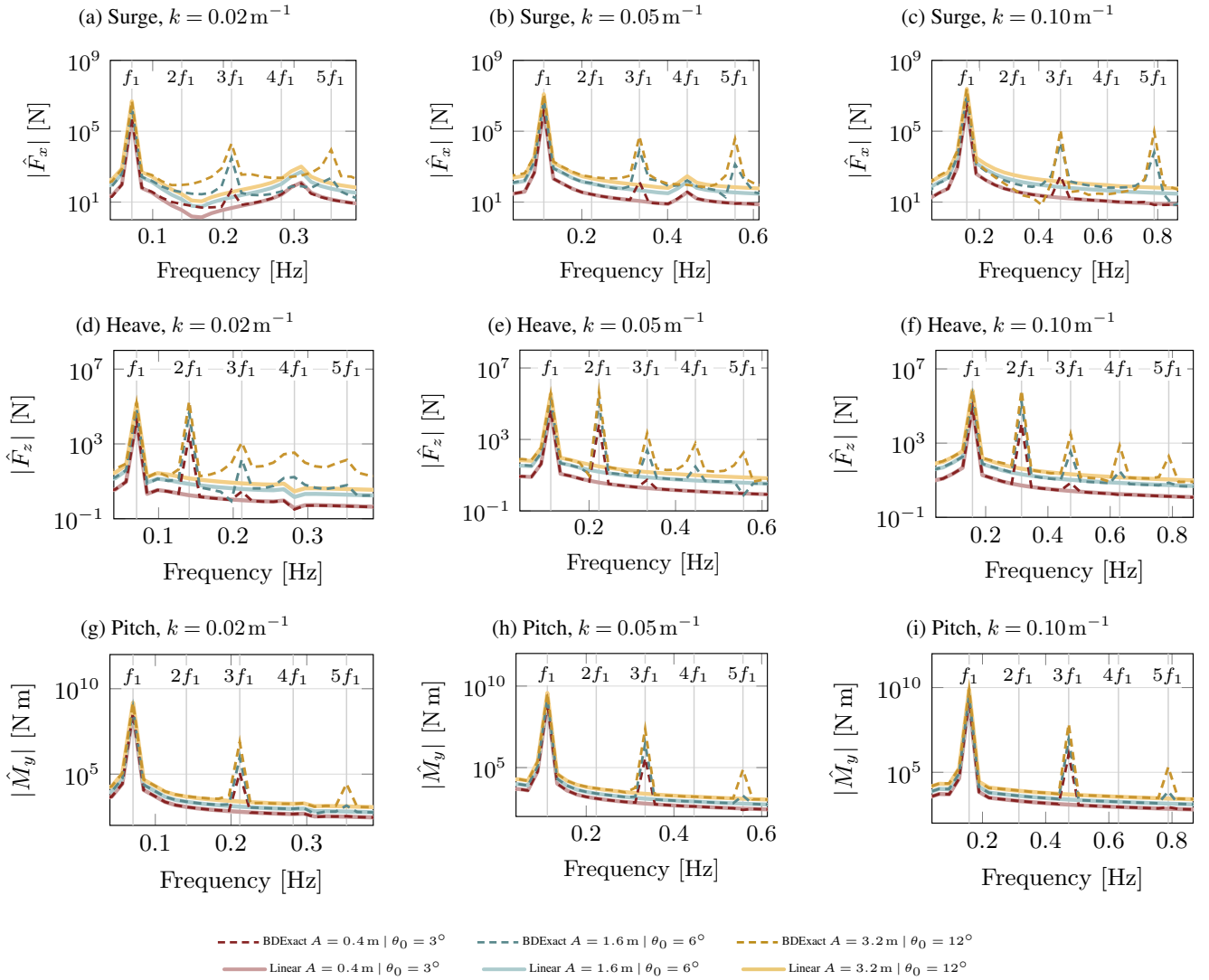


Figure 9. Hydrodynamic radiation-load spectra for the OC3-Hywind spar buoy in surge (a–c), heave (d–f), and pitch (g–i), at $k = 0.02, 0.05$, and 0.10 m^{-1} from left to right.

The amplitude dependence of the leading higher-harmonic components is shown in Fig. 10 together with reference slopes. At all three wave numbers, the heave second harmonic grows with the square of the motion amplitude, and the surge and pitch third harmonics grow with its cube.

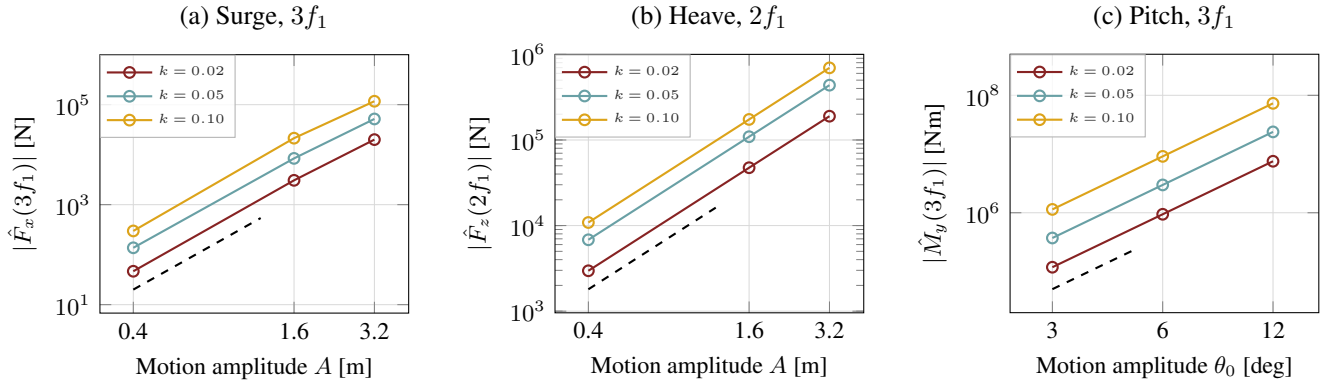


Figure 10. Higher-harmonic radiation load amplitudes against motion amplitude for the OC3-Hywind spar buoy: (a) surge force F_x at $3f_1$, (b) heave force F_z at $2f_1$, and (c) pitch moment M_y at $3f_1$. Dashed lines indicate reference power-law scaling of A^3 for surge, A^2 for heave, and θ_0^3 for pitch.

305 The higher-harmonic contribution is largest for heave. At the largest motion amplitude, the second harmonic reaches 99–126 % of the fundamental over the investigated wave-number range. In contrast, the third-harmonic components of surge and pitch remain below 1 % of the fundamental. Further harmonic amplitudes are listed in Table B1 in Appendix B.

