

Chapter

An Overview of Analysis and Adaptive Pitch Control of an Offshore Floating Multi-Wind-Turbine Platform

Srikanth Bashetty and Selahattin Ozcelik

Abstract

This chapter outlines the findings of research focused on the creation of a new semi-submersible Offshore Floating Multi-Wind-Turbine Platform (OFFWIND). The primary concerns addressed involve modeling the aerodynamic forces caused by wind speed on the turbines, as well as the hydrodynamic forces resulting from wind and wave interactions on the entire system. To simulate the rotation of the rotors on the five wind turbines placed on the platform, a multiple-moving reference frame combined with a sliding mesh technique is employed. The evaluation of pressure, velocity, and turbulence intensity contours of the OFFWIND is conducted, particularly concentrating on the downstream turbine which operates in the partial wake of the turbines located upstream. The aerodynamic forces acting on the wind turbines are assessed to analyze their aerodynamic efficiency. The determined aerodynamic loads are integrated with the hydrodynamic forces to assess the platform's movements in response to wind and wave conditions. An adaptive control algorithm has been developed for blade pitch control. The performance of the adaptive control is evaluated against a standard Proportional-Integral (PI) controller. Simulation results demonstrate that the adaptive controller significantly improves rotor speed stability and reduces power output fluctuations under varying operational conditions.

Keywords: offshore wind turbine, modeling, aerodynamics, hydrodynamics, adaptive control

1. Introduction

Recent advancements in technology and supportive policies worldwide have fostered growth in the offshore wind industry. Offshore floating wind turbines hold great potential for tapping into vast wind energy resources available on the continental shelf, benefiting coastal communities globally. For water depths exceeding 50 meters, these floating platforms can harvest wind energy while minimizing visual and environmental concerns. The idea of installing multiple turbines on a single floating platform is gaining traction, as it offers the potential to reduce installation and mooring expenses while improving stability [1].

Advancements in technology have positioned this multi-turbine approach as a competitive solution for generating substantial wind energy [2–10]. Numerous studies have explored the dynamics of single wind turbine platforms, focusing on aerodynamics and hydrodynamics; however, research on the dynamics of multi-wind-turbine platforms—an extension of single floater designs—is limited. Analyzing the dynamic properties of an offshore floating multi-wind turbine platform (OFFWIND) is complex due to the intricate interaction between aerodynamics and hydrodynamics. Accurately predicting these loads is crucial for evaluating how they affect the power generation of the OFFWIND. This research aims to fill the gap regarding the dynamic analysis of OFFWIND [11] and assess the impact of blade pitch control on the performance of wind turbines.

Lefranc and Torud [2] analyzed the feasibility, design, and costs of a semi-submersible platform equipped with three wind turbines. Their study highlighted considerable power losses caused by interactions between upwind and downwind turbines at low wind speeds, whereas the effect was negligible at higher wind speeds. The economic considerations of the multi-wind turbine approach were found to be comparable to those of single platforms, especially regarding energy production costs. Hu et al. [3] validated their numerical models experimentally using a 1:50 scale model of a semi-submersible floating multi-wind turbine platform. They analyzed linear wave-body interactions through the potential flow method and measured pressure distributions on the platform caused by waves using a CFD model. Kim et al. designed a large semi-submersible platform equipped with four wind turbines located at each corner, gathering hydrodynamic force data using ANSYS AQWA, which was then applied in GL-DNV Bladed [12]. In South Korea, a square-shaped semisubmersible multi-unit floating offshore wind turbine (MUFOWT) platform is equipped with four 3 MW wind turbines positioned at each corner, complemented by 24 power absorber-type wave energy converters (WEC). Model tests were conducted on a scaled MUFOWT model by a research institute in Korea, without considering the dynamic motions of the fixed wave energy converters [1, 4, 5]. Lee et al. [6] examined multi-body hydrodynamic interactions in the frequency domain for a hybrid floating offshore wind-wave platform. Jang and colleagues [7] demonstrated that incorporating lightweight heave plates can effectively reduce pitch and heave motions in a multi-unit offshore floating wind turbine. Studies [9, 10] investigated a triangular-shaped floating platform with three wind turbines at its corners, focusing exclusively on hydrodynamic loads to assess the motion and elastic responses of the structure. Bae et al. [13] conducted a comprehensive dynamic analysis that included the blades, towers, floater, drivetrains, and mooring system of a multi-unit floating offshore wind turbine, though their study did not consider wake effects between the turbines.

This chapter details the research findings on designing a semi-submersible floating platform intended for hosting multiple wind turbines. The configuration model of the platform took into account the wake effects among the wind turbines to determine the wake expansion and velocity reductions downstream of the turbines [11]. The advanced platform, featuring five BMW wind turbines, is examined using ANSYS Fluent to study velocity profiles, pressure variations, and turbulence intensity patterns. This analysis employs the unsteady Reynolds-averaged Navier-Stokes (RANS) equations combined with the k- ω shear stress transport (SST) turbulence model. Aerodynamic forces acting on the wind turbines are calculated and incorporated into the hydrodynamic framework in ANSYS Aqwa. This integration evaluates added mass, response amplitude operators (RAOs), pressure distributions, motion responses, and wave and viscous damping effects using the potential flow

diffraction/radiation approach. The dynamics of the OFFWIND system are modeled by accounting for all forces acting upon it. A state-space representation of the governing equations is employed to perform simulations in MATLAB Simulink. This study implements an adaptive control algorithm, previously developed for its robustness to parameter variations [14], to manage blade pitch control. The impact of this adaptive control [14] on the blade pitch angle's performance is analyzed under wind conditions exceeding the rated speed. Key performance metrics evaluated include generated power output, platform surge, heave, and pitch motions. To verify its effectiveness, the adaptive controller is compared against a standard proportional-integral (PI) controller.

The remainder of the chapter is structured as follows and described in the flow-chart below. Section 2 offers a description of the model. Section 3 presents the governing equations, numerical setup, and results related to the aerodynamics and hydrodynamics of the OFFWIND. Section 4 discusses dynamics and the impact of adaptive blade pitch control on the OFFWIND's performance. Finally, Section 5 provides conclusions and recommendations for future research (**Figure 1**).

2. Model description

The OFFWIND platform, modeled in SolidWorks with a focus on wake analysis, is a semi-submersible structure that features five 8 MW wind turbines affixed to columns that are linked by pontoons, as demonstrated in **Figure 2**. This platform is

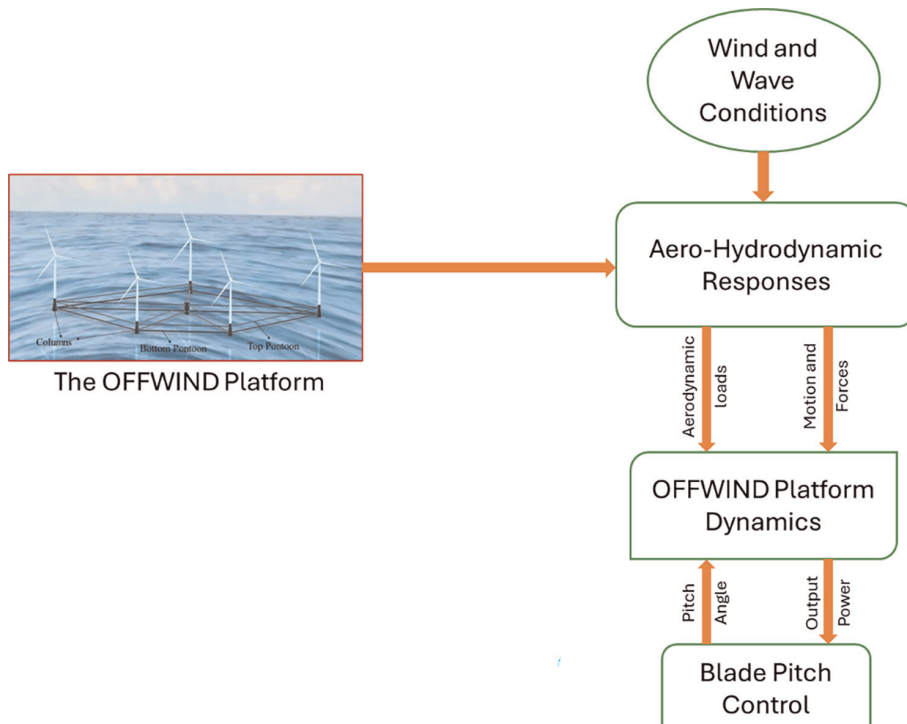


Figure 1.
 The framework of the analysis and control of the OFFWIND.

engineered to reduce the wake impacts among the wind turbines and aims to produce a power output that closely matches the rated capacity. The wind turbine utilized for this study is based on the LEANWIND 8 MW reference model intended for offshore wind energy projects [15].

The design specifications for the semi-submersible platform and wind turbine are outlined in **Table 1**. To support the 8 MW wind turbine tower base with appropriate margins, the cylindrical column is designed with a height of 30 meters and a diameter of 15 meters. The diameters of the top and bottom pontoons are set at 2 meters and 3.5 meters, respectively. The platform is anchored to the seabed via a central turret system, utilizing catenary mooring lines connected to the seabed through embedded anchors.

