

A study on a floating type shrouded wind turbine: Design, modeling and analysis

Zhu, Hongzhong

Research and Education Center for Green Technology, Kyushu University

Sueyoshi, Makoto

Research Institute for Applied Mechanics, Kyushu University

Hu, Changhong

Research Institute for Applied Mechanics, Kyushu University

Yoshida, Shigeo

Research Institute for Applied Mechanics, Kyushu University

<https://hdl.handle.net/2324/7234384>

出版情報 : Renewable Energy. 134, pp.1099-1113, 2019-04. Elsevier

バージョン :

権利関係 :



A Study on a Floating Type Shrouded Wind Turbine: Design, Modeling and Analysis

Hongzhong Zhu^{a,*}, Makoto Sueyoshi^b, Changhong Hu^b, Shigeo Yoshida^b

^a*Research and Education Center for Green Technology, Kyushu University, Kasuga
816-8580, Japan*

^b*Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan*

Abstract

This paper addresses a fundamental study of a floating type shrouded wind turbine on the design, mathematical model and motion analysis. Several novel concepts are introduced to the system for cost reduction: a revolute hinge is applied between the tower and the nacelle to maintain the orientation of the nacelle even in a large tower inclination, a swashplate mechanism with cyclic control is employed for blade pitch regulation to improve the system controllability, a novel mooring system with a slewing bearing is utilized to build the passive yawing system, and an advanced spar-type floater is used to obtain high restoring performance with a short spar. Firstly, the design aspects of the main components of the system are given. Then, the numerical model including the structural model, hydrodynamic/aerodynamic model, and the control system is presented. The static and dynamic responses under both the operational situation and survival conditions are finally studied. The paper illustrates the probability of the shrouded wind turbine on floating offshore application, and can provide critical information for the optimization design in next stage.

Keywords: shrouded wind turbine; passive yawing system; cyclic pitch control; floating offshore application; multi-body simulation method

1. Introduction

Countries around the world are putting substantial effort into the development of wind energy technologies for decarbonization. In 2016, wind power generated about 4% of global electricity while its capacity shows steady expansion [1]. The International Energy Agency (IEA) targets 15% to 18% share
5 of global electricity from wind power by 2050 in its roadmap, which will avoid

*Corresponding author

Email addresses: zhuhongzhong@riam.kyushu-u.ac.jp (Hongzhong Zhu),
sueyoshi@riam.kyushu-u.ac.jp (Makoto Sueyoshi), hu@riam.kyushu-u.ac.jp (Changhong
Hu), yoshidas@riam.kyushu-u.ac.jp (Shigeo Yoshida)

emissions of up to 4.8 gigatonnes (Gt) of carbon dioxide (CO₂) per year [2]. Off-shore wind energy is recognized as an important component part for addressing the targets [3, 4, 5].

10 To reduce the cost of energy, people are making their efforts in the wind turbine upscaling. Currently, 10 MW-class wind turbines have already been developed for commercial installation [6]. Moreover, a size up to 20 MW is also within the EU supported UpWind research project [7]. The large scale wind turbines are becoming main models in industrial/populated areas with
15 fine power grid system. In remote area or offshore fishery industries, however, a relatively small scale wind turbine would be more suitable for their small power consumption. For these applications, compact and high-efficient wind turbines with low cost are preferred.

Shrouded wind turbines, which can augment the wind speed at the rotor
20 plane, have attracted a lot of attention [8, 9, 10, 11]. It has been reported that a power augmentation of approximately two can be obtained by placing a well-designed diffuser around the rotor [9, 10]. Besides, Ohya *et al.* developed a new-type shroud that places a flange on the diffuser exit [12, 13]. By the structure, the wind speed at the rotor plane increases about 1.6-2.4 times over
25 the upwind flow, which leads to 2-3 times increase of power extraction. In addition, small-scale shrouded type wind turbines have high potential for cost reduction. Bukala *et. al* compared some modern small wind turbines including a bared horizontal axis wind turbine, a shrouded wind turbine and a vertical axis wind turbine, and illustrated that the shrouded wind turbine has the lowest
30 installation cost [14].

Although a large power augmentation can be obtained, the shroud increases the axial thrust force on the wind turbine. Werle and Presz have analyzed the characteristics of the ducted/shrouded wind turbines based on momentum-balance-based model [15], and pointed out that at the peak power coefficient, the ratio of the shroud thrust to the rotor thrust can be expressed by

$$\frac{F_s}{F_r} = \frac{3}{2} \frac{V_p}{U_\infty} - 1, \quad (1)$$

where F_s is the shroud thrust force, F_r is the rotor thrust force, V_p is the wind speed at the rotor plane, and U_∞ is the upstream wind speed. According to (1), the thrust of a wind turbine would increase by 100% when the wind speed is augmented by 20%. For onshore or bottom-fixed offshore applications, the large
35 thrust would be overcome by strengthening the tower structure. For floating offshore applications, however, it would require a very large floating platform to provide sufficient restoring force to suppress the tower from fall. The energy benefit from the shroud would be less than the increases of mass and cost.

To relax the limitation, a novel design of a floating type shrouded wind turbine is proposed. The two-dimensional sketch draw is shown in Fig. 1. The shroud is mounted on the nacelle via radially distributed tensioned guy wires. A revolute hinge providing one-degree-of-freedom motion in pitch is applied to mount the nacelle on the tower. By this structure, the nacelle is possible to stay horizontal even with large tower inclination. Therefore, the power variation

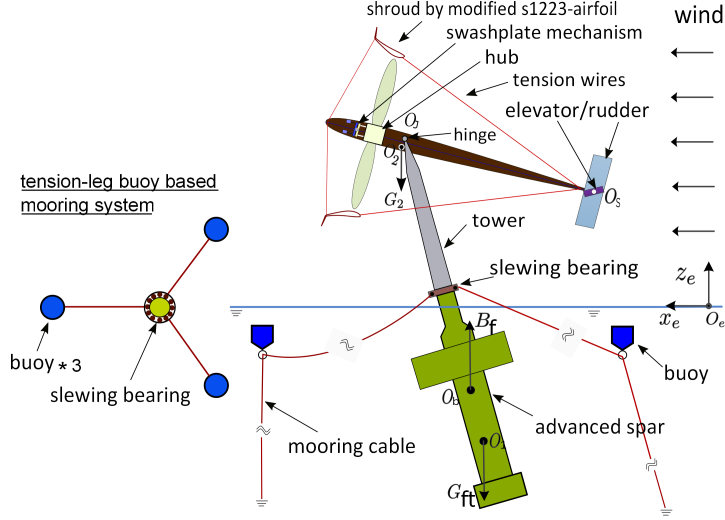


Figure 1: Two-dimensional sketch draw.

owing to the floater motion is reduced as well as the shroud thrust coefficient is able to be maintained at its minimum value. A swashplate mechanism with cyclic pitch is applied to control the blade pitch angles. The cyclic control can help on stabilizing the nacelle motion so that the fatigue loads on the wind turbine are possible to be reduced. An elevator and a rudder mounted on the upwind side of the nacelle are applied to stabilize the wind turbine in parked conditions. An advanced spar type floating platform with a large cylindrical column at the upper side of the spar is applied to provide high restoring performance for the floating wind turbine. The mooring system consisting of a slewing bearing at the top of floater and three triangularly arranged tension-leg buoys is employed to build the passive yawing system. The mooring force on the floater is toward horizontal so that the thrust force on the wind turbine can be handled effectively. The survivability of the conceptual model in extreme conditions has been studied in [16] with a simplified model. However, the study on design, aero-hydro-servo analysis were not provided. For the present concept having hinge structure and tension buoy-based mooring system, the couple motion between the mechanical components is complex. Therefore, high fidelity aero-hydro-servo coupled analysis is required.