The higher harmonics discussed above stem from the P_u load. Values of the second-harmonic P_u load above 100 % do not represent a physical load on their own, since P_u and P_q are parts of the same pressure field. For the total load, P_q must also be considered. Although the load from P_q differs only slightly between the two formulations, its second harmonic in heave, at the largest oscillation amplitudes across the investigated wave numbers, reaches 43–53 % of the linear fundamental, and acts nearly out of phase with the second harmonic of the load from P_u . The total second harmonic is therefore reduced from 99–126 % to 56–73 % of the fundamental (Table B2). In surge and pitch, the second-harmonic contributions of P_q vanish due to the symmetry of the body and motion.

315 5.2.1 Radiated wave field

Wave elevation time series at $x = 40$ m are shown in Fig. 11 for the same cases as the loads in Fig. 8. In the body-exact solution, the crests and troughs become asymmetric as motion amplitude increases, while the linear solution remains harmonic.

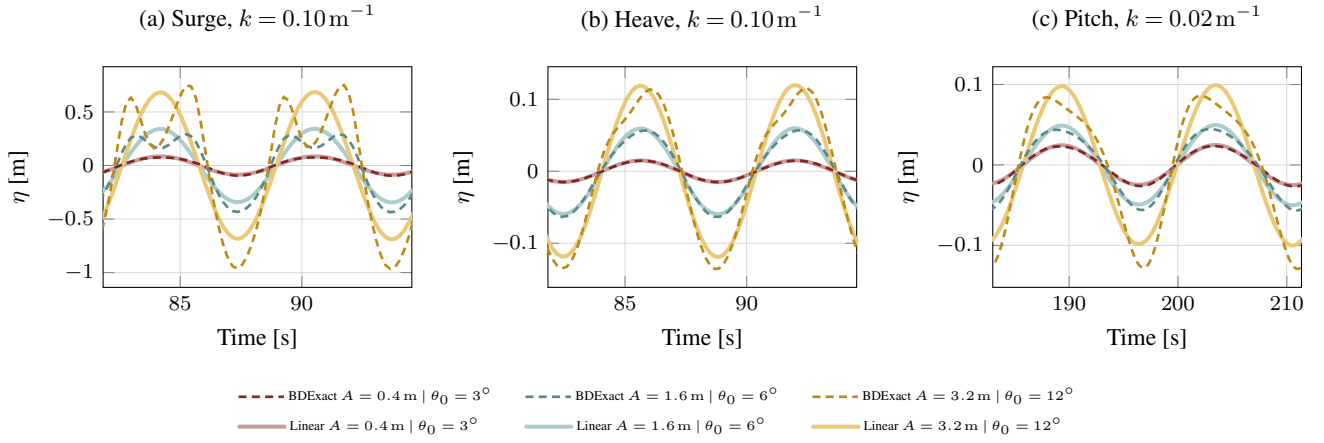


Figure 11. Time series of the radiated wave elevation at $x = 40$ m for the OC3-Hywind spar buoy: (a) surge at $k = 0.10 \text{ m}^{-1}$, (b) heave at $k = 0.10 \text{ m}^{-1}$, and (c) pitch at $k = 0.02 \text{ m}^{-1}$. Translation amplitudes are $A = 0.4, 1.6$, and 3.2 m, and pitch amplitudes are $\theta_0 = 3^\circ, 6^\circ$, and 12° . The final two periods of each plotted time window are shown.

The radiated-wave spectra are shown in Fig. 12. The body-exact spectra show peaks at all multiples from $2f_1$ to $5f_1$. These peaks grow with motion amplitude, while the linear spectra contain only the fundamental above the numerical background.