Parameter	Value
Rating of the wind turbine	8 MW
Diameter of the rotor	164 m
Height of the hub	110 m
Nominal speed of the rotor	10.5 rpm
Wind speeds (cut-in, rated, cut-out)	4, 12.5, 25 m/s
Mass of the wind turbine	1,038,000 kg
OFFWIND mass with ballast	37,839,000 kg
OFFWIND roll inertia	$8.667 \times 10^{11} \text{ kg m}^2$
OFFWIND pitch inertia	$4.452 \times 10^{11} \text{ kg m}^2$
OFFWIND yaw inertia	$1.209 \times 10^{12} \text{ kg m}^2$
Number of mooring lines	4
Mooring line length	600 m

Table 1.
Properties of the OFFWIND.

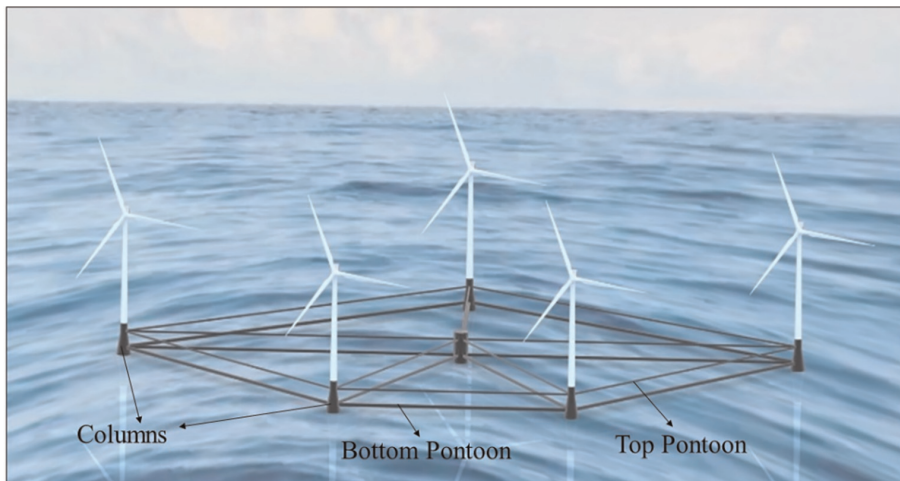


Figure 2.
Multi-wind-turbine platform.

3. Aero-hydrodynamics analysis

3.1 Aerodynamics

The continuity equation and unsteady Reynolds-averaged Navier-Stokes (RANS) equations, combined with the shear stress transport (SST) $k - \omega$ turbulence model [16], are formulated to describe the transient, incompressible and viscous fluid flow as follows.

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

This equation gives divergence of the velocity field is equal to zero.

$$\frac{\partial \bar{\mathbf{v}}}{\partial t} + (\bar{\mathbf{v}} \cdot \nabla) \bar{\mathbf{v}} = -\frac{1}{\rho} \nabla \bar{p} + \nu \nabla^2 \bar{\mathbf{v}} - \nabla \cdot (\overline{\mathbf{v}' \mathbf{v}'}) \quad (2)$$

The above equation gives the change in the time-averaged velocity over time, plus the convective term of the velocity field, is equal to the negative gradient of pressure divided by fluid density, plus the kinematic viscosity times the Laplacian of the velocity field, minus the divergence of the Reynolds stress tensor.

$$\frac{\partial}{\partial t} (\rho k) + \nabla \cdot (\rho k \mathbf{v}) = \nabla \cdot [\Gamma_k \nabla k] + \tilde{P}_k - D_k \quad (3)$$

The time rate of change of the product of density and turbulent kinetic energy, augmented with the divergence of the product of density and the velocity field, is equal to the divergence of the effective diffusivity of turbulent kinetic energy times the gradient of kinetic energy, plus the turbulence production term minus the dissipation term.

$$\frac{\partial}{\partial t} (\rho \omega) + \nabla \cdot (\rho \omega \mathbf{v}) = \nabla \cdot [\Gamma_\omega \nabla \omega] + P_\omega - D_\omega + Y_\omega \quad (4)$$

The time rate of change of the product of density and specific dissipation rate, along with the divergence of the product of density and the velocity field, equals the divergence of the effective diffusivity of the specific dissipation rate multiplied by the gradient of the dissipation rate, plus the turbulence production term, minus the dissipation term, added to the cross-diffusion term.

In these equations, the variable $\mathbf{v}$ represents the flow field velocity, p is pressure, ν is the kinematic viscosity, and ρ is the fluid density. The effective diffusivity terms Γ_k and Γ_ω relate to both turbulent kinetic energy k and specific dissipation rate ω . $\tilde{P}_k$ and P_ω are the turbulence generation terms and D_k and D_ω are the turbulence dissipation terms. Y_ω is the cross-diffusion contribution originating from a combination of standard $k - \epsilon$ and $k - \omega$ models [17–22]. The RANS equations can analyze the intricate dynamics within a wind turbine rotor's flow fields [23].

3.1.1 Numerical setup

This research involves solving the unstable RANS equations to simulate the rotor's rotation and its interaction with the surrounding airflow using ANSYS Fluent. The

simulation employs a pressure-velocity coupling technique based on the SIMPLE (semi-implicit method for pressure-linked equations) algorithm. A predictor-corrector framework ensures the coupling between the continuity and momentum equations. For modeling convection terms in the flow equations, a second-order upwind scheme is utilized, while a second-order implicit approach is applied for temporal discretization during transient analysis.

The computational domain, measuring $6D(X) \times 6D(Y) \times 3D(Z)$, is constructed in ANSYS Design Modeler following the import of the OFFWIND model from SolidWorks. The mesh, generated using the ANSYS meshing module, consists of unstructured tetrahedral elements created through a patch-conforming algorithm chosen for its reliable convergence behavior. The mesh contains a total of 10.5 million cells, encompassing the entire OFFWIND system, as illustrated in **Figure 3**. An over-set mesh methodology is applied to manage the relative motion between rotating components (rotors) and stationary structures (tower, nacelle, and platform), shown in **Figures 4** and **5**. The layout includes two upstream turbines (T1 and T2) in the first row, two additional turbines (T3 and T4) in the second row, and a downstream turbine (T5) positioned at the rear.

A fixed wind velocity of 11 m/s is specified for the inlet boundary condition, with default turbulence intensity set at 5% and a viscosity ratio of 10%. The outlet boundary condition is set to atmospheric pressure. To simulate the moving rotors of the five wind turbines placed on the platform, a multiple-moving reference frame with a sliding mesh technique is employed. The rotors are assigned the nominal rotational speed in the cell zone conditions. A no-slip boundary condition is enforced on the blade surfaces. Transient simulations are performed with a step size of 0.1 seconds, equating to a 6° blade rotation per step. The simulation spans 120 seconds of runtime, necessitating 40,000 iterations to complete.

3.1.2 Results

This section presents the pressure, velocity, and turbulence intensity contours of the OFFWIND, focusing primarily on the downstream wind turbine, which operates within the partial wake of two upstream turbines. Analyzing the downstream turbine

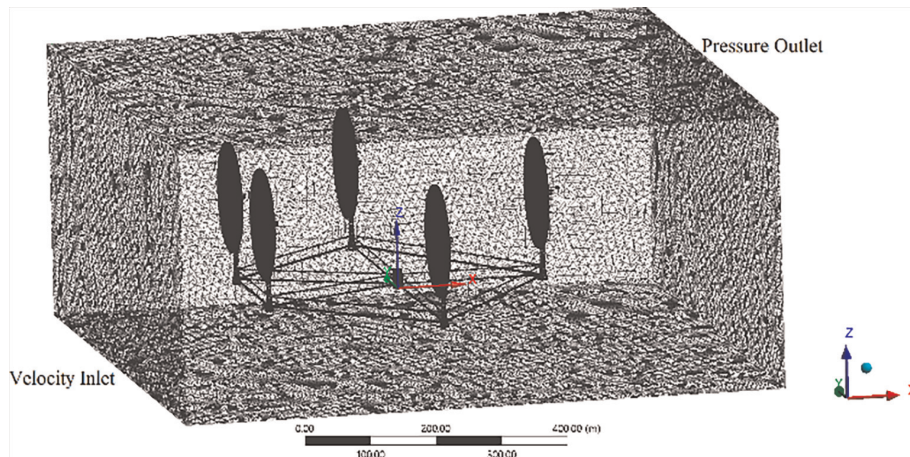


Figure 3.
Computational domain model.