In the remainder of this paper, design aspects of a floating type shrouded wind turbine are firstly presented. Then, the structural model, hydrodynamic model, aerodynamic model, drivetrain model and control system are introduced. Static and stochastic aero-hydro-servo integrated numerical simulations are finally performed to investigate the performance of the model.

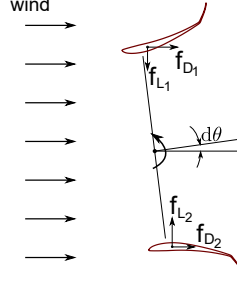


Figure 2: Sectional view of shroud.

2. Design Aspects

2.1. Wind Turbine

70 A shrouded wind turbine with rated power of 500 kW at wind speed of 9 m/s is studied. The shroud and the nacelle are firstly designed to investigate the axial velocity distribution at the rotor plane. The geometry of a blade is then designed based on the velocity distribution. At the first stage of this study, the interference of the rotor and the shroud on the wind speed augmentation is
75 ignored.

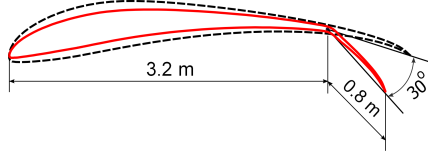
2.1.1. Shroud and Nacelle

For the present wind turbine with passive yawing system, the shroud is preferred to be self-stabilization to reduce the burden of control system. This can be explained by using the sectional view of the shroud shown in Fig. 2. Suppose that the shroud rotates a small angle $d\theta$ in a uniform wind, self-stabilization states that the shroud should have the ability to move back to its original orientation passively. The aero-loads on the shroud sections are required to satisfy the following condition:

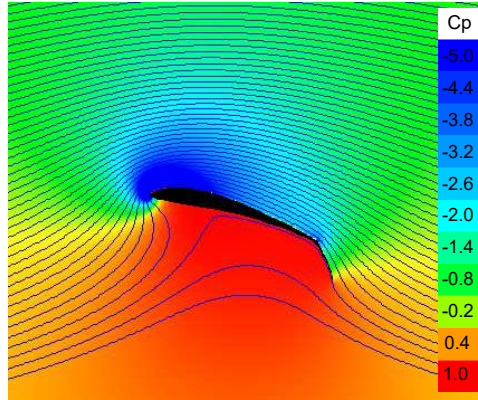
$$(f_{L1} + f_{L2})R_0 \sin d\theta < (f_{D1} - f_{D2})R_0 \cos d\theta, \quad (2)$$

where f_L is the lift force, f_D is the drag force, and R_0 is the rotational radius of the aerodynamic center of the airfoils. The subscript ₁ and ₂ represent the upper section and the lower section, respectively.

80 The Selig S1223 airfoil is adopted for shroud design for its high lift and good power augmentation [17, 18]. The airfoil is modified based on the self-stabilization condition (2) and an in-house comprehensive evaluation of the mass flow increase, the shroud surface area, and the shroud thrust, and the result is shown in Fig. 3(a). The thickness of the airfoil is reduced to 7.2% and the
85 mean camber line for the last 20% of the chord length is rotated downward by 30 deg. The three-dimensional shroud is generated with the cross section of the modified airfoil-S1223 having the angle of attack of 20 deg. The contour of pressure and the streamlines around the airfoil based on potential flow analysis are illustrated in Fig. 3(b). Owing to the stagnation region in the lower side of



(a)



(b)

Figure 3: (a) Dimensions of the shroud airfoil (dashed line shows the original S1223 airfoil and solid line shows the modified airfoil), and (b) contour of pressure and streamlines of shroud airfoil.

the airfoil, the approaching flow is pushed upwards and great mass flow increase can be induced by the airfoil.

The nacelle is designed from a symmetrical airfoil having maximum thickness of 5% at 20.2% chord. The schematic diagram of the nacelle and the components attached to it are shown in Fig. 4. The location of the maximum thickness of the nacelle is reserved for the hub.

The shroud is mounted on the nacelle via 12 sets radially distributed tensioned guy wires. The mechanism can be consulted to the rim of a ferris wheel. A light and rigid supporting structure can be obtained by the mounting method. In the upwind side, the wires are connected to the nacelle with a small angle (30 deg to the nacelle axis) to tangle with the wind drag on the shroud. In the downwind side, the wires are connected to the nacelle with a large angle (75 deg to the nacelle axis) to handle the gravitational force on the shroud. The hinge center where the nacelle is mounted on the tower locates at the 30% chord of nacelle. The combined center of mass (CoM) of nacelle, rotor, shroud, elevator and rudder is adjusted to be under the hinge so that the nacelle can

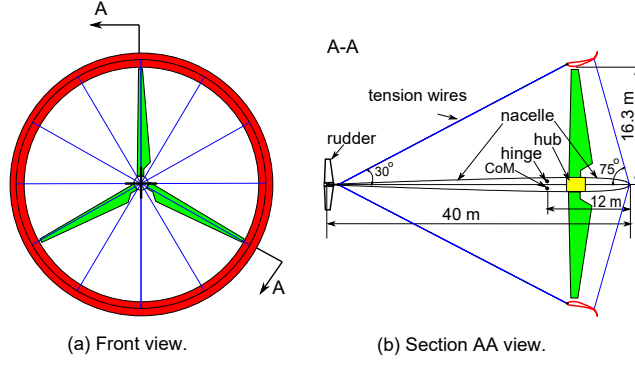


Figure 4: Schematic diagram of the nacelle and the associated components.

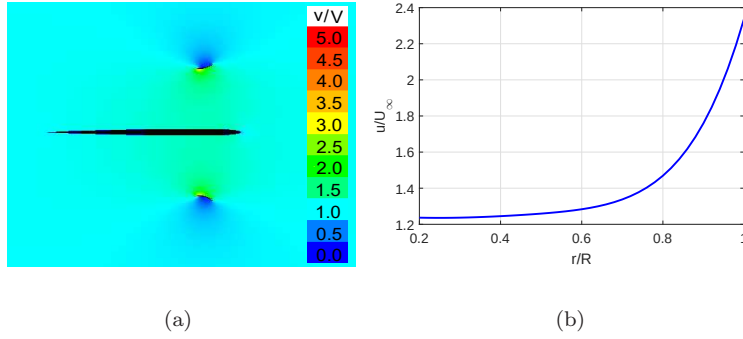


Figure 5: (a) Velocity field (without the rotor) in 2-dimensional analysis, and (b) axial velocity distribution at the rotor plane.

stay horizontal in calm weather conditions.

The potential flow analysis in two dimensions using JavaFoil [19] is applied to analyze the flow field around the shroud and the nacelle, and the velocity distribution (without the present of blades) is shown in Fig. 5(a). The axial velocity distribution at the rotor plane is illustrated in Fig. 5(b).