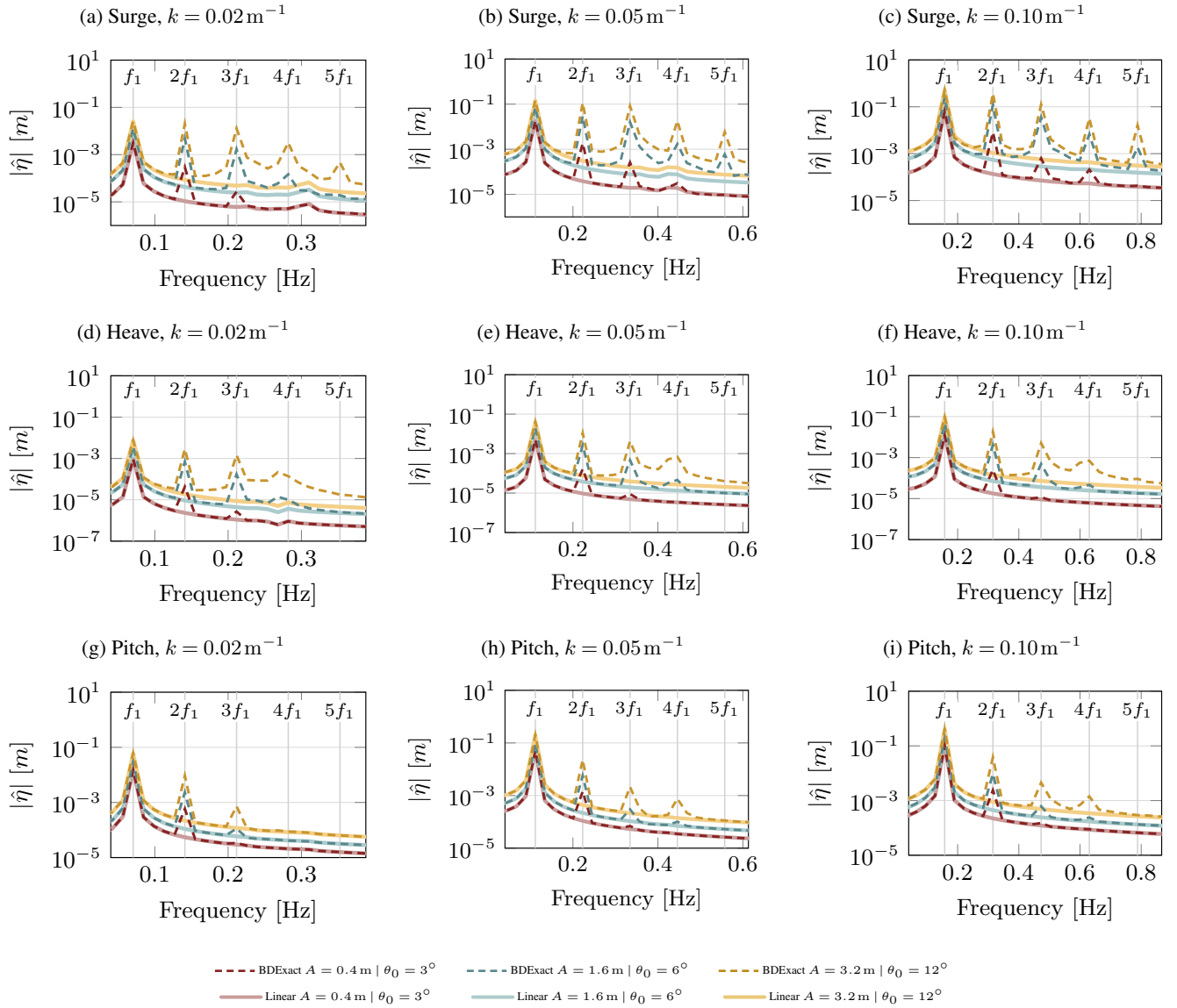


Figure 12. Radiated wave-elevation spectra for the OC3-Hywind spar buoy in surge (a–c), heave (d–f), and pitch (g–i), at $k = 0.02, 0.05$, and 0.10 m^{-1} from left to right.

320 These higher harmonics are limited by the spatial resolution discussed in Sect. 4. Linear calculations at the second-harmonic wave number show that a free wave at $2f_1$ is resolved at $\text{PPW} = 25$ for all three degrees of freedom. This indicates adequate resolution but does not confirm convergence of the nonlinear $2f_1$ amplitude. Components above $2f_1$ are interpreted qualitatively.



5.3 VoltturnUS-S

325 Representative time series are shown in Fig. 13, for the same frequencies as the spar with surge at $k = 0.10 \text{ m}^{-1}$, pitch at $k = 0.02 \text{ m}^{-1}$, and heave at $k = 0.10 \text{ m}^{-1}$. As the motion amplitude increases, the body-exact loads increasingly deviate from the harmonic linear response.

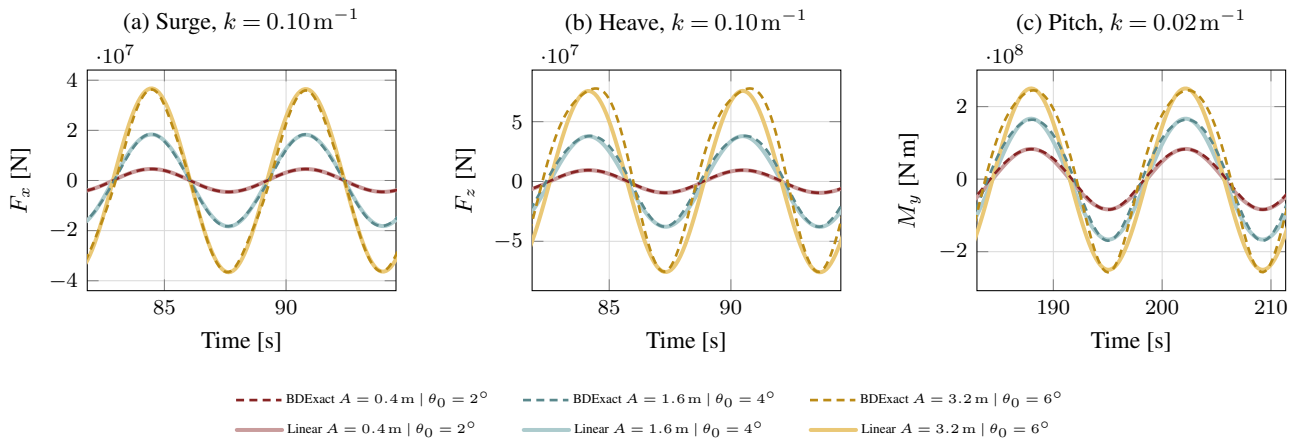


Figure 13. Time series of the unsteady-pressure contribution to the hydrodynamic radiation loads for the VoltturnUS-S semi-submersible: (a) surge force F_x at $k = 0.10 \text{ m}^{-1}$, (b) heave force F_z at $k = 0.10 \text{ m}^{-1}$, and (c) pitch moment M_y at $k = 0.02 \text{ m}^{-1}$. Translation amplitudes are $A = 0.4, 1.6$, and 3.2 m , and pitch amplitudes are $\theta_0 = 2^\circ, 4^\circ$, and 6° . The final three periods of each plotted time window are shown.

Figure 14 shows the radiation load spectra for the VoltturnUS-S. Unlike the axisymmetric cylinder and spar, the VoltturnUS-S also exhibits even harmonics in surge and pitch. The higher harmonics increase with motion amplitude, while the linear response contains only the fundamental.