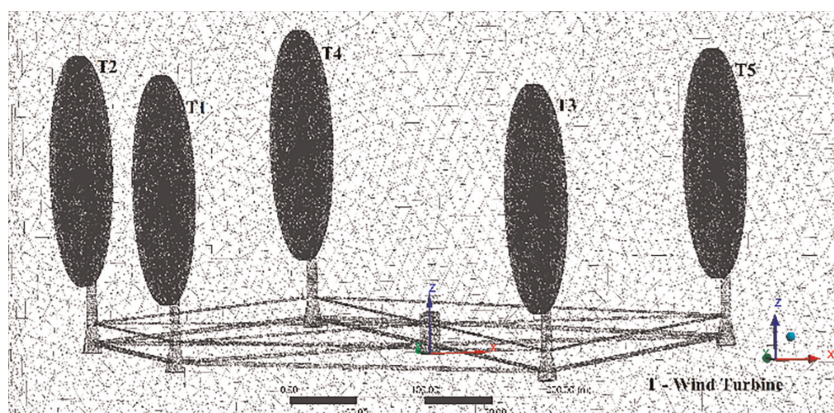


Figure 4.
 Full configuration of OFFWIND with overset regions.

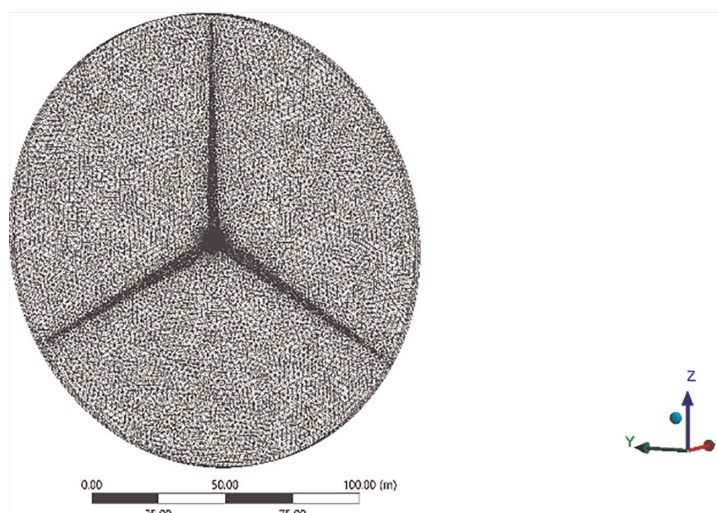


Figure 5.
 The discretized representation of the rotating area.

is crucial for assessing the overall aerodynamic performance of the OFFWIND. **Figure 6** illustrates the pressure distribution along the rotor, depicting both the pressure and suction surfaces. As anticipated, a high-pressure area is visible on the pressure side, while a low-pressure area is present on the suction side. The difference in pressure generates the necessary lift, contributing to the blade's rotation. The velocity contours for the downstream turbine at various blade positions are illustrated in **Figure 7**. The interaction between the rotating blade and the tower generates fluctuations in velocity magnitudes and alters flow patterns around both structures, as illustrated in the figure.

Figure 8 depicts the turbulent intensity profiles around the wind turbines. For the upstream turbines, wake vortices lead to an increase in both the extent and magnitude of turbulence intensity in their wake. Meanwhile, the downstream turbine experiences a further escalation in turbulence intensity due to the combined effects of wake vortices generated by both the upstream and downstream turbines. This also indicates

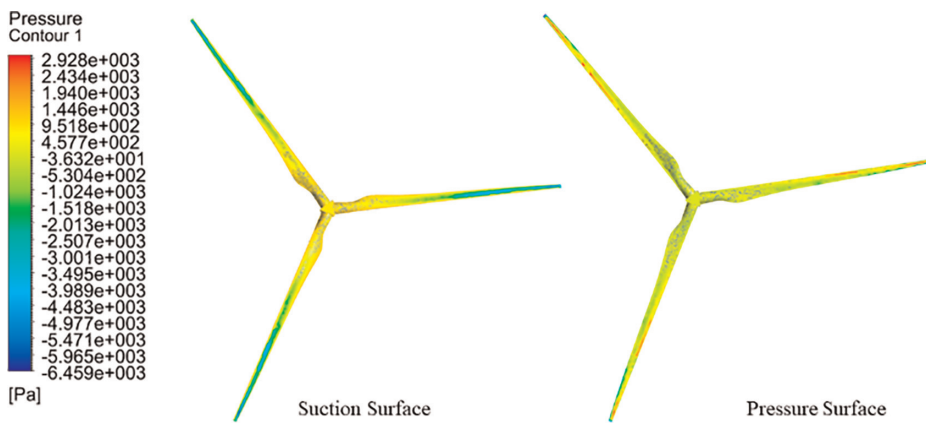


Figure 6.
Pressure curves along the rotor surface.

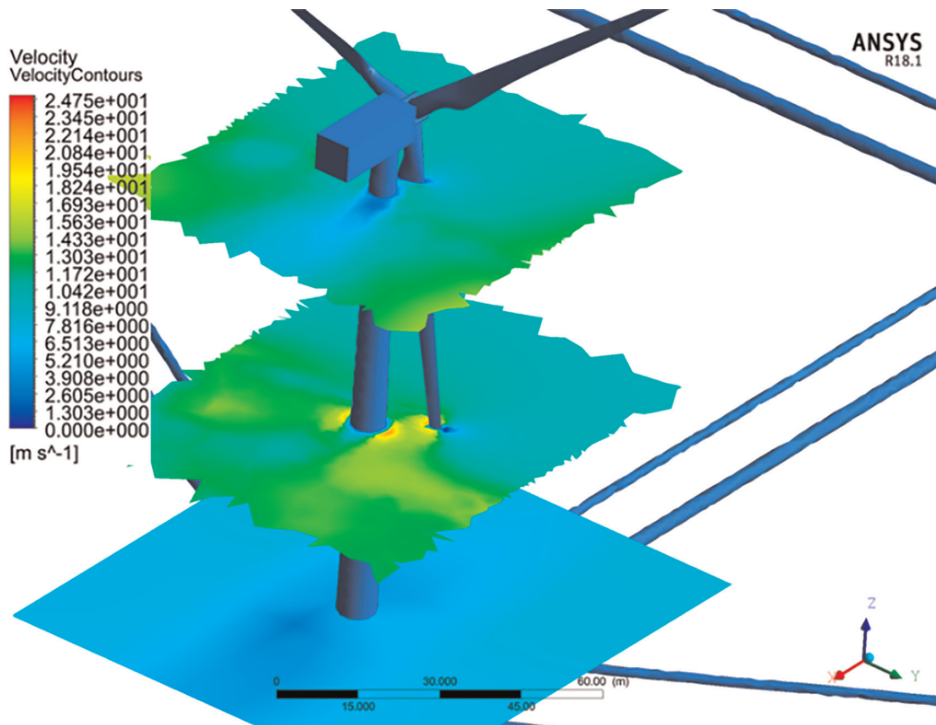


Figure 7.
Velocity contours of the downstream turbine.

that the second-row wind turbines are not affected by the wakes of the upstream turbines, thanks to their optimized arrangement based on prior research [11].

Aerodynamic thrust and torque are key parameters for evaluating the aerodynamic performance of a wind turbine. The thrust force (F) represents the total force acting perpendicular to the rotor plane, while the aerodynamic torque (T) is defined as the total moment acting along the turbine's axis of rotation [18, 24]. These parameters can be defined as follows.

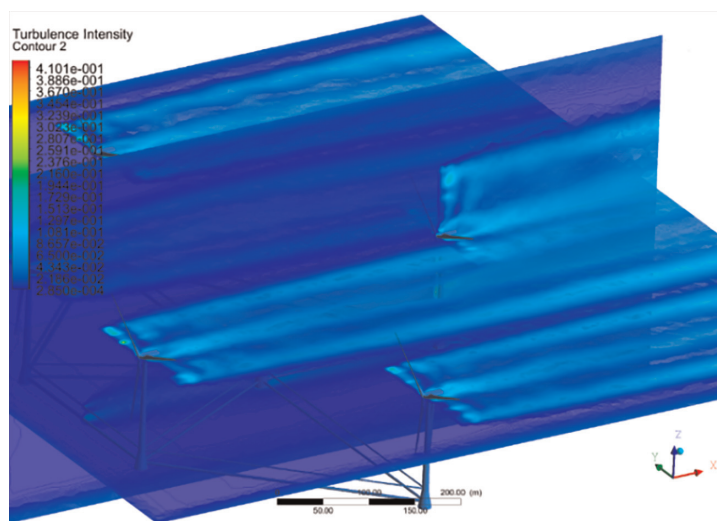


Figure 8.
 Turbulence intensity contours for OFFWIND.

$$F = \oint p \mathbf{n} \cdot d\mathbf{S} \quad (5)$$

$$T = \oint (\mathbf{r} \times p \mathbf{n}) \cdot d\mathbf{S} \quad (6)$$

where $\mathbf{n}$ represents the normal direction vector of the rotor plane, $d\mathbf{S}$ denotes the infinitesimal surface area vector, and $\mathbf{r}$ is the position vector from the center of rotation to the surface. The time history of aerodynamic thrust forces acting on the wind turbines is shown in **Figure 9**. The downstream turbine experiences greater aerodynamic forces compared to the upstream turbines due to increased turbulence caused by the partial wake effect generated by the upstream turbines, as highlighted in the magnified portion of the graph.