2.1.2. Blade Geometry

Since the wind turbine is a variable-speed pitch-regulated wind turbine with rotor diameter about 30 m, the S825 airfoil is utilized to design the blades as recommended in [20]. An in-house algorithm based on blade-element/momentum theory [21] considering the non-uniform velocity (shown in Fig. 5(b)) is applied to design the blade geometry. The optimal tip speed ratio (defined by $\lambda = \frac{\Omega R}{u_R}$ where Ω is rotor angular speed, R the rotor radius and u_R the augmented wind speed at the blade tip) is set to be $\lambda_{\text{opt}} = 4$. To reduce the geometry complexity, the chord length along the blade span is tapered by two straight line

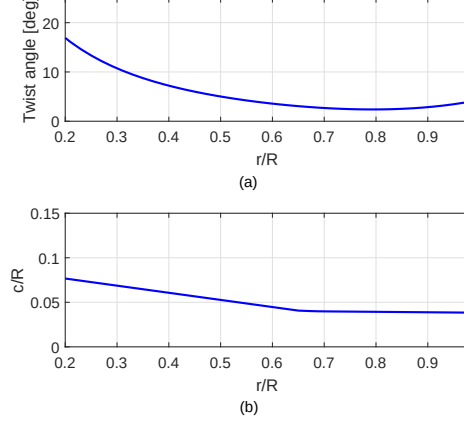


Figure 6: Span-wise distribution of the twist angle and the chord length normalized by blade length.

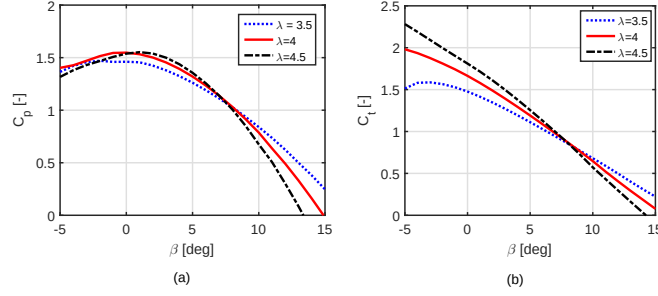


Figure 7: (a) Power coefficient and (b) thrust coefficient.

using the least-square approximation method. The span-wise distribution of the twist angle and the chord length are shown in Fig. 6. The power coefficient and thrust coefficient are shown in Fig. 7 when $\lambda = 3.5, 4$, and 4.5 . The coefficients described here are defined with respect to the rotor plane area by

$$C_p = \frac{P}{\frac{1}{2}\rho_a A U_\infty^3}, \quad (3)$$

$$C_t = \frac{T}{\frac{1}{2}\rho_a A U_\infty^2}, \quad (4)$$

where ρ_a is the air density, A is the rotor plane area, P is the converted power and T is the thrust on the rotor.

2.1.3. Drivetrain and Generator

115 The drivetrain consists of a low-speed shaft connected to the hub, a high-speed shaft connected to the generator and a gearbox. The gearbox is assumed

Table 1: Properties of drivetrain

Property	Value
Moment of inertia of low-speed shaft* (kgm ²)	2.6×10^4
Moment of inertia of high-speed shaft** (kgm ²)	25
Gearbox ratio	41.06:1

* includes the rotor, hub and low-speed shaft of gearbox.

** includes the high-speed shaft of gearbox and generator.

Table 2: Properties of generator

Property	Value
Pole pairs	4
Stator resistance (mΩ)	16
d-axis Inductance (mH)	0.26
q-axis Inductance (mH)	0.32
Efficiency (%)	94

to be high-stiffness so that the vibration of the drivetrain is not considered. A permanent-magnet synchronous generator having rated speed of 2000 rpm is employed. The properties of the drivetrain and the generator are shown in Table 1 and Table 2, respectively. A full-rated back-to-back voltage source converter is utilized to connect the generator to the power grid or battery sets. The details of the power converter system are referred to the study in [22].

2.1.4. Other Components

A swashplate with cyclic control is utilized to regulate the blade pitch angles. A fundamental study about the application of cyclic pitch control on wind turbine is referred to [23].

NACA 0012 symmetric airfoil with maximum thickness 12% at 30% chord is employed to design the rudder and the elevator. In addition, the tower is designed to be a truncated cone that the radius of the tower are linearly tapered from the tower base to the tower top.

The main properties of the wind turbine are listed in Table 3. Note that the shroud mass and the nacelle mass are much larger than the rotor mass owing to their large surface area. In the following, a floating platform with high restoring performance is designed to support the wind turbine.

2.2. Floating Platform

2.2.1. Floater

An advanced spar is applied as the supporting platform for the wind turbine, and the design aspects are shown in Fig. 8. The upper large cylinder can not only shift the center of buoyancy upward, but also increase the hydrodynamic resistance on the heave motion [24]. The properties of the floater is listed in Table 4.

Table 3: Properties of shrouded wind turbine

Property	Value
Rated power (kW)	500
Rated wind speed (m/s)	9.0
Cut-in wind speed (m/s)	2.0
Cut-out wind speed (m/s)	20.0
Rated rotor speed (rpm)	48.7
Rotor diameter (m)	32
Rotor mass (kg)	2130
Shroud mass (kg)	8,760
Elevator/rudder mass (kg)	150
Elevator/rudder area (m ²)	12
Nacelle mass (kg)	7,800
Nacelle inertia* (Ixx,Iyy,Izz) (kgm ²)	(2.89,2.89,11.1) × 10 ⁶
Distance between hinge and CoM** (m)	0.75
Tower mass (kg)	12,000
Elevation of tower top (m)	30.0
CoM of tower (w.r.t tower base) (m)	9.2
Tower inertia (Ixx,Iyy,Izz) (kgm ²)	(4.25,4.25,0.06) × 10 ⁵

* includes the moment of inertia of nacelle, rotor, shroud, elevator and rudder w.r.t the hinge.

** the mass of nacelle, rotor, shroud, elevator and rudder.

Potential-flow theory is applied to evaluate the hydrodynamic loads on the floater, and the linear potential-flow problem is solved using the WAMIT computer program [25]. The magnitude and phase of the wave excitation force from solving the linear diffraction problem are shown in Fig. 9 for incident waves propagating along the positive x -axis. The loads in the direction of sway, roll and yaw are zero due to the symmetries of the floater. The magnitudes of the force and moment in the direction of surge, heave and pitch reach a peak near a wave frequency of 1 rad/s. The hydrodynamic-added-mass and -damping matrices from the linear radiation problem are shown in Fig. 10. Owing to the symmetries of the floater, the surge-surge elements of the added-mass and damping matrices, A_{11} and B_{11} , are identical to the sway-sway elements, A_{22} and

Table 4: Properties of advanced spar type floater

Property	Value
Floater draft (m)	23.0
Displacement (m ³)	411
Floater mass (kg)	380,000
Center of buoyancy below SWL* (m)	9.3
CoM location below SWL (m)	19.2
Floater inertia (Ixx,Iyy,Izz) (kgm ²)	(1.39,1.39,0.01) × 10 ⁸

* still water level.