330

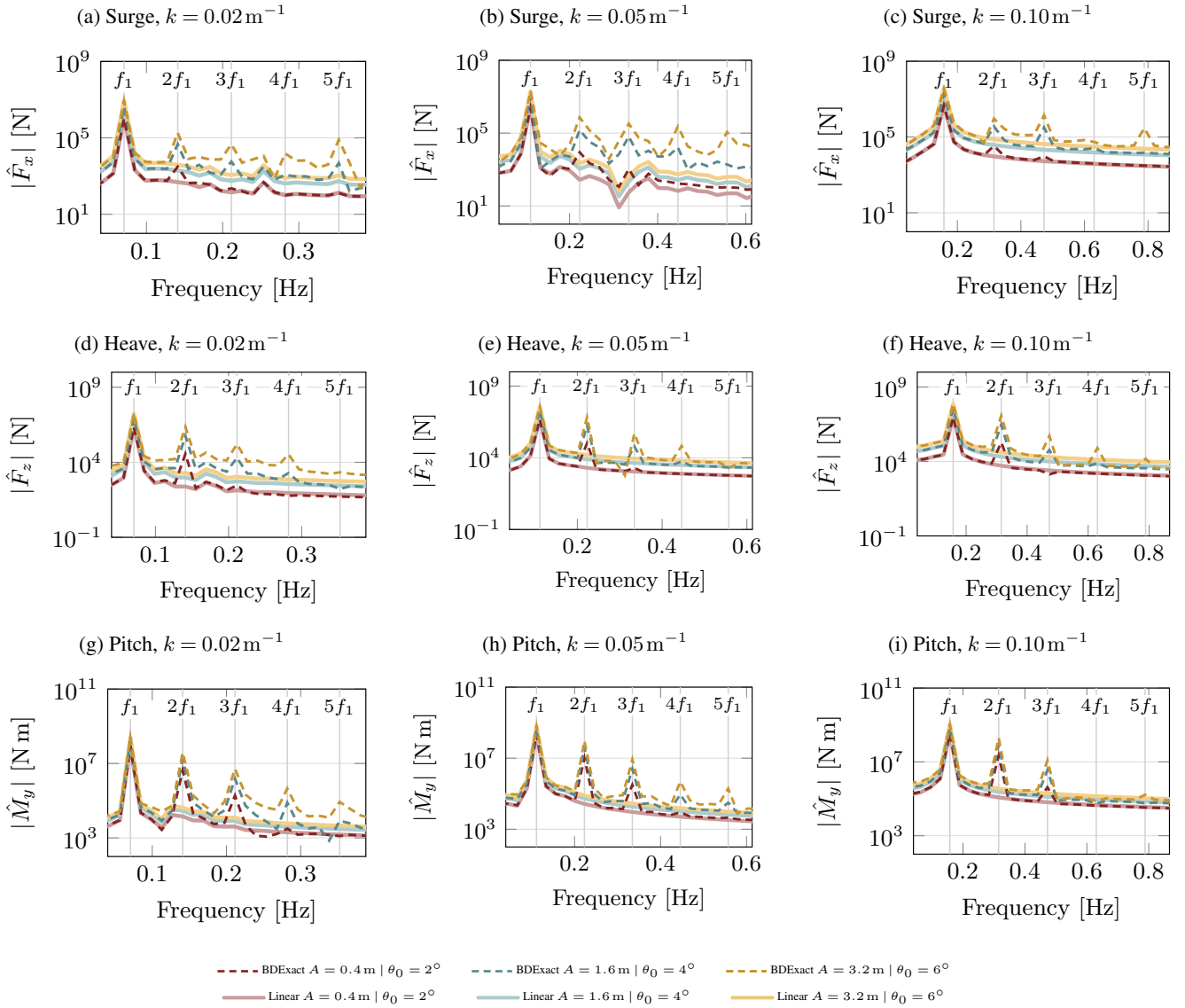


Figure 14. Hydrodynamic radiation-load amplitude spectra for the UMaine VoltturnUS-S in surge (a–c), heave (d–f), and pitch (g–i), at $k = 0.02, 0.05, \text{ and } 0.10 \text{ m}^{-1}$ from left to right.

As discussed in Sect. 4, the VoltturnUS-S free surface resolution is insufficient for a quantitative assessment of propagating higher-harmonic waves. The nonlinear analysis of this platform is therefore limited to the integrated hydrodynamic loads.

At the largest motion amplitude, the second harmonic reaches 3.7 % of the fundamental in surge, 18 % in heave, and 19 % in pitch, with the highest values at $k = 0.05 \text{ m}^{-1}$ for surge and heave, and at $k = 0.10 \text{ m}^{-1}$ for pitch. Figure 15 shows that the second harmonics increase with the square of the motion amplitude, except for surge at $k = 0.10 \text{ m}^{-1}$, where the growth weakens at the largest amplitude.



Unlike for the axisymmetric bodies, forward and backward displacements of the three-column platform do not produce equivalent wetted geometries, so the loads do not simply change sign under motion reversal. Hence, the second-harmonic contributions of P_q do not vanish in surge and pitch. At the largest motion amplitude and the wave numbers with the highest second harmonics ($k = 0.05 \text{ m}^{-1}$ for surge and heave, $k = 0.10 \text{ m}^{-1}$ for pitch), including P_q reduces the total second harmonic load from 3.7, 18, and 19 % to 3.4, 15, and 12 % of the fundamental in surge, heave, and pitch, respectively (Table C2 in Appendix C).

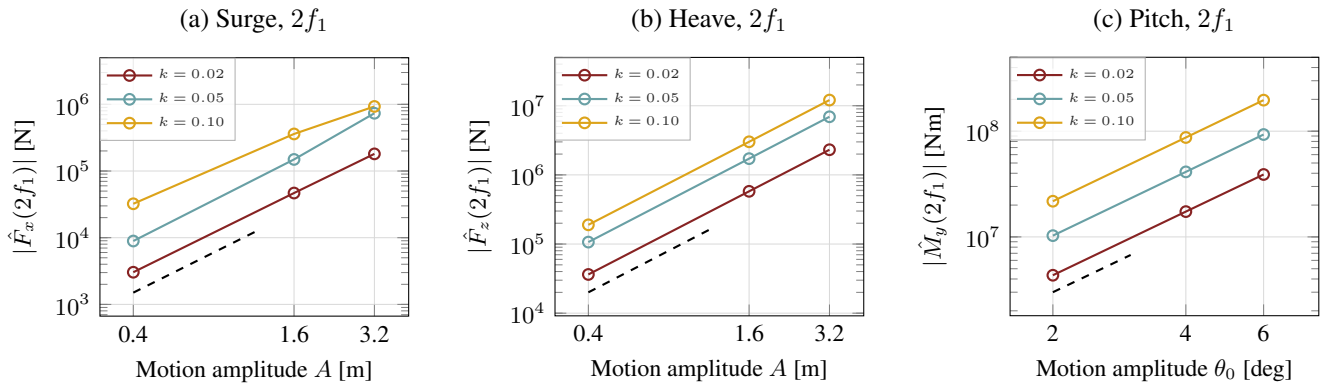


Figure 15. Second-harmonic radiation load amplitudes for the UMaine VoltturnUS-S semi-submersible: (a) surge force F_x , (b) heave force F_z , and (c) pitch moment M_y , with varying motion amplitude. Dashed lines indicate reference quadratic scaling, A^2 for surge and heave and θ_0^2 for pitch.

6 Conclusions

This study shows that accounting for the instantaneous wetted geometry introduces amplitude-dependent higher-harmonic contributions to hydrodynamic radiation loads under linear free surface boundary conditions. These contributions are absent from the radiation loads calculated from the unsteady-pressure term in the fixed-geometry linear formulation. Using a direct time-domain Rankine source boundary element formulation, the influence of instantaneous wetted geometry was investigated for a vertical cylinder, the OC3-Hywind spar buoy, and the UMaine VoltturnUS-S semi-submersible. The results demonstrate that the magnitude and harmonic structure of these contributions depend on body geometry, motion symmetry, and amplitude. This is relevant to the discrepancies in structural loads that recent code comparisons attributed to the instantaneous wetted surface. The body-exact formulation directly resolves this effect from pressure on the moving geometry.