3.2 Hydrodynamics

When it comes to hydrodynamic analysis, the selection of the mathematical model is influenced by the structure's size, the height of the waves, and the wavelength of the incoming waves. For this hydrodynamic analysis, the first-order potential flow is utilized to address diffraction and radiation waves. The velocity potential resulting from the incident waves (ϕ_I), diffraction waves (ϕ_D), and radiation waves (ϕ_R) can be expressed [19, 25, 26] as

$$\phi = \phi_I + \phi_D + \sum_{j=1}^{6 \text{ DOF}} \zeta_j \phi_{Rj} \quad (7)$$

$$\phi_I = -\frac{Ag}{\omega} e^{\kappa z} e^{i(\kappa(x \cos \beta + y \sin \beta))} \quad (8)$$

where ζ_j refers to the displacement due to motion, A is the wave's amplitude, β indicates the direction in which the wave propagates, ω represents the wave

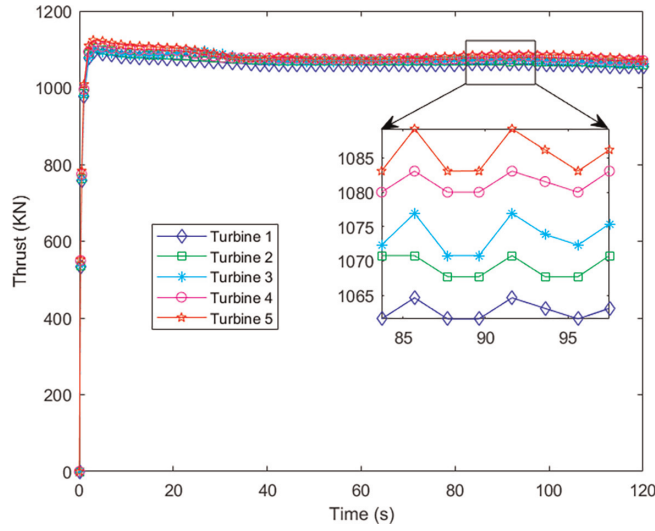


Figure 9.
Aerodynamic thrust on the rotor.

frequency, κ denotes the wavenumber, and g is the acceleration due to gravity. The structure's motion displacements are evaluated using the following motion equations.

$$\sum_{j=1}^6 \zeta_j (-\omega^2 (A_{ij} + M_{ij}) - i\omega B_{ij} + C_{ij}) = X_i \quad (9)$$

where C_{ij} is the hydrostatic restoring force, A_{ij} and B_{ij} are the added mass and radiation damping respectively, M_{ij} is the generalized mass of the offshore floating body, and X_i is the wave excitation force.

3.2.1 Numerical setup

In this analysis, the 3D diffraction/radiation module in ANSYS Aqwa is employed within the frequency domain to calculate the first-order wave forces and hydrodynamic coefficients. These findings are subsequently utilized to determine the platform's response over time under varying wind and wave conditions. To account for the non-linearity of the system, direct numerical integration of the equations of motion is used in the time domain analysis. The hydrodynamic characteristics of the OFFWIND are presented in **Table 2**.

Using ANSYS Aqwa, mooring cables for floating platforms can be effectively simulated. These mooring lines contribute to increased damping of the platform by exerting drag forces on the structure. The reaction forces from the mooring lines are determined through cable dynamics during time response analysis. For this OFFWIND project, there are four identical catenary mooring lines that are fixed at one end to the center of the platform, while the other end is anchored to the seabed using fixed anchor points, as depicted in **Figure 10**. Each non-linear catenary mooring line is modeled using 100 elements. The lines are symmetrically positioned relative to the X-axis. The specific parameters of the mooring lines are outlined in **Table 3**.

Parameter	Value
Depth of the water	250 m
Draft	20 m
Platform's freeboard	10 m
Center of buoyancy above the keel	7.55 m
Center of gravity above the keel	24 m
Volumetric displacement	36,915.34 m ³

Table 2.
 Specifications of the OFFWIND.

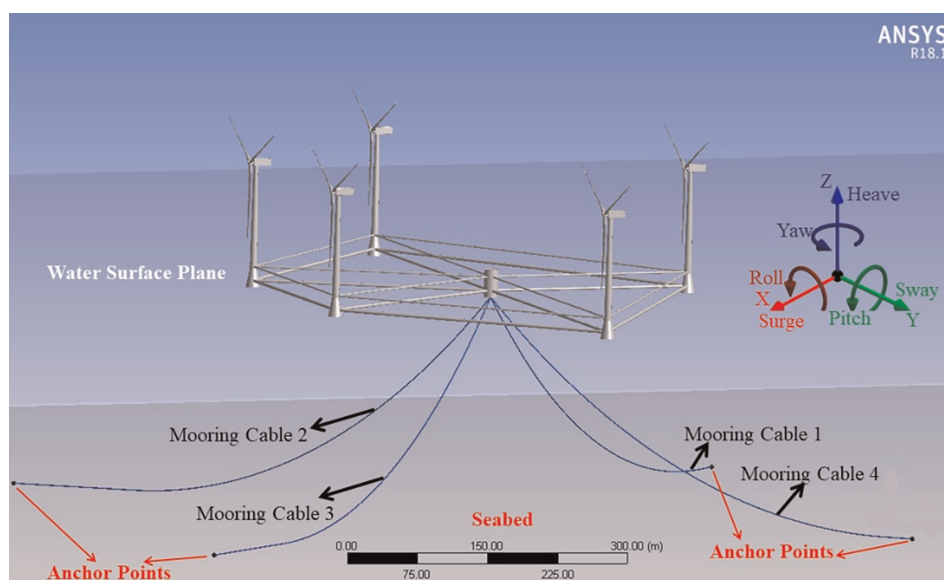


Figure 10.
 OFFWIND with catenary mooring lines.

A selection of wave directions ranging from 180° to −180° with an interval of 45°, is utilized for the analysis of hydrodynamic diffraction. The spectrum of JONSWAP wave [27] depicted in **Figure 11**, is employed to simulate the asymmetrical waves under the conditions, which include a substantial wave height (H_s) of 4 m, a wave period of 9 s, and a peak parameter (γ) of 3. It is represented as.

$$S(\omega) = 5A_\gamma \left(\frac{H_s}{4} \right)^2 \frac{\omega_p^4}{\omega^5} e^{\left(-\frac{5}{4} \left(\frac{\omega_p}{\omega} \right)^4 \right)} \gamma^{\exp \left(-\frac{1}{2} \left(\frac{\omega - \omega_p}{\sigma \omega_p} \right)^2 \right)} \quad (10)$$

where $\omega_p = \frac{2\pi}{T_p}$ peak-spectral frequency, $A_\gamma = 1 - 0.287 \ln(\gamma)$ is a normalizing factor, σ is a spectral width parameter with $\sigma = 0.07$ for $\sigma \leq \omega_p$ and $\sigma = 0.09$ for $\sigma > \omega_p$, and T_p is the peak wave period. The incident wave's frequency range for the simulation extends from 0.1 to 2.18337 rad/s, during which the structure's hydrodynamic parameters are assessed.

Parameter	Value
Number of mooring lines	4
Length	600 m
Unit length's mass	120 kg/m
Maximum tension	7.5 MN
Stiffness, EA	900 MN
Added mass coefficient	1
Equivalent cross-section area	0.01 m ²
Longitudinal drag coefficient	0.025
Equivalent diameter	100 mm
Transverse drag coefficient	1

Table 3.
Properties of the mooring lines.

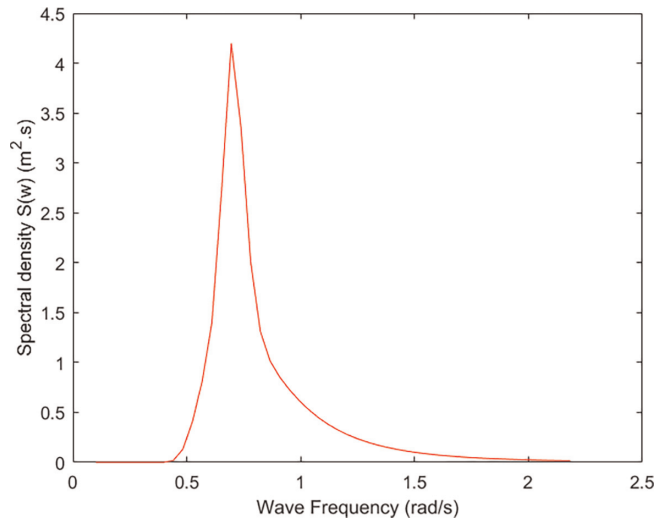


Figure 11.
JONSWAP wave spectrum.

The radiation forces in the time-domain analysis are calculated using the convolution technique. Aerodynamic loads, evaluated at a steady wind speed of 11 m/s, are imported into ANSYS Aqwa to simulate the platform's motion under the combined influence of wind and wave forces. The time-history responses are generated for a wave heading angle of 0° (aligned with the X-axis) within the hydrodynamic response module of Ansys Aqwa over a duration of 600 seconds, using a time-step size of 0.1 seconds.