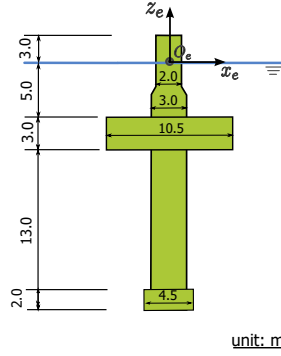


Figure 8: Dimensions of the advanced spar type floater.

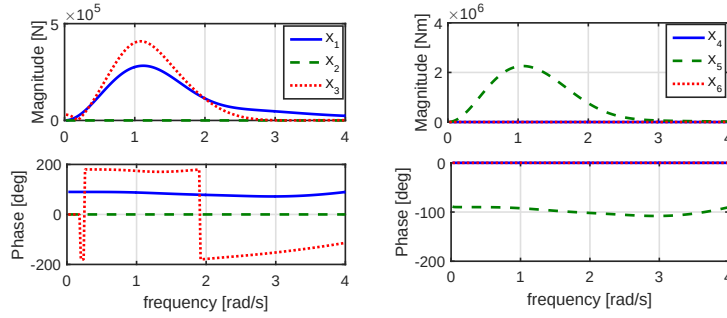


Figure 9: Hydrodynamic wave excitation force per unit amplitude for the floater.

B_{22} . And, the roll-roll elements, A_{44} and B_{44} , are identical to the pitch-pitch elements, A_{55} and B_{55} . Other elements not shown in the figure are zero-valued.

2.2.2. Mooring System

The mooring system consists of three triangularly arranged tension-leg buoys, a slewing bearing, mooring lines, anchors, and connectors. The buoys are a submerged cylindrical bodies with radius 1.5 m and height 3 m. The mooring system properties are listed in Table 5. The anchors are placed directly under the buoys. Instead of the conventional mooring system that the mooring chains are supported by the buoyancy of floater [26], they are supported by the buoys so that the floater can be lightened.

According to the design, the center of mass of the floating wind turbine is located at -16.33 m, and the meta-center height is 7.05 m. The numerical model and the analysis of the system are discussed in the following sections.

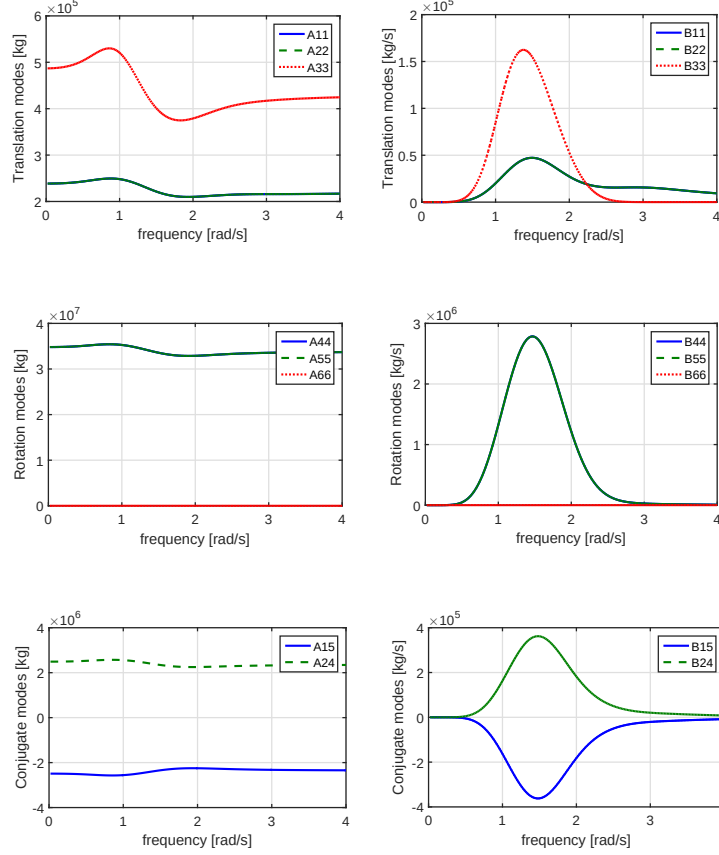


Figure 10: Hydrodynamic added mass and damping for the floater.

3. Numerical Modeling of the System

3.1. Structural Modeling

The general formulation of the motion equation of a rigid-body can be written by [27]

$$M\dot{\mathbf{v}} + C(\mathbf{v})\mathbf{v} + D\mathbf{v} + g(\boldsymbol{\eta}) = \boldsymbol{\tau}, \quad (5)$$

where $\mathbf{v} \in \mathbb{R}^6$ is the velocity vector, $\boldsymbol{\eta} \in \mathbb{R}^3 \times \mathbb{S}^3$ the position and orientation vector, M the generalized mass matrix, C the Coriolis and centripetal matrix due to the rotation, D the damping matrix, g the restoring force, and $\boldsymbol{\tau}$ the vector of external forces and moments. The SimMechanicsTM, which provides a multi-body simulation environment for 3D mechanical systems, is used to model the structure system of the floating wind turbine. Each blade, the hub, the nacelle, the shroud, the elevator, the rudder, the tower, the slewing bearing,

Table 5: Properties of mooring system

Property	Value
Buoy mass (kg)	3,000
Buoy diameter (m)	3.0
Buoy height (m)	3.0
CoM location of buoy below SWL (m)	6.0
Distance between buoys (m)	129
Depth of sea bed (m)	50
Chain length between floater and buoy (m)	75.7
Chain mass (per unit length) (kg)	5.0
Buoy inertia (Ixx,Iyy,Izz) (kgm ²)	(3.90,3.90,2.22)×10 ³

the floater and each buoy are represented by rigid body blocks in the model. One degree-of-freedom revolute joints are applied to connect the blades to the hub, the hub to the nacelle, the rudder/elevator to the nacelle, and the nacelle to the tower. A weld joint is applied to mount the tower on the top of the floater. The six degree-of-freedom joints are used to locate the floater and the buoys in the world frame.

Since a mooring line consists of a tensioned part (between the buoy and anchor) and a loose part (between the floater and the buoy), the model is considered separately. The mooring line between the buoy and the anchor is modeled as a hybrid linear elastic spring expressed by

$$F_m = \begin{cases} 0, & \text{if } l_m \leq d_m \\ -k(l_m - d_m), & \text{if } l_m > d_m \end{cases} \quad (6)$$

where l_m is the distance between the connection points, and d_m is the nominal length of the mooring line. The coefficient $k = 2.0 \times 10^7$ N/m is the stiffness of the mooring line. Note that the mooring force is generated only when the lines are strained. On the other hand, the mooring line between the floater and each buoy is modelled by 13 end-to-end connected slender bodies. The isometric view of the structure system is shown in Fig. 11. The world frame is set at the center of the water plane of the floater at the still water level. The z -axis is vertical and positive upwards.

By using the toolbox, the left terms of the equation (5) are computed automatically. The external forces are modeled in the following subsections.