For the vertical cylinder and the OC3-Hywind spar, the integrated radiation loads exhibit a clear symmetry-dependent harmonic structure. Heave is dominated by a second-harmonic contribution, while surge and pitch predominantly show odd higher harmonics, with the leading contribution at $3f_1$. For the spar, the heave second harmonic scales approximately quadratically with motion amplitude, while the leading surge and pitch third harmonics scale approximately cubically. The strongest nonlinear response occurs in heave, where the unsteady pressure second harmonic reaches 99–126 % of the fundamental at the largest motion amplitude across the investigated wave numbers, while the surge and pitch third harmonics remain below 1 %.



The non-axisymmetric VoltturnUS-S semi-submersible exhibits even and odd harmonics in surge, heave, and pitch. Its second harmonic reaches 3.7 % of the fundamental in surge, 18 % in heave, and 19 % in pitch, growing with the square of the motion amplitude, except in surge at the highest wave number. The loss of axisymmetry changes which harmonics appear without altering the order of the producing mechanism.

The second-harmonic P_q load changes only slightly between the linear and body-exact formulations relative to the unsteady fundamental. It is therefore not a primary source of differences between the two formulations, although its magnitude can be comparable to that of the P_u load second harmonic and significantly affects the total second-harmonic load. Acting nearly out of phase with the P_u second harmonic load, it reduces the total second harmonic load of the spar in heave from 99–126 % to 56–73 % of the linear fundamental load, and that of the semi-submersible to at most 3.4, 15, and 12 % in surge, heave, and pitch, respectively. For axisymmetric geometries, the P_q second-harmonic contributions vanish in surge and pitch due to symmetry, but reappear for the VoltturnUS-S.

The radiated wave field also develops higher-harmonic content in the body-exact formulation. The effective spatial resolution decreases with increasing harmonic order, limiting quantitative interpretation to the second harmonic for the spar buoy. For the semi-submersible, the higher-harmonic wave field is not assessed quantitatively. Once incident waves are included, resolving the higher-harmonic content of the wave field near the platform can support assessments of local wave conditions, for example for vessel access during maintenance.

This study investigates the higher-harmonic radiation response resulting from the body-exact treatment of the instantaneous wetted surface in BEMUseRS. Since the body-exact formulation resolves the pressure distribution on the instantaneous wetted surface, the distributed hydrodynamic loads can be mapped directly onto structural nodes once a structural model is coupled, rather than being applied at a single platform reference point. Future work will extend the solver to interactions with incident waves through a weak-scatterer formulation and investigate matrix-free acceleration techniques. The long-term objective is to couple the solver with flexible structural models to enable computationally efficient hydroelastic analysis of floating wind turbine platforms.



Appendix A: Additional cylinder results

Figure A1 shows the cylinder's load spectra at $k = 1.5 \text{ m}^{-1}$. The harmonic structure matches that at $k = 3.0 \text{ m}^{-1}$ (Fig. 7). Heave displays a leading second harmonic, while surge and pitch contain odd harmonics at $3f_1$ and $5f_1$.

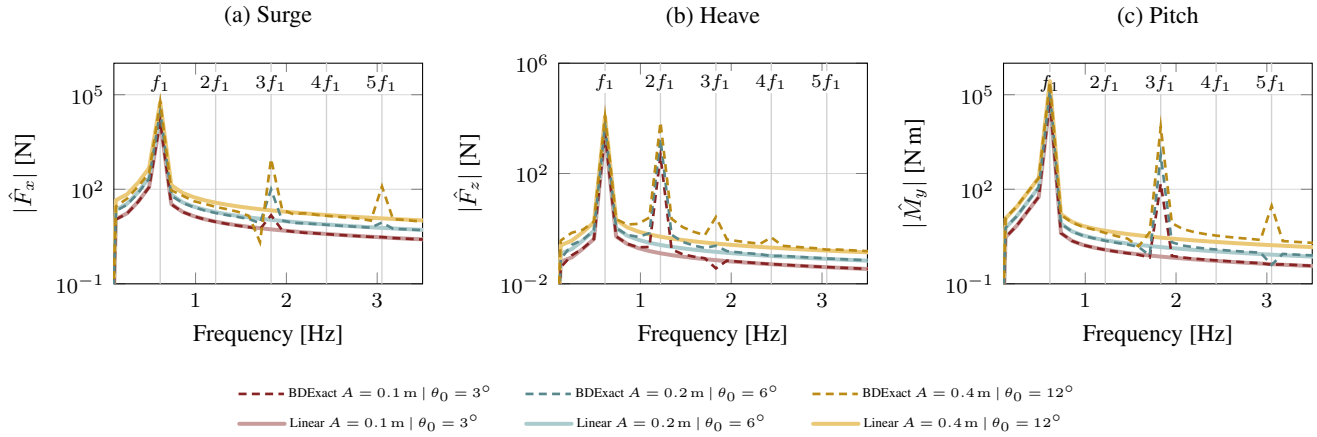


Figure A1. Hydrodynamic load spectra for the cylinder at $k = 1.5 \text{ m}^{-1}$: (a) surge force F_x , (b) heave force F_z , and (c) pitch moment M_y . Translation amplitudes are $A = 0.1, 0.2$, and 0.4 m , and pitch amplitudes are $\theta_0 = 3^\circ, 6^\circ$, and 12° .



Appendix B: OC3-Hywind harmonic data

385 Table B1 lists the fundamental and leading higher-harmonic load amplitudes of the OC3-Hywind spar for all motion amplitudes and wave numbers. Table B2 shows the contributions of P_u and P_q to the second-harmonic loads at the largest motion amplitude. All ratios refer to the linear fundamental. In surge and pitch, the P_q contributions vanish by symmetry.

Table B1. Leading higher-harmonic load amplitudes of the OC3-Hywind spar buoy from P_u in the body-exact formulation, in percent of the linear fundamental $|\hat{q}^{\text{Linear}}(f_1)|$. The amplitudes are background-corrected by power subtraction of the linear spectral level (Eq. 5). The leading harmonic is $2f_1$ in heave and $3f_1$ in surge and pitch. $|\hat{q}^{\text{Linear}}(f_1)|$ is given at the largest motion amplitude. Forces in N, moments in N m. Motion amplitudes: $A = 0.4, 1.6, 3.2$ m and $\theta_0 = 3^\circ, 6^\circ, 12^\circ$.