3.2.2 Results

This section presents the pressure contours, frequency domain, time-domain dynamic responses, and mooring line tensions of the OFFWIND. **Figures 12–14**

illustrate the frequency response amplitude operator (RAO) for the platform's surge (X), heave (Z), and pitch (RY) motions. These responses are depicted for wave direction ranges from 180° to -135° with an interval of 45° based on the hydrodynamic diffraction analysis. As illustrated in the figures, the platform responses for wave directions of -180° and 0° , -90° and 90° , -135° and -45° , and 45° and 135° respectively are essentially the same.

The response to surges at wave-heading angles of 0° and 90° respectively is greater because of the wave forces acting in those directions. The heave response remains fairly uniform across various wave directions, with the maximum peak observed at a wave-heading angle of 90° . In contrast, the platform's pitch response is most significant at wave-heading angles of 0° and 180° .

Figure 15 presents the contour plot of the pressure distribution on the platform at a frequency of 0.99287 rad/s, with an incident wave amplitude of 2 m and a wave

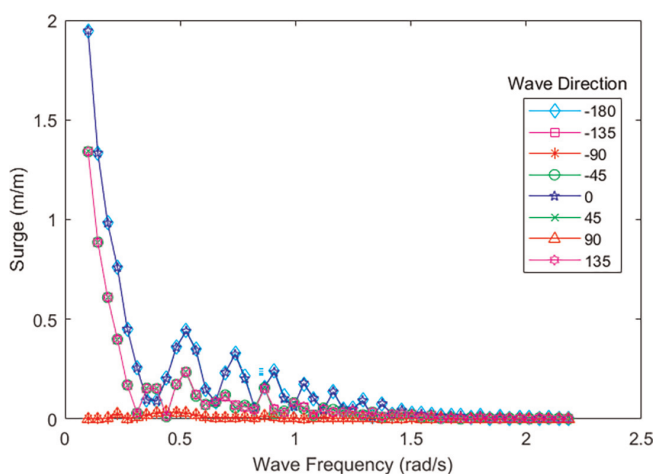


Figure 12.
 The frequency response of surge motion.

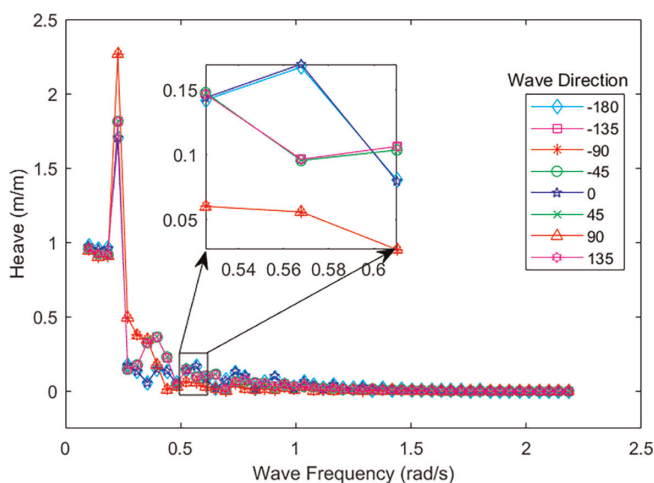


Figure 13.
 The frequency response of heave motion.

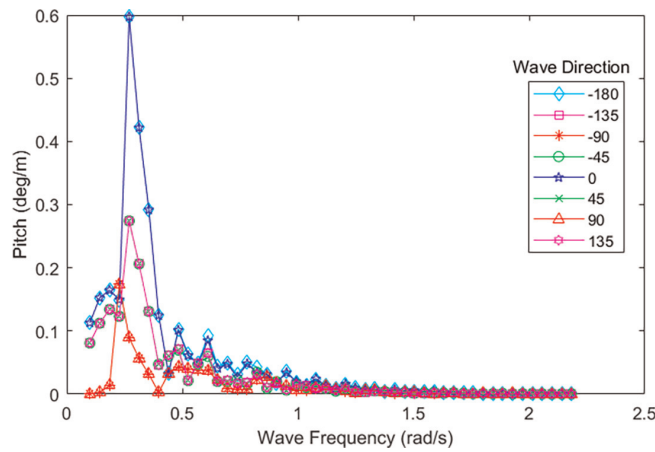


Figure 14.
The frequency response associated with pitch motion.

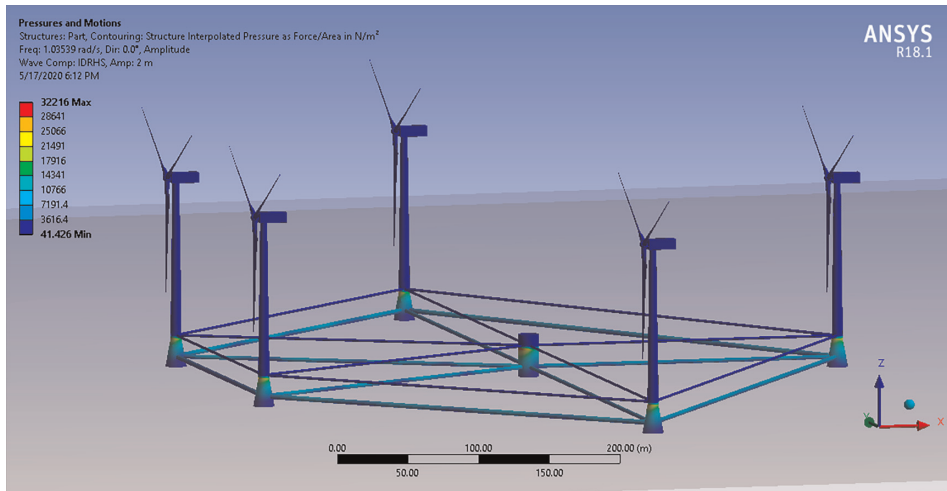


Figure 15.
Pressure contours on the OFFWIND.

direction of 0° . The highest pressure rates are observed at the surface of the water, where it interacts with the platform, as illustrated in **Figure 15**.

The response amplitude operators (RAO) for the OFFWIND under the influence of wind and wave conditions are displayed in **Figures 16–18**. The forces produced by both wind and waves significantly impact the platform's motion. The figures indicate that the six degrees of freedom (DOF) motions of the platform are periodic, albeit with varying periods for each motion.

The platform undergoes an average surge motion of 8.58 m, driven by the combined thrust force from the wind turbines and the waves traveling in the same direction. The tension in the mooring lines counteracts this motion.

The pitch and heave motions of the platform significantly influence the wind turbine's power generation, as these motions are influenced by wave energy. The average heave response is 0.267 m, while the average pitch response is 0.291 degrees,

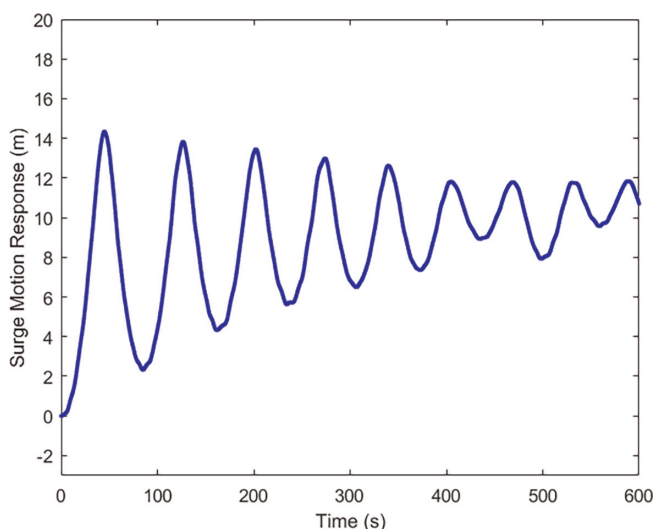


Figure 16.
 Time histories of the surge motion.

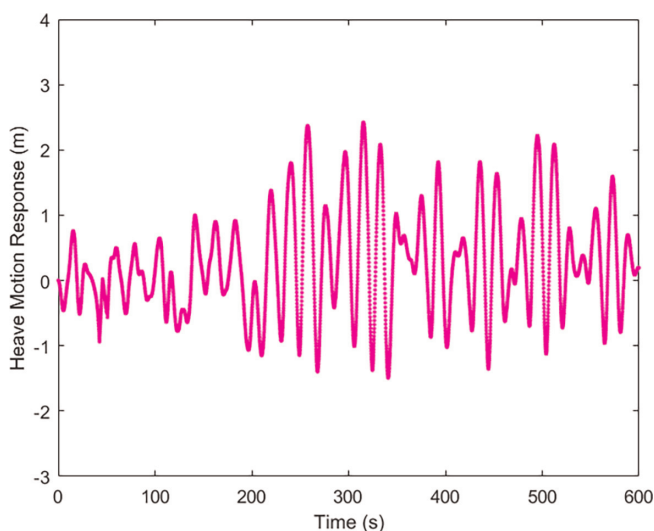


Figure 17.
 Time histories of the heave motion.

which may be equal, but their maximum amplitudes are different at 2.423 m and 1.123 degrees. Utilizing heave plates can help mitigate the amplitudes of pitch and heave motions [7, 28].