3.2. Hydrodynamic Loads

Since the distance between the floating bodies are much larger than their diameters, their coupling interaction is small and therefore ignored in this study. The hydrodynamic loads on a floating body can be separated into four components:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{res} + \boldsymbol{\tau}_{rad} + \boldsymbol{\tau}_{visc} + \boldsymbol{\tau}_{exc}, \quad (7)$$

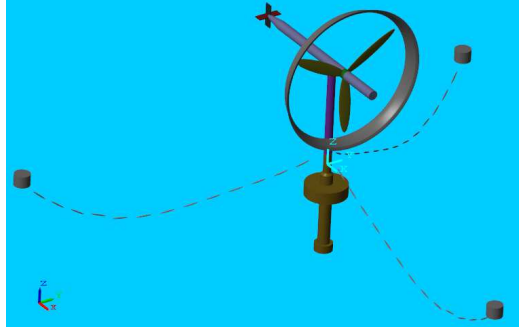


Figure 11: The structure system modelled in SimMechanics™.

where τ_{res} is the restoring force due to the gravity and buoyancy, τ_{rad} is the radiation force arising from the change in momentum of the fluid, τ_{visc} is the viscous hydrodynamic force due to the fluid-viscous effects, and τ_{exc} is wave excitation loads. The term τ_{visc} is neglected because the natural periods of the floating wind turbine are designed outside the modal periods of wave (referred to Section 4) and the viscous hydrodynamic force contributes small to the total loads compared to the other terms.

The hydrostatic restoring force τ_{res} is computed based on the displacement in heave, the attitude (Euler angles), and the metacentric height of the body (referred to Chapter 4 in [27]). The radiation force is determined by the frequency-dependent added mass $A(\omega)$ and potential damping $B(\omega)$ according to

$$\tau_{rad} = -A_{\infty}\dot{v} - \int_0^t K(t - \tau)v(t')dt', \quad (8)$$

where A_{∞} is the constant infinite-frequency added mass matrix and $K(t)$ is a matrix of retardation functions given by

$$K(t) = \frac{2}{\pi} \int_0^{\infty} B(\omega) \cos(\omega t) d\omega. \quad (9)$$

$K(t)$ is expressed by a linear model using state-space equations in order to reduce the computational load. A comprehensive study of the method can be referred to [28, 29]. In addition, the wave force τ_{exc} is computed based on force response amplitude operators (RAOs) by

$$\begin{aligned} \tau_{exc} = & \sum_{k=1}^N \sum_{i=1}^M |\Gamma(\omega_k)| \sqrt{2S(\omega_k, \beta_{wi}) \Delta\omega \Delta\beta_w} \cdot \\ & \cos(\omega_k t - k(x \cos \beta_{wi} + y \sin \beta_{wi}) + \angle\Gamma(\omega_k) + \epsilon_{k,i}), \end{aligned} \quad (10)$$

where $|\Gamma|$ and $\angle\Gamma$ are the amplitude and phase of the force RAOs, respectively, S is the wave spectrum, ω is the wave frequency, k is the wave number, β_w represents the wave propagation direction, and ϵ is the random phase angles.

The terms $\Delta\omega$ and $\Delta\beta_w$ are constant difference between successive frequencies and propagation directions, respectively. The force RAOs of the floating bodies can be computed using a hydrodynamic program, such as WAMIT [25].

205 3.3. Aerodynamic Loads

3.3.1. Aerodynamic Force on Blades

Based on the blade element momentum theory and the conservation of momentum analysis, the thrust force and the torque on a blade element are expressed by

$$dF = \frac{1}{2}\rho_a \frac{v_{b\text{-rel-x}}^2 (1-a)^2}{\sin^2(\phi)} c(r) C_n dr, \quad (11)$$

$$dT = \frac{1}{2}\rho_a \frac{v_{b\text{-rel-x}}^2 (1-a)^2}{\sin^2(\phi)} c(r) C_t r dr, \quad (12)$$

where r is the local radius, dr the length of blade element along the central line, $c(r)$ the local chord length, ϕ the local inflow angle, a the axial induction factor. The local relative upstream wind speed $v_{b\text{-rel-x}}$ is calculated by

$$v_{b\text{-rel-x}} = [\kappa \mathbf{R}_n^b \mathbf{u}_\infty(z) - \mathbf{v}_b]_x, \quad (13)$$

where κ is the local wind speed augmentation factor shown in Fig. 5(b), $\mathbf{u}_\infty(z)$ the local non-augmented wind velocity expressed in world frame, $\mathbf{R}_n^b$ is the rotation matrix to transfer a vector expressed in the world frame to the blade element-fixed frame which is defined at the aerodynamic center with x -axis pointing perpendicular to the rotor plane and z -axis pointing to the tip of blade (y -axis is defined according to the right-hand rule). The term $\mathbf{v}_b$ is the blade element velocity expressed in the blade element-fixed frame. The subscript $[\cdot]_x$ denotes the x -axis component. The velocity components in y -axis and z -axis are neglected for computing the torque and thrust force since they are relatively small. The terms C_n and C_t are the coefficients denoted as

$$\begin{aligned} C_n &= C_l(\phi - \beta) \cos(\phi) + C_d(\phi - \beta) \sin(\phi), \\ C_t &= C_l(\phi - \beta) \sin(\phi) - C_d(\phi - \beta) \cos(\phi), \end{aligned}$$

where β is the blade pitch angle, C_l and C_d are the lift coefficient and the drag coefficient, respectively. The flow induction factor a is a function of ϕ , C_l , C_d , and solidity, and can be obtained by iterative calculation [21, 30]. The hub loss correction model based on Prandtl's model [31] is applied during solving a :

$$F_{\text{hub}} = \frac{2}{\pi} \cos^{-1} \left[\exp \left(-\frac{B(r - R_{\text{hub}})}{2r \sin(\phi)} \right) \right], \quad (14)$$

where B is the blade number, and R_{hub} the radius of the hub.

Note that when the wind turbine is in parked conditions, the drag on a blade element is calculated based on the quasi-steady aerodynamics theory:

$$dF = \frac{1}{2}\rho_a v_{b\text{-rel-x}}^2 c(r) C_n dr. \quad (15)$$

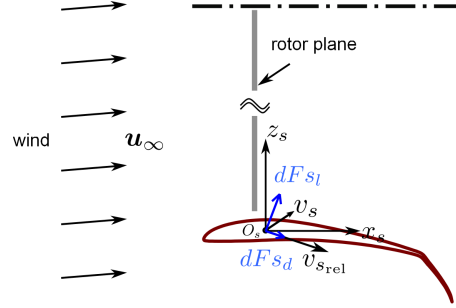


Figure 12: Velocity and force analysis of a shroud element.