DOF	k [m ⁻¹]	$ \hat{q}^{\text{Linear}}(f_1) $	Ratio [%]		
			small	mid	large
Surge	0.02	5.003×10^6	0.007	0.123	0.400
	0.05	1.246×10^7	0.009	0.135	0.416
	0.10	2.485×10^7	0.010	0.172	0.471
Heave	0.02	1.509×10^5	15.71	62.83	125.61
	0.05	3.652×10^5	14.95	59.78	119.61
	0.10	7.009×10^5	12.40	49.59	99.30
Pitch	0.02	1.523×10^9	0.031	0.124	0.495
	0.05	3.816×10^9	0.039	0.156	0.624
	0.10	7.680×10^9	0.059	0.238	0.950

Table B2. Second-harmonic ($2f_1$) radiation loads of the OC3-Hywind spar buoy in heave at the largest motion amplitude from P_q , P_u , and their sum, in percent of the linear unsteady fundamental (Table B1).

DOF	k [m ⁻¹]	P_q [%]		P_u [%]	Total [%]
		Linear	BDExact	BDExact	BDExact
Heave	0.02	52.90	52.90	125.61	72.72
	0.05	49.36	49.37	119.61	70.25
	0.10	43.03	43.05	99.30	56.26



Appendix C: VoltturnUS-S harmonic data

390 Tables C1 and C2 provide data for the VoltturnUS-S. Unlike the spar, P_q contributes to second-harmonic loads in all three degrees of freedom.

Table C1. Leading higher-harmonic load amplitudes of the UMaine VoltturnUS-S from P_u in the body-exact formulation, in percent of the linear fundamental $|\hat{q}^{\text{Linear}}(f_1)|$. The amplitudes are background-corrected by power subtraction of the linear spectral level (Eq. 5). The leading harmonic is $2f_1$ in all degrees of freedom. $|\hat{q}^{\text{Linear}}(f_1)|$ is given at the largest motion amplitude. Forces in N, moments in N m. Motion amplitudes: $A = 0.4, 1.6, 3.2$ m and $\theta_0 = 2^\circ, 4^\circ, 6^\circ$.

DOF	$k \text{ [m}^{-1}\text{]}$	$ \hat{q}^{\text{Linear}}(f_1) $	Ratio [%]		
			small	mid	large
Surge	0.02	8.487×10^6	0.286	1.10	2.13
	0.05	1.964×10^7	0.364	1.52	3.74
	0.10	3.693×10^7	0.699	1.95	2.52
Heave	0.02	1.712×10^7	1.70	6.76	13.49
	0.05	3.777×10^7	2.26	9.10	18.34
	0.10	7.547×10^7	2.01	7.98	16.01
Pitch	0.02	2.501×10^8	5.20	10.41	15.57
	0.05	6.386×10^8	4.83	9.68	14.56
	0.10	1.043×10^9	6.26	12.54	18.86

Table C2. Second-harmonic ($2f_1$) radiation loads of the UMaine VoltturnUS-S at the largest motion amplitude from P_q , P_u , and their sum, in percent of the linear unsteady fundamental (Table C1).

DOF	$k \text{ [m}^{-1}\text{]}$	P_q [%]		P_u [%]	Total [%]
		Linear	BDExact	BDExact	BDExact
Surge	0.02	0.51	0.50	2.13	1.66
	0.05	0.33	0.31	3.74	3.44
	0.10	0.73	0.78	2.53	1.80
Heave	0.02	1.71	1.67	13.49	11.83
	0.05	3.54	3.60	18.34	14.90
	0.10	2.77	2.88	16.01	13.36
Pitch	0.02	5.24	5.24	15.57	10.37
	0.05	4.89	4.87	14.56	9.69
	0.10	6.93	6.94	18.86	11.93



Code availability. The time-domain Rankine source solver BEMUseRS is implemented within the BEMUse framework (Saverin and Grüter, 2022; Uçar et al., 2025). The source code used in this study is available at <https://gitlab.com/ZeppSav/BEMUse.git>.

395 *Author contributions.* Ronja Olsmats Baumeister developed and implemented the numerical methodology, carried out the simulations and data analysis, prepared the figures, and wrote the original manuscript. Joseph Saverin implemented the grid-generation and geometry modules, supervised the work, and reviewed and edited the manuscript. Christian Oliver Paschereit supervised the work and reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Data availability. All results can be reproduced with the BEMUseRS solver (see code availability). The input configurations for each case presented in this study are included in the repository as test cases, which generate the corresponding simulation output automatically.

400 *Acknowledgements.* Ronja Olsmats Baumeister gratefully acknowledges funding through the Elsa-Neumann-Stipendium des Landes Berlin (NaFöG). ChatGPT and Claude were used for assistance in copy editing. Claude was used for code completion.