Figure 18 presents the time histories of pitch motion.

Figure 19 illustrates the time histories of tensile forces in the catenary mooring lines. The tension forces in cables 1 and 4, as well as in cables 2 and 3, show similar patterns because the mooring lines are symmetrically distributed around the X-axis, while wind and wave directions align with the X-axis. As the mooring tensions are influenced by the surge motion response, it is evident from the figure that the front cables (2 and 3) experience greater force to counteract the aerodynamic thrust force.

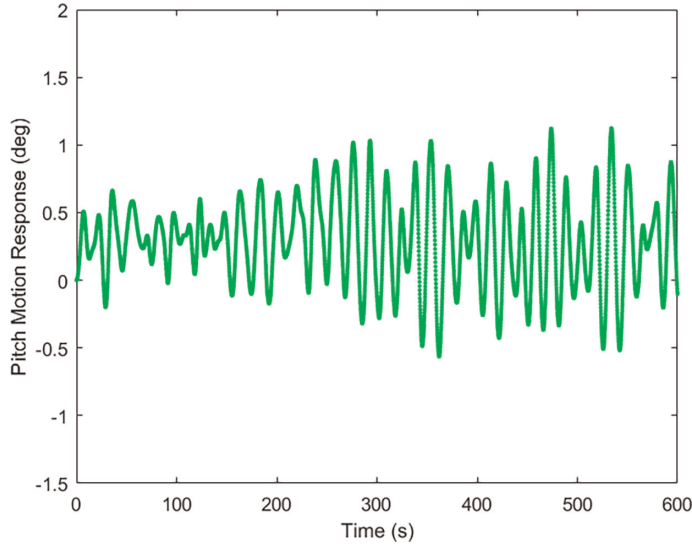


Figure 18.
Time histories of the pitch motion.

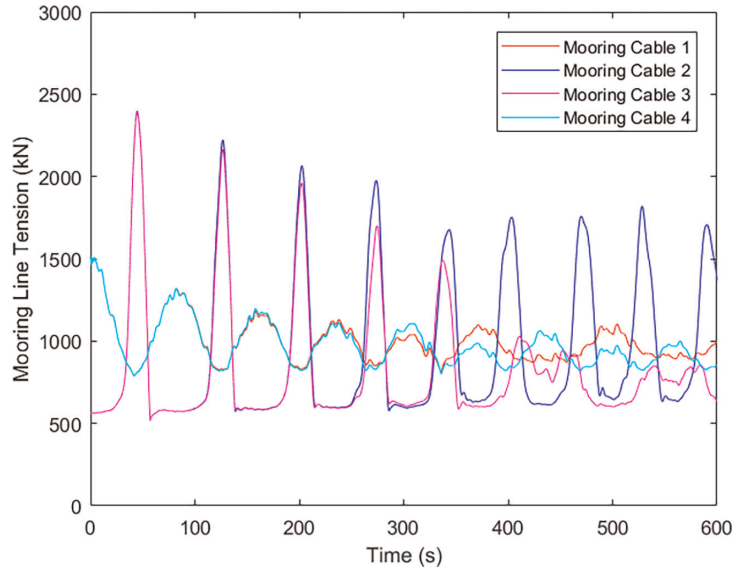


Figure 19.
Mooring line tensile forces.

4. Blade pitch control of OFFWIND

The dynamics of the system are established based on a rigid platform assumption represented by 6 DOF. Utilizing Newton's second law, the governing equation for the interconnected platform and wind turbines can be expressed as.

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{u}} = \sum_{T=1}^5 \mathbf{F}_{AD}^T + \mathbf{F}_{HS} + \mathbf{F}_{HD} + \mathbf{F}_M \quad (11)$$

where $\mathbf{A}$ is an added inertia matrix, $\mathbf{M}$ is a generalized inertia matrix containing mass and moment of inertia components, $\sum_{T=1}^5 \mathbf{F}_{AD}^T$ is the summation of the aerodynamic forces from the five wind turbines, $\mathbf{F}_{HD}$ are the hydrodynamic forces, $\mathbf{F}_{HS}$ are the hydrostatic forces, $\mathbf{F}_M$ is the force in mooring line and $\ddot{\mathbf{u}}$ is the acceleration vector. The aerodynamic thrust force (T) acting on the rotor blades of the wind turbine and the aerodynamic torque (Q) that the wind exerts on the wind turbine rotor are stated as.

$$T = \frac{1}{2} \rho_{air} A C_T(\lambda, \beta) v^2 \quad (12)$$

$$Q = \frac{1}{2} \rho_{air} A R C_Q(\lambda, \beta) v^2 \quad (13)$$

where A is the rotor-swept area, ρ_{air} is the density of the air, R is the rotor radius, C_T is the aerodynamic thrust, C_Q is the torque coefficient as a function of the tip speed ratio, λ , and pitch angle, β , and v is the wind speed. The thrust force is directed horizontally along the wind's path, while the torque acts as a horizontal vector aligned with the wind, based on the assumption that the rotor remains continually oriented into the wind [29]. The hydrostatic restoring forces can be described in the following manner.

$$\mathbf{F}_{HS} = -\mathbf{K}_h \mathbf{u}(t) \quad (14)$$

$$\mathbf{K}_h = [C_{ij}] \quad i, j = 1, 2, \dots, 6 \quad (15)$$

where the hydrostatic restoring coefficient matrix is denoted by $\mathbf{K}_h$ which contains the values of $C_{33} = -\rho_s g A_0$, $C_{44} = -mg GM_X$, $C_{55} = -mg GM_Y$ and the other elements are set to zero and $\mathbf{u}$ represents the displacement vector. m is the mass of the body, A_0 refers to the waterplane area, ρ_s is the seawater density, GM_X and GM_Y represent the metacentric heights in X and Y directions, respectively and g is gravity [30, 31]. The hydrodynamic force acting on the support platform is formulated as

$$\mathbf{F}_{HD} = \mathbf{F}_{HD}^{wave} - \int_0^t \mathbf{K}_k(t - \tau) \dot{\mathbf{u}}(\tau) d\tau \quad (16)$$

where the first component signifies the overall excitation load resulting from incoming waves, and the second component represents the added load input resulting from the wave radiation. The velocity vector is represented by $\dot{\mathbf{u}}$, $\mathbf{K}_k$ denotes the wave-radiation-retardation kernel matrix, and τ is a dummy variable [32]. The wave excitation force can be expressed as

$$\mathbf{F}_{HD}^{wave} = \sum_{n=1}^N A_{jn} A_n \cos(-\omega_n t + k_n \bar{x} \cos \theta + k_n \bar{y} \sin \theta + \Phi_{jn} + \phi_n) \quad (17)$$

where ω_n signifies the wave frequency, A_n represents the amplitude of the incident wave, k_n denotes the wavenumber, $(\bar{x}, \bar{y})$ is the mean horizontal offset of the structure, θ indicates the angle at which the wave is incident, ϕ_n represents the randomly generated phase, A_{jn} and Φ_{jn} denote the amplitude and phase of the n^{th} excitation harmonic in the j^{th} degree of freedom, respectively. A linearized model of the mooring system can describe the mooring line restoring forces in the following manner:

$$F_M = -K_m u(t) \quad (18)$$

where u indicates the displacement vector and K_m represents the mooring stiffness matrix.

4.1 State space representation

Eq. (11) is rearranged by grouping the linear terms associated with velocities, accelerations, and displacements as shown:

$$M\ddot{u} + D\dot{u} + Ku = F \quad (19)$$

where K is the stiffness matrix comprising terms linked to displacements, D is the damping matrix with terms connected to velocities, M represents the mass matrix containing all terms related to accelerations, and F is the generalized force vector that encompasses the nonlinear aerodynamic and hydrodynamic forces. Eq. (19) can be rewritten as follows:

$$\ddot{u} = -M^{-1}D\dot{u} - M^{-1}Ku + M^{-1}F \quad (20)$$

Eq. (20) can be transformed into a conventional state-space representation as given below:

$$\begin{aligned} \dot{x} &= A x + B f_u \\ y &= C x \end{aligned} \quad (21)$$

where

$$A = \begin{bmatrix} -M^{-1}D & -M^{-1}K \\ I & 0 \end{bmatrix}; B = \begin{bmatrix} -M^{-1} \\ 0 \end{bmatrix}; x = \begin{bmatrix} \dot{u} \\ u \end{bmatrix}; f_u = \begin{bmatrix} F \\ 0 \end{bmatrix} \quad (22)$$

In this configuration, A corresponds to the system matrix, x denotes the state vector, y is the output vector, f_u is the nonlinear input vector, B is the input matrix and C represents the output matrix.