3.3.2. Aerodynamic Force on Shroud

The shroud is uniformly split into several strips along the circumferential direction and the quasi-steady aerodynamics theory is applied for computing the aerodynamic force. The velocity and force analysis of an element is shown in Fig. 12. For the ease of explanation, the element-fixed frame $O_s - x_s y_s z_s$ is defined at the aerodynamic center with x -axis pointing perpendicular to the rotor plane and z -axis pointing to the center line of the shroud (y -axis is defined by the right-hand rule). The term $\mathbf{v}_s$ is the shroud element velocity expressed in the element-fixed frame. The relative velocity of the shroud element is formulated by

$$\mathbf{v}_{s\text{rel}} = R_n^s \mathbf{u}_\infty - \mathbf{v}_s, \quad (16)$$

where R_n^s is the rotation matrix to transfer the wind velocity $\mathbf{u}_\infty$ to the frame $O_s - x_s y_s z_s$. The angle of attack α_s can be calculated based on the angle between the $\mathbf{v}_{s\text{rel}}$ and the plane $O_s - x_s y_s$, and the lift force and drag force on the element can be calculated based on

$$dF_{sl} = \frac{1}{2} \rho_a |\mathbf{v}_{s\text{rel}}|^2 C_{sl}(\alpha_s) c_s dl, \quad (17)$$

$$dF_{sd} = \frac{1}{2} \rho_a |\mathbf{v}_{s\text{rel}}|^2 C_{sd}(\alpha_s) c_s dl, \quad (18)$$

where dl is the arc length of the shroud element, c_s is the chord length of the shroud airfoil, and C_{l_s} and C_{d_s} are the lift coefficient and drag coefficient of the shroud airfoil, respectively. Note that the coefficients are affected by the rotor plane in operational situations and can be evaluated by CFD (Computational Fluid Dynamics analysis) or experiments. Five cases of the coefficients under steady-state conditions at $\alpha_s = 0$ are demonstrated in Fig. 13. For comparison, the coefficients in parked situation are also given in the figure.

3.3.3. Aerodynamic Force on Nacelle, Tower, Rudder and Elevator

The aerodynamic force on the nacelle, the rudder, the elevator and the tower are calculated based on the quasi-steady aerodynamics theory, which can be referred to the equation (15).

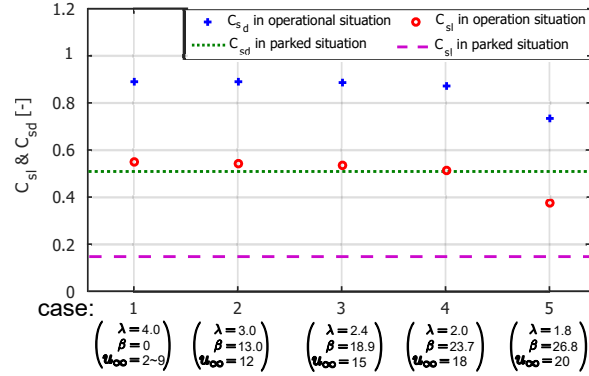


Figure 13: Lift and drag coefficients of the shroud airfoil under steady-state conditions.

220 3.4. Generator and Drivetrain Model

The permanent-magnet synchronous generator can be described by [32]

$$\frac{d}{dt}i_d = -\frac{R_s}{L_d}i_d + \omega_e \frac{L_q}{L_d}i_q + \frac{1}{L_d}v_d, \quad (19)$$

$$\frac{d}{dt}i_q = -\frac{R_s}{L_q}i_q - \omega_e \frac{L_d}{L_q}i_d - \omega_e \frac{\phi_e}{L_q} + \frac{1}{L_q}v_q, \quad (20)$$

$$T_g = \frac{3}{2}n_p[\phi_e i_q + (L_d - L_q)i_d i_q], \quad (21)$$

where i and v are the current and voltage, respectively, L is the self-inductance, R_s is the stator resistance, ω_e is the electrical rotating speed, n_p is the number of pole pairs, ϕ_e is the permanent magnetic flux, and T_g is the electromagnetic torque. The subscripts d and q refer to the physical quantities in rotating reference frame via Park transformation.

In addition, according to the assumption that the drivetrain is rigid, the rotational motion of the rotor-gearbox-generator system is expressed by

$$J\dot{\Omega} = T_a - T_g N^2, \quad (22)$$

where Ω is the rotor speed, T_a is the aerodynamic torque computed by (12), N is the gearbox ratio, and J is the sum of the moments of inertia of the hub, blades, shaft, gearbox and generator.

3.5. Control System

230 3.5.1. Generator Current Control

Proportional-integral (PI) controllers combined with decoupling control terms are applied for generator current control [33]. The d -axis current i_d is regulated to be zero so that the generator torque is proportional to the q -axis current. The q -axis current demand i_q^d is calculated from the generator torque demand T_g^d that

$$i_q^d = T_g^d / K_t, \quad (23)$$

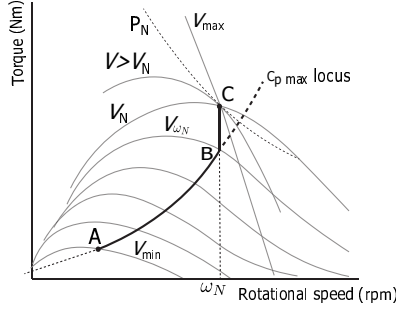


Figure 14: Control strategy of the rotational motion.

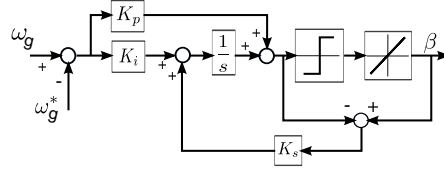


Figure 15: Block diagram of the blade pitch control.

where K_t is the torque coefficient assigned by $K_t = \frac{3}{2}n_p\phi_e$. By the method, the transfer function from the torque demand to the generated torque becomes the first-order system expressed by

$$G_t(s) = \frac{1}{\tau s + 1}, \quad (24)$$

where τ is the time constant determined by the parameters of the PI controller. In this study, τ is set to be 0.01 s by tuning the PI controller.

3.5.2. Generator Torque Demand and Collective Pitch Control

For a variable-speed pitch-regulated wind turbine, the basic control objectives are to maximize the energy capture at low wind speeds whereas to limit the aerodynamic power at above-rated wind speeds. Fig. 14 depicts the basic control strategy on the torque-rotational speed plane.

In low wind speeds, the rotor speed is controlled by regulating generator torque demand to keep the tip-speed ratio, λ , at its optimal value. The turbine is operated along the optimal locus with the peak power efficiency between the point A and B. The torque demand for the generator is given by

$$T_g^d = \frac{\pi \rho_a R^5 C_{p\max}}{2 \lambda_{\text{opt}}^3 N^3} \omega_g^2, \quad (25)$$

where ω_g is the generator rotation speed. At point B, the rotation speed arrives to its rated rotational speed ω_N at wind speed V_{ω_N} . Then, a PI controller is applied to regulate the rotational speed at this value along the segment BC.

In above-rated wind speeds, the generator torque demand is set as constant while the pitch angle of the blades is increased (pitch-to-feather) to shed the aerodynamic power so as to keep the turbine operating at point C. A PI controller with anti-windup manner is adopted for pitch control, as shown in Fig. 15. Pitch angle and pitch rate limiters are applied considering the practical situation. The parameters K_p and K_i are the gains of PI controller and K_s is the anti-windup coefficient. Gain-scheduled approach is applied to tune the parameters to handle the sensitivity of the aerodynamic torque to the pitch angle [21]. The output of the blade pitch control is used as the reference of the collective pitch of the swashplate.

3.5.3. Cyclic Pitch Control

The lateral cyclic pitch is controlled to stabilize the pitch motion of the nacelle and the vertical cyclic pitch is controlled to assist the wind turbine on following the wind direction. Gain-scheduled PI controllers are also utilized for cyclic pitch control to cope with the strong nonlinearity caused by the aerodynamics and hydrodynamics.