References

- Abdelmoteleb, S.-E., Escalera Mendoza, A., dos Santos, C., Bachynski-Polić, E. E., Griffith, D., and Oggiano, L.: Preliminary Sizing and Optimization of Semisubmersible Substructures for Future Generation Offshore Wind Turbines, *J. Phys. Conf. Ser.*, 2362, 012001, <https://doi.org/10.1088/1742-6596/2362/1/012001>, 2022.
- Abdelmoteleb, S.-E., Rogne, Ø. Y., Krathe, V. L., Bachynski-Polić, E. E., and Sauder, T. M.: A multi-body approach for distributing first-order hydrodynamic and hydrostatic loads on flexible structures, with application to coupled simulations of large floating wind turbines, *Mar. Struct.*, 111, 104202, <https://doi.org/10.1016/j.marstruc.2026.104202>, 2027.
- Allen, C., Viscelli, A., Dagher, H., Goupee, A., Gaertner, E., Abbas, N., Hall, M., and Barter, G.: Definition of the UMaine VoltumUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine, Tech. Rep. NREL/TP-5000-76773, National Renewable Energy Laboratory (NREL), Golden, CO, USA, <https://doi.org/10.2172/1660012>, 2020.
- ANSYS, Inc.: Aqwa Theory Manual, Release 2025 R2, Canonsburg, PA, USA, https://ansyshelp.ansys.com/public/Views/Secured/corp/v252/en/aqwa_thy/aqwathy_intro.html, last access: 21 October 2026, 2025.
- Babarit, A. and Delhommeau, G.: Theoretical and Numerical Aspects of the Open Source BEM Solver NEMOH, in: Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 6–11 September 2015, 2015.
- Behrens de Luna, R., Perez-Becker, S., Saverin, J., Marten, D., Papi, F., Ducasse, M.-L., Bonnefoy, F., Bianchini, A., and Paschereit, C. O.: Quantifying the impact of modeling fidelity on different substructure concepts for floating offshore wind turbines – Part 1: Validation of the hydrodynamic module QBlade-Ocean, *Wind Energ. Sci.*, 9, 623–649, <https://doi.org/10.5194/wes-9-623-2024>, 2024.
- Bergua, R., Carmo, L., Jonkman, J., Robertson, A., Tessier, L., de Lauzon, J., Berdugo-Parada, I., Garcia-Espinosa, J., Servan-Camas, B., Yu, J., Rajasree, V. R. N., Abdelmoteleb, S.-E., Bachynski-Polić, E. E., Niosi, F., Dell’Edera, O., Bracco, G., Nicolini, T., Heurtier, J. M., Le Cunff, C., Cheng, Z., Shao, W., Zhou, W., Albers, M., Lemmer, F., Marten, D., Rahman, S., Sarker, D., and Ngo, T.: OC7 Project Phase II: Code Comparison and Experimental Validation of Hydroelastic Effects and Member-Level Loads in Floating Structures, *J. Phys. Conf. Ser.*, 3224, 082024, <https://doi.org/10.1088/1742-6596/3224/8/082024>, 2026.
- Borg, M., Bredmose, H., and Hansen, A. M.: Elastic Deformations of Floaters for Offshore Wind Turbines: Dynamic Modelling and Sectional Load Calculations, in: Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, Volume 10: Ocean Renewable Energy, p. V010T09A044, Trondheim, Norway, 25–30 June 2017, <https://doi.org/10.1115/OMAE2017-61446>, 2017.
- Cummins, W. E.: The Impulse Response Function and Ship Motions, Tech. Rep. 1661, David Taylor Model Basin, Washington, DC, USA, 1962.
- Dagum, L. and Menon, R.: OpenMP: An Industry-Standard API for Shared-Memory Programming, *IEEE Comput. Sci. Eng.*, 5, 46–55, <https://doi.org/10.1109/99.660313>, 1998.
- DTU Wind Energy: Hydrodynamic model, <https://www.hawc2.dk/about-hawc2/hydrodynamic-model>, last access: 1 October 2026, 2026.
- Faltinsen, O. M.: Sea Loads on Ships and Offshore Structures, Cambridge University Press, Cambridge, UK, ISBN 9780521458702, 1990.
- Gao, Z., Merino, D., Han, K.-J., Li, H., and Fiskvik, S.: Time-domain floater stress analysis for a floating wind turbine, *J. Ocean Eng. Sci.*, 8, 435–445, <https://doi.org/10.1016/j.joes.2023.08.001>, 2023.
- Guennebaud, G., Jacob, B., et al.: Eigen: A C++ template library for linear algebra, <https://eigen.tuxfamily.org>, 2010.
- Huang, Y.: Nonlinear Ship Motions by a Rankine Panel Method, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 1997.



- Jonkman, J. M.: Definition of the Floating System for Phase IV of OC3, Tech. Rep. NREL/TP-500-47535, National Renewable Energy Laboratory (NREL), Golden, CO, USA, <https://doi.org/10.2172/979456>, 2010.
- Jonkman, J. M.: The New Modularization Framework for the FAST Wind Turbine CAE Tool, in: 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, AIAA 2013-0202, Grapevine, TX, USA, 7–10 January 2013, <https://doi.org/10.2514/6.2013-202>, 2013.
- Jonkman, J. M. and Musial, W.: Offshore Code Comparison Collaboration (OC3) for IEA Task 23 Offshore Wind Technology and Deployment, Tech. Rep. NREL/TP-5000-48191, National Renewable Energy Laboratory (NREL), Golden, CO, USA, <https://doi.org/10.2172/1004009>, 2010.
- Kim, Y., Kim, K.-H., Kim, J.-H., Kim, T., Seo, M.-G., and Kim, Y.: Time-domain analysis of nonlinear motion responses and structural loads on ships and offshore structures: development of WISH programs, *Int. J. Nav. Archit. Ocean Eng.*, 3, 37–52, <https://doi.org/10.2478/IJNAOE-2013-0044>, 2011.
- Kvittem, M. I., Bachynski, E. E., and Moan, T.: Effects of Hydrodynamic Modelling in Fully Coupled Simulations of a Semi-submersible Wind Turbine, *Energy Procedia*, 24, 351–362, <https://doi.org/10.1016/j.egypro.2012.06.118>, 2012.
- Larsen, T. J. and Hansen, A. M.: How 2 HAWC2, the User's Manual, Tech. Rep. Risø-R-1597 (ver. 13.0), Risø National Laboratory, Technical University of Denmark, Roskilde, Denmark, <https://tools.windenergy.dtu.dk/HAWC2/downloads/13.1.0/manual/How2HAWC2.pdf>, 2023.
- Leroy, V., Bachynski-Polić, E. E., Babarit, A., Ferrant, P., and Gilloteaux, J.-C.: A Weak-Scatterer Potential-Flow Theory-Based Model for the Hydroelastic Analysis of Offshore Wind Turbine Substructures, *Ocean Eng.*, 238, 109702, <https://doi.org/10.1016/j.oceaneng.2021.109702>, 2021.
- Letournel, L.: Développement d'un outil de simulation numérique basé sur l'approche "Weak-Scatterer" pour l'étude des systèmes houlomoteurs en grands mouvements, Ph.D. thesis, École Centrale de Nantes, Nantes, France, <https://hal.science/tel-01207477>, 2015.
- Mantić, V.: A new formula for the C -matrix in the Somigliana identity, *J. Elast.*, 33, 191–201, <https://doi.org/10.1007/BF00043247>, 1993.
- National Renewable Energy Laboratory: HydroDyn User Guide and Theory Manual, OpenFAST documentation v5.0, <https://openfast.readthedocs.io/en/main/source/user/hydrodyn/index.html>, last access: 21 October 2026, 2026.
- Newman, J. N.: Distributions of sources and normal dipoles over a quadrilateral panel, *J. Eng. Math.*, 20, 113–126, <https://doi.org/10.1007/BF00042771>, 1986.
- Olsnats Baumeister, R., Saverin, J., and Paschereit, C. O.: Unsteady Rankine Source Solver for Hydrodynamic Analysis of Surface-Piercing Structures, *J. Phys. Conf. Ser.*, 3224, 082040, <https://doi.org/10.1088/1742-6596/3224/8/082040>, 2026.
- Orcina Ltd.: OrcaWave User Documentation, <https://www.orcina.com/webhelp/OrcaWave/>, last access: 1 October 2026, 2026.
- Ran, X., Leroy, V., and Bachynski-Polić, E. E.: Hydroelastic response of a flexible spar floating wind turbine: Numerical modelling and validation, *Ocean Eng.*, 286, 115635, <https://doi.org/10.1016/j.oceaneng.2023.115635>, 2023.
- Ran, X., Rodriguez, C. A., Rui, S., Wang, X., Brennan, F., and Collu, M.: A review of fluid–structure interaction modelling for integrated analysis of floating offshore wind turbine substructures, *Renew. Sust. Energ. Rev.*, 240, 117223, <https://doi.org/10.1016/j.rser.2026.117223>, 2026.
- Robertson, A. N., Jonkman, J., Masciola, M., Song, H., Goupee, A., Coulling, A., and Luan, C.: Definition of the Semisubmersible Floating System for Phase II of OC4, Tech. Rep. NREL/TP-5000-60601, National Renewable Energy Laboratory (NREL), Golden, CO, USA, <https://doi.org/10.2172/1155123>, 2014a.