4.2 Adaptive control

The adaptive control process created in earlier research is utilized in this simulation. The proposed control strategy was applied to 2, 3, and 5 MW wind turbines to evaluate its reliability in the face of parameter uncertainty. The findings showed that the adaptive controller is applicable to any size of the wind turbine, provided that the plant meets the almost strictly positive real (ASPR) condition [14]. The primary goal of this algorithm is to determine a control input that aligns with the output of the reference model expressed by

$$\begin{aligned} \dot{x}_m &= A_m x_m + B_m u_m \\ y_m &= C_m x_m \end{aligned} \quad (23)$$

where A_m , C_m , and B_m denote the state, output, and input matrices of the reference model, respectively. The adaptive control signal (u_p) which consists of feedback error, model states, and model input in the feedforward path, is defined as.

$$\mathbf{u}_p(t) = \mathbf{K}_e(t)\mathbf{e}_y(t) + \mathbf{K}_x(t)\mathbf{x}_m(t) + \mathbf{K}_u(t)\mathbf{u}_m(t) \quad (24)$$

where $\mathbf{K}_e(t)$, $\mathbf{K}_u(t)$, $\mathbf{K}_x(t)$ represents the adaptive gains on error, model input, and model state respectively, and $\mathbf{e}_y(t)$ represents the output error. The state-space model described earlier is implemented in MATLAB Simulink to evaluate how adaptive blade pitch control influences the performance of OFFWIND under combined wind-wave conditions. **Figure 20** illustrates the adaptive control algorithm applied to the floating platform. The reference model supplies the nominal rotor speed as an input to the adaptive pitch controller, which analyzes the difference between the target and actual rotor speeds. This analysis generates the adaptive control signal (u_p), represented by the pitch angle, which is then fed into the system plant. Output parameters are assessed while maintaining a constant generator torque.

4.3 Simulation

The aim of this research is to examine the OFFWIND operating in the region where the wind speed exceeds the rated level, with the rotor speed adjusted to produce rated power through modifications to the blade pitch. Consequently, the main goal of the controller is to reduce power oscillations of the floater, while the secondary goal is to lessen the platform movements and ensure structural integrity. The controller's performance is assessed under a mean stochastic wind speed of 18 m/s, featuring a turbulence intensity of 15% and wind speed variations of 2 m/s. The wave data is simulated with irregular waves having a significant wave height of 4 m and a peak spectral period of 9 seconds for the incoming waves. The performance metrics of the OFFWIND utilizing adaptive pitch control are compared to those of the baseline PI controller to demonstrate the effectiveness of the adaptive system. The distribution of wind speed and the elevation of wave surfaces used for the 600-second runtime simulation are displayed in **Figures 21** and **22**, respectively.

This study investigates the effect of blade pitch control on power generation, platform surge, heave, and pitch motions. **Figure 23** illustrates the changes in the blade pitch angle for a specific wind turbine. The adaptive controller adjusts the pitch angle based on the discrepancy between the target rotor speed and the measured rotor speed. It is noticeable that the rate of change in pitch angle with the adaptive control is lower compared to that of the PI controller. The regulation of rotor speed for the

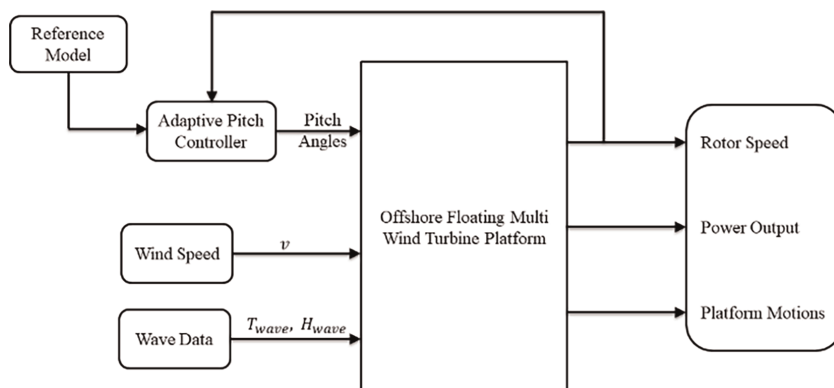


Figure 20.
 Adaptive control block diagram of OFFWIND.

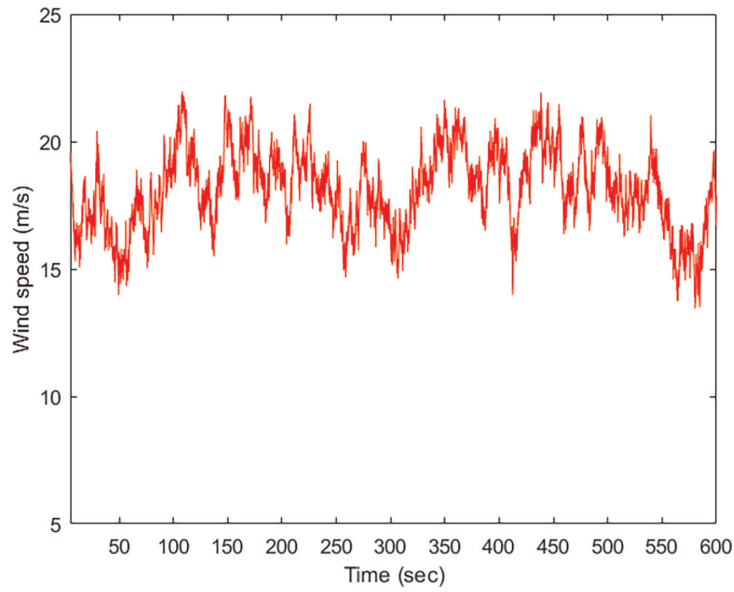


Figure 21.
Distribution of the wind speed.

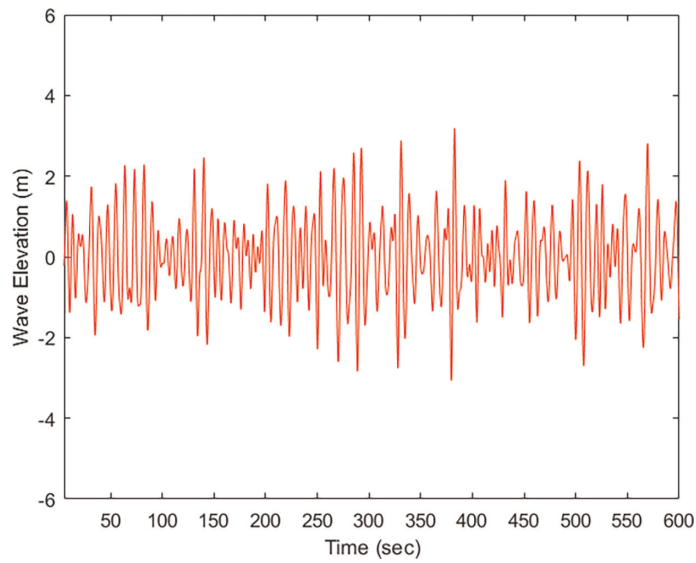


Figure 22.
Elevation of the wave surface.

chosen wind turbine in conditions above the rated wind speed is presented in **Figure 24**. The output power generated by the particular wind turbine is demonstrated in **Figure 25**. In this operating region, the power output closely follows the rotor speed due to the constant torque generated by the generator.

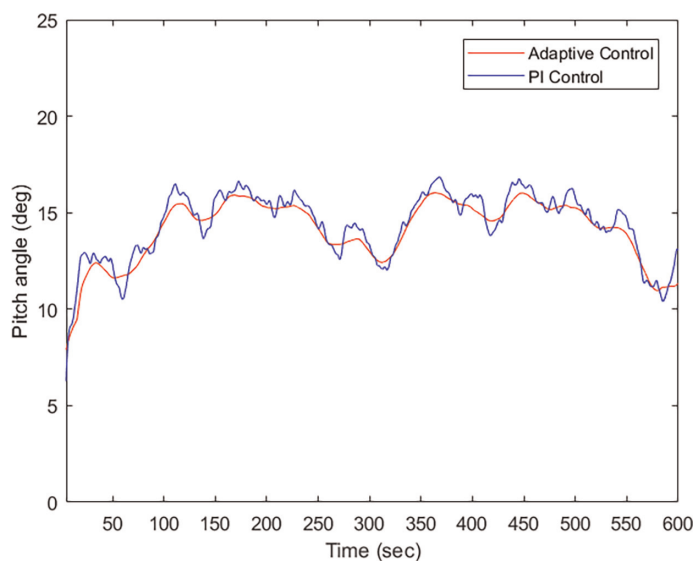


Figure 23.
Pitch angle variation of a wind turbine.

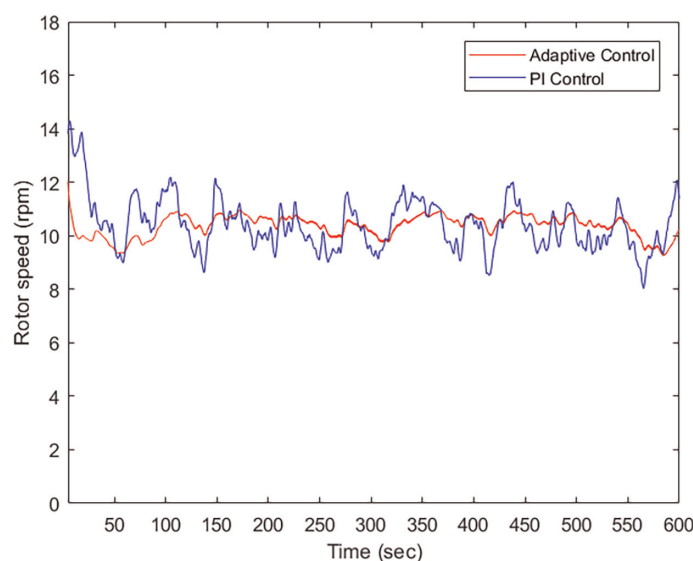


Figure 24.
Rotor speed regulation in the above-rated wind speed region.