3.5.4. Rudder/Elevator Control

In this study, the rudder and elevator are applied to stabilize the nacelle only in the parked situation. PD (Proportional-Derivative) controllers acting on the difference between the direction of wind and the orientation of nacelle are applied to regulate the angle of attack of the rudder and the elevator. The angle limiter is applied to prevent them from working in stall situation.

3.6. Environmental Model

3.6.1. Wave Model

Irregular sea state having two-dimensional wave spectrum is employed for this study. The sea state is modeled by

$$S(\omega, \beta_w) = S(\omega)g(\beta_w), \quad (26)$$

where $S(\omega)$ is the wave spectrum, β_w is the encounter angle and $g(\beta_w)$ is the spreading function expressed by

$$g(\beta_w) = \begin{cases} \frac{2}{\pi} \cos^2 \beta_w, & -\pi/2 \leq \beta_w \leq \pi/2 \\ 0, & \text{elsewhere} \end{cases} \quad (27)$$

A fully developed wind-generated sea state characterized by the Modified Pierson-Moskowitz (MPM) Spectrum [27]

$$S(\omega) = A\omega^{-5}\exp(-B\omega^{-4}) \quad (28)$$

is applied. The terms A and B are the parameters given by

$$A = \frac{4\pi^3 H_s^2}{T_z^4}, \quad B = \frac{16\pi^3}{T_z^4},$$

where H_s is the significant wave height and T_z is the average zero-crossing wave period. The modal wave frequency ω_0 and the corresponding wave spectrum can be calculated by

$$\omega_0 = \sqrt[4]{\frac{4B}{5}},$$

$$S(\omega_0) = \frac{5A}{4B\omega_0} \exp(-5/4).$$

265 3.6.2. Wind Speed Model

The mean wind speeds are given by a logarithmic wind profile expressed as

$$\frac{u_\infty(z)}{u_\infty(H)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{H}{z_0}\right)}, \quad (29)$$

where z is the height, $H = 10 \text{ m}$ is the reference height, and z_0 is the roughness length depending on the type of surface. For offshore application, z_0 is assigned by $z_0 = 0.001$.

In addition, a linearized von Karman model is applied as the wind turbulence model [34]:

$$H_f = K_f \frac{(aT_f s + 1)}{(T_f s + 1)(a_2 T_f s + 1)}, \quad (30)$$

where s is Laplace operator. The parameters a_1 and a_2 are assigned as $a_1 = 0.4$ and $a_2 = 0.25$. The terms T_f and K_f are expressed by

$$T_f = \frac{L}{v_d}, \quad K_f \approx \sqrt{\frac{2\pi}{B(\frac{1}{2}, \frac{1}{3})} \cdot \frac{T_f}{T_s}},$$

where L is the turbulence length scale, T_s the sampling period, and B is the beta function. According to IEC edition 2 standard, the longitudinal turbulence intensity is set as [21]

$$I_u = I_{\text{ref}} \left(0.75 + \frac{5.6}{u_\infty(z_h)} \right), \quad (31)$$

270 where I_{ref} is given by $I_{\text{ref}} = 0.14$ and $u_\infty(z_h)$ is the mean wind speed at hub height.

4. Properties

Natural periods of the system, which can significantly affect the performance of the wind turbine in response to the sea conditions, should be designed to avoid overlapping with the wave periods. The free decay tests under calm water

Table 6: Natural periods (s)				
surge	sway	heave	roll	pitch
66.3	67.5	30.6	25.9	26.2

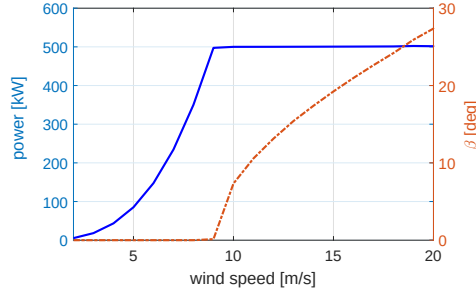
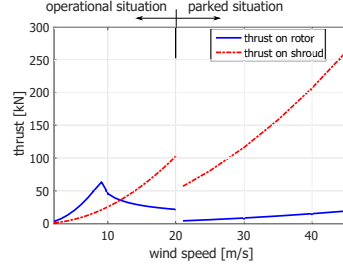


Figure 16: Power curve and the corresponding pitch angle of blades.

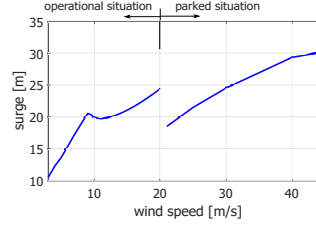
conditions are performed using the aforementioned model, and the results are illustrated in Table 6. The design the presented floating wind turbine meets the DNV Offshore Standard since the natural periods are out of the typical wave periods which are in the range of 4 s to 25 s [35]. Dynamic wave motion analysis and the effect of natural periods will be discussed in Section 5.

Then, the performance of the wind turbine is investigated under uniformly distributed wind with constant speeds. To avoid the effects of the structural motion, the nacelle is fixed in the world frame. The power curve and the corresponding blade pitch angle are illustrated as functions of wind speeds in Fig. 16. In below-rated wind speeds, the wind turbine operates at peak power coefficient so that the power increases with the cube of wind speeds. In above-rated wind speeds, pitch-to-feather control strategy is applied to control the blade pitch to shed the aerodynamic power. The generator is maintained to work at the rated condition.

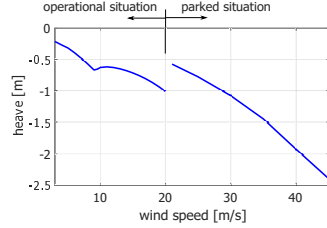
The thrust on the rotor plane/shroud and the floater motion under constant wind speeds are also evaluated, and the results are shown in Fig. 17. Owing to the symmetries of the whole system, the floater motion in sway, roll and yaw directions are zero and not displayed. In low wind speeds, as the blade pitch angle is fixed to the optimal position, the thrust on the wind turbine increases with the square of wind speeds. At the above-rated wind speeds, the blade pitch is controlled (pitch-to-feather) to regulate the power so that the thrust on rotor plane decreases with an increase in wind speeds. The total force on the wind turbine decrease first and then increase again due to the continuously increase of the shroud thrust. In parked situation, the pitch angle of the blades is set to 90° , the force on the rotor becomes the drag force on the blades so that it is much smaller than the operational cases. Moreover, as the drag coefficient of the shroud is reduced in parked situation (illustrated in Fig. 13), the shroud thrust decreases sharply at the cut-out speed, as shown by the discontinuities



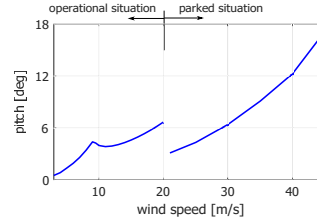
(a) Rotor thrust and shroud thrust.



(b) Surge of floater.



(c) Heave of floater.



(d) Pitch of floater.

Figure 17: Thrust on the wind turbine and the resulting surge, heave and pitch angle of the floater under constant wind speeds.

in Fig. 17(a). The same behaviors can be observed in the floater motion in Figs. 17(b)~17(d).