- Robertson, A. N., Jonkman, J., Vorpahl, F., Popko, W., Qvist, J., Frøyd, L., Chen, X., Azcona, J., Uzunoglu, E., Guedes Soares, C., Luan, C., Yutong, H., Pengcheng, F., Yde, A., Larsen, T., Nichols, J., Buils, R., Lei, L., Nygaard, T. A., Manolas, D., Heege, A., Vatne, S. R., Ormberg, H., Duarte, T., Godreau, C., Hansen, H. F., Nielsen, A. W., Riber, H., Le Cunff, C., Abele, R., Beyer, F., Yamaguchi, A., Jung, K. J., Shin, H., Shi, W., Park, H., Alves, M., and Guérinel, M.: Offshore Code Comparison Collaboration Continuation Within IEA Wind Task 30: Phase II Results Regarding a Floating Semisubmersible Wind System, in: Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, Volume 9B: Ocean Renewable Energy, OMAE2014-24040, San Francisco, CA, USA, 8–13 June 2014, <https://doi.org/10.1115/OMAE2014-24040>, 2014b.
- Robertson, A. N., Wendt, F., Jonkman, J. M., Popko, W., Dagher, H., Gueydon, S., Qvist, J., Vittori, F., Azcona, J., Uzunoglu, E., Guedes Soares, C., Harries, R., Yde, A., Galinos, C., Hermans, K., de Vaal, J. B., Bozonnet, P., Bouy, L., Bayati, I., Bergua, R., Galvan, J., Mendikoa, I., Barrera Sanchez, C., Shin, H., Oh, S., Molins, C., and Debruyne, Y.: OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine, *Energy Procedia*, 137, 38–57, <https://doi.org/10.1016/j.egypro.2017.10.333>, 2017.
- Robertson, A. N., Gueydon, S., Bachynski, E. E., Wang, L., Jonkman, J., Alarcón, D., Amet, E., Beardsell, A., Bonnet, P., Boudet, B., Brun, C., Chen, Z., Féron, M., Forbush, D., Galinos, C., Galvan, J., Gilbert, P., Gómez, J., Harnois, V., Haudin, F., Hu, Z., Le Dreff, J., Leimeister, M., Lemmer, F., Li, H., Mckinnon, G., Mendikoa, I., Moghtadaei, A., Netzband, S., Oh, S., Pegalajar-Jurado, A., Nguyen, M. Q., Ruehl, K., Schünemann, P., Shi, W., Shin, H., Si, Y., Surmont, F., Trubat, P., Qwist, J., and Wohlfahrt-Laymann, S.: OC6 Phase I: Investigating the underprediction of low-frequency hydrodynamic loads and responses of a floating wind turbine, *J. Phys. Conf. Ser.*, 1618, 032 033, <https://doi.org/10.1088/1742-6596/1618/3/032033>, 2020.
- Saverin, J. and Grüter, L.: Quadrature Schemes for the Integration of the Free-Surface Green’s Function Within the Open-Source Boundary Element Method Library BEMUse, in: Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering, Volume 7: CFD and FSI, OMAE2022-80831, Hamburg, Germany, 5–10 June 2022, <https://doi.org/10.1115/OMAE2022-80831>, 2022.
- Shin, Y. S., Belenky, V., Lin, W. M., Weems, K. M., Engle, A. H., McTaggart, K., Falzarano, J., Hutchison, B. L., Gerigk, M., and Grochowalski, S.: Nonlinear time domain simulation technology for seakeeping and wave-load analysis for modern ship design, *Trans. Soc. Nav. Archit. Mar. Eng.*, 111, 557–583, 2003.
- Souza, C. E. S. and Bachynski-Polić, E. E.: Design, structural modeling, control, and performance of 20 MW spar floating wind turbines, *Mar. Struct.*, 84, 103 182, <https://doi.org/10.1016/j.marstruc.2022.103182>, 2022.
- Teng, B., Cong, P., and Gou, Y.: Nonlinear Time-Domain Theory for the Simulation of Moored Floating Body Motion, *J. Mar. Sci. Appl.*, 17, 341–352, <https://doi.org/10.1007/s11804-018-0049-x>, 2018.
- Uçar, M., Hmedi, M., Uzunoglu, E., and Oguz, E.: Effect of Panel Method Codes in Estimating the Time-Domain Responses of Floating Wind Turbines, *Brodogradnja*, 76, 76 203, <https://doi.org/10.21278/brod76203>, 2025.
- WAMIT, Inc.: WAMIT User Manual, Version 7.6, Needham, MA, USA, https://www.wamit.com/manual7.x/v76_manual.pdf, last access: 21 October 2026, 2026.
- Wang, L., Robertson, A. N., Jonkman, J., and Yu, Y.-H.: OC6 phase I: Improvements to the OpenFAST predictions of nonlinear, low-frequency responses of a floating offshore wind turbine platform, *Renew. Energ.*, 187, 282–301, <https://doi.org/10.1016/j.renene.2022.01.053>, 2022.
- Watai, R. A., Ruggeri, F., and Simos, A. N.: A new time domain Rankine panel method for simulations involving multiple bodies with large relative displacements, *Appl. Ocean Res.*, 59, 93–114, <https://doi.org/10.1016/j.apor.2016.05.002>, 2016.



- Williams, R., Zhao, F., Cheong, J., and Melkonyan, N.: Global Offshore Wind Report 2026, Global Wind Energy Council, Lisbon, Portugal,
515 <https://www.gwec.net/reports/globaloffshorewindreport>, last access: 20 October 2026, 2026.
- Wuillaume, P.-Y.: Numerical Simulation of Installation Operations for Offshore Wind Farms, Ph.D. thesis, École Centrale de Nantes, Nantes,
France, <https://theses.hal.science/tel-02390021v1>, 2019.