The findings indicate that implementing adaptive control leads to a notable decrease in the variability of both rotor speed and power output compared to the PI controller. The surge, heave, and pitch motions of the floating platform are illustrated in **Figures 26–28**, respectively. The response of platform surge motion demonstrates that adaptive control effectively diminishes the peak amplitudes of surge motion in contrast to the PI controller. Both controllers exhibit a similar profile in the heave motion response. Additionally, the pitch motion of the platform shows reduced peak amplitudes with adaptive control compared to the PI controller.

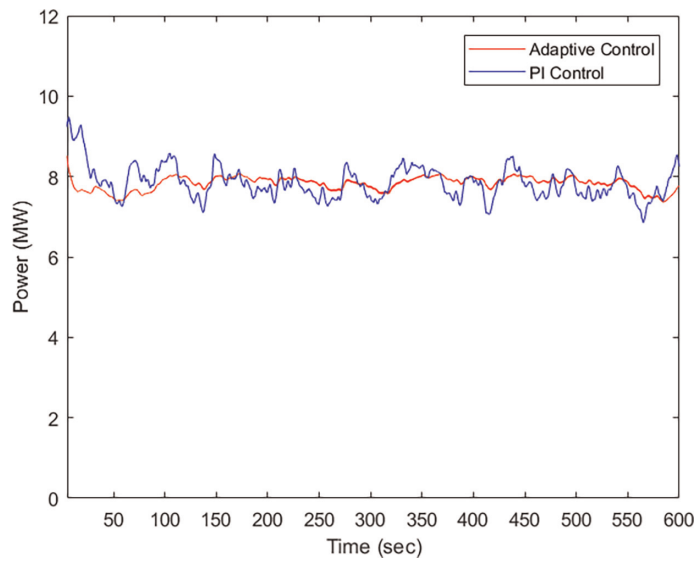


Figure 25.
The power output of a selected wind turbine.

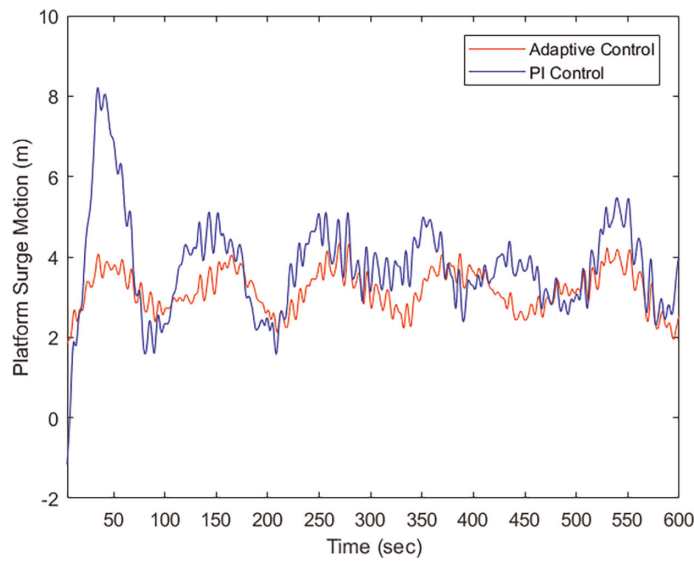


Figure 26.
Surge motion of the platform.

5. Conclusions

The study of unsteady fluid flow around the rotating rotor of a wind turbine entails a complex sequence of processes. Aerodynamic evaluations are conducted on the complete OFFWIND novel configuration, which incorporates five 8 MW wind turbines using CFD simulations to determine the aerodynamic loads on the turbines while the blades rotate simultaneously. The study discusses the contours of pressure,

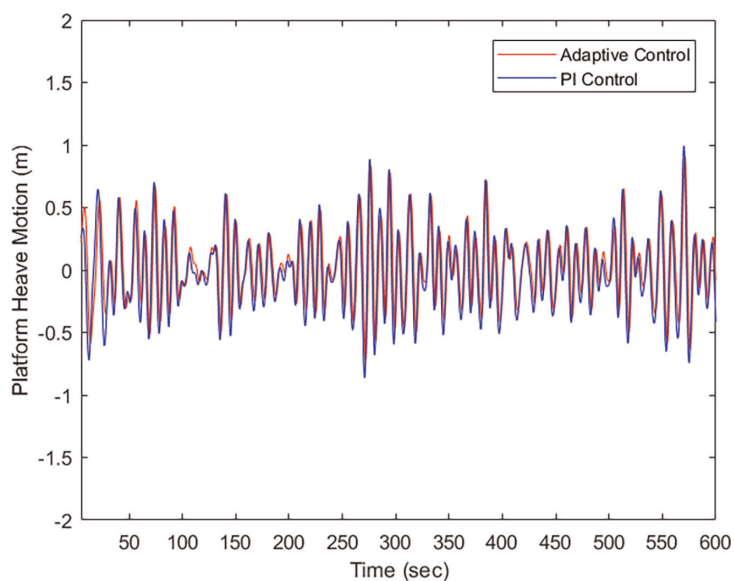


Figure 27.
Heave motion of the platform.

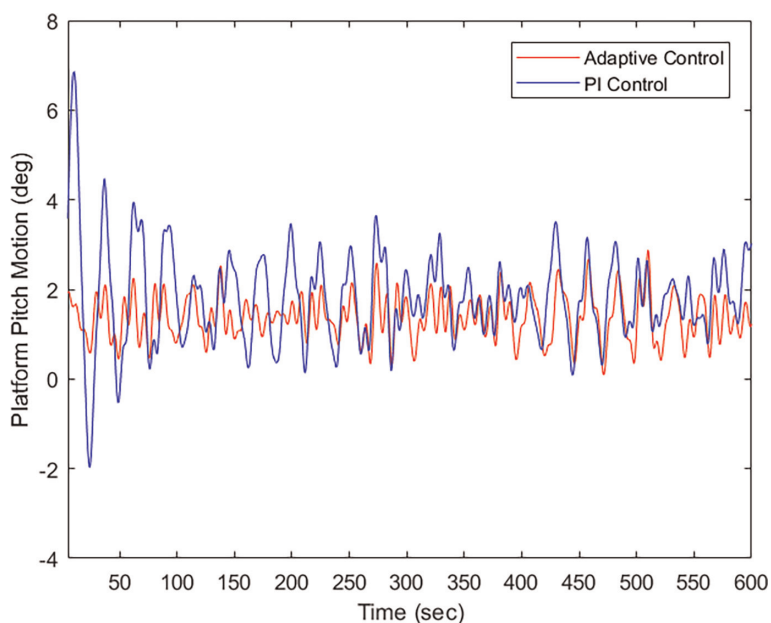


Figure 28.
Pitch motion of the platform.

velocity, and turbulence intensity for the downstream wind turbine. The time histories of aerodynamic thrust for the wind turbines indicate periodic variations in thrust force attributed to the tower shadow effect. The aerodynamic loads are subsequently integrated into the hydrodynamic module to evaluate the platform's motions in both

the frequency and time domains. The structural frequency responses, analyzed for eight distinct wave heading angles, demonstrate that the responses at -180° and 0° , -90° and 90° , -135° and -45° and 45° and 135° are consistent with one another. The interpolated pressures on the structure are observed to be highest at the intersection of the water surface plane and the platform. The controller plays a crucial role in a wind turbine by managing power output and minimizing loads. The behavior of the OFFWIND system under turbulent wind and irregular wave conditions is modeled. Blade pitch regulation is managed using an adaptive control strategy developed in prior research. The influence of this adaptive control on key performance indicators, including power output and platform dynamics, is analyzed. Results indicate that the adaptive blade pitch control outperforms the conventional proportional-integral controller in enhancing overall system performance. Additionally, the rate of blade pitch change with the adaptive control is less than observed with the PI controller. Implementing an adaptive controller results in a notable decrease in fluctuations in rotor speed and output power. The platform motions also exhibit reduced peak amplitudes in surge and pitch motion responses. In terms of heave motion response, both controllers display similar behaviors. The adaptive control can effectively be applied to the OFFWIND system when operating in winds exceeding rated speeds. This control methodology may further be analyzed for other scenarios close to the rated wind speeds. In this investigation, the simulation assumes that the wind turbines are always oriented into the wind. Future assessments could involve the development of a comprehensive yaw control system to continually align the wind turbines with the wind direction.

Author details

Srikanth Bashetty¹ and Selahattin Ozcelik^{2*}

¹ The University of Oklahoma, Norman, OK, USA

² Texas A&M University—Kingsville, Kingsville, TX, USA

*Address all correspondence to: selahattin.ozcelik@tamuk.edu

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