305 The relationship between the cyclic pitch of the swashplate and the rotor moment is investigated. The pitch angle of a blade as a function of the azimuth angle is demonstrated in Fig. 18. Suppose that the collective pitch demand is set as β_0 and the lateral cyclic pitch is set as some positive value ϖ , the pitch angle of a blade reaches its maximum value $\beta_0 + \varpi$ at the top position (where the azimuth angle is 0 deg), and decreases and reaches its minimum value $\beta_0 - \varpi$ at the bottom position (where the azimuth angle is 180 deg). It increases gradually back to $\beta_0 + \varpi$ as the rotor rotates and the process is repeated again. The rotor moment induced by the cyclic pitch is illustrated in Fig. 19(a), and the power coefficient variation is shown in Fig. 19(b). It can be observed that a relatively large moment can be induced for nacelle orientation control at the cost of small power variation. Therefore, cyclic pitch control can improve the controllability of the wind turbine.

310

315

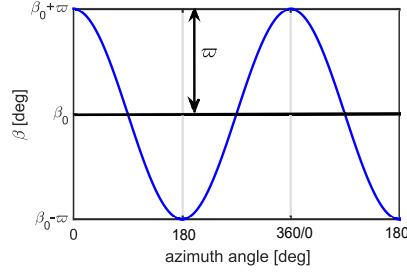


Figure 18: Pitch angle of a blade with respect to the azimuth angle when the lateral cyclic angle is ϖ .

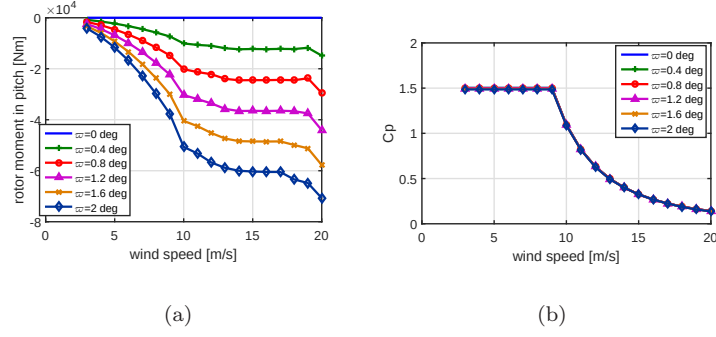


Figure 19: Rotor moment (a) and power coefficient (b) caused by the lateral cyclic angle of the swashplate.

5. Stochastic Dynamics Analysis

320 In this section, four operational cases and three survival cases are chosen to investigate the motion responses of the presented floating wind turbine. The environmental conditions are presented in Table 7. This study is limited to pure operational and survival conditions, and the transient conditions and fault load cases are not taken into account.

The simulation time is set as 2000 s and the sampling period is 0.2 ms. The

Table 7: Environment conditions for dynamic analysis

	operating cases				parked cases		
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
$u_\infty(z_h)$ [m/s]	6	9	15	20	25	35	45
I_u [-]	0.24	0.19	0.16	0.14	0.14	0.13	0.12
H_s [m]	1.00	2.20	3.2	4.0	6.0	8.2	10.5
T_z [s]	6.20	9.5	10.0	10.9	11.3	12.5	13.6

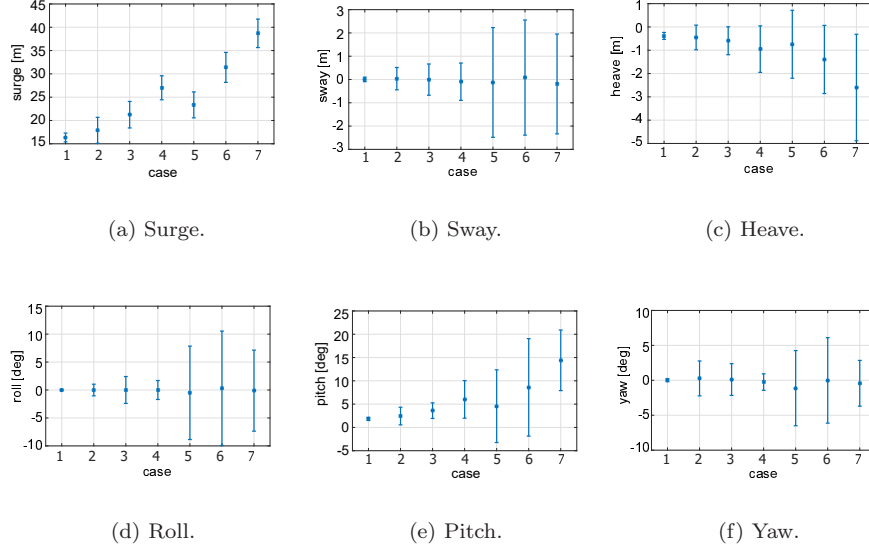
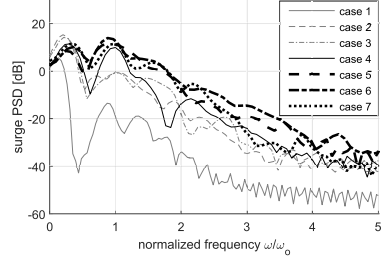


Figure 20: Mean values and standard deviation of the floater motion.

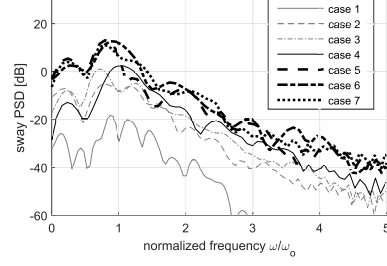
325 data of last 500 s are applied for analysis to avoid the effect of transient process.
 The mean values and standard deviations, and the power spectral density of
 the floater motion are shown in Figs. 20~21. The motion characteristics of the
 nacelle in pitch direction are shown in Fig. 22. Only the nacelle pitch motion is
 demonstrated here for the sake of brevity since the motion in other directions
 330 are restricted by the tower and can be estimated from the floater motion.

In operational cases, the floater motion are small because of not only the
 moderate waves but also the effects of the cyclic control of swashplate. Besides,
 owing to the large damping induced by the shroud, the floater motion in surge
 and yaw directions, and the nacelle motion in pitch direction are small even in
 335 survival cases. Note that in case 2, as the wind turbine operates at the rated
 condition and the sensitivity of the aerodynamic torque to pitch angle is very
 small, the pitch of the blades varies largely in order to maintain the power
 output under the wind turbulence and waves. However, the sensitivity of rotor
 thrust to pitch angle varies in a different way (shown in Fig. 7). The fluctuation
 340 of the rotor thrust deteriorates the pitch motion of the nacelle in case 2.

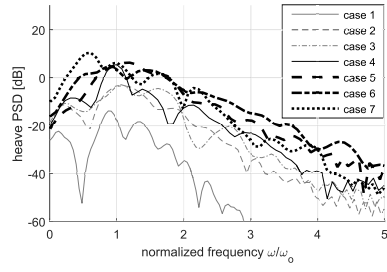
From Fig. 21 and Fig. 22(b), it can be observed that the dynamics of the
 floating wind turbine are dominated by the waves and the natural frequencies
 since the peaks of the power spectral density are in the wave frequency range
 (near $\omega/\omega_0 = 1$) and resonant frequency range (close to 0). In small/moderate
 345 environment conditions such as case 1 and case 2, both the resonant response
 and the wave-induced response have significant influence on the total dynamic
 response. In survival conditions, however, the dynamic motion of the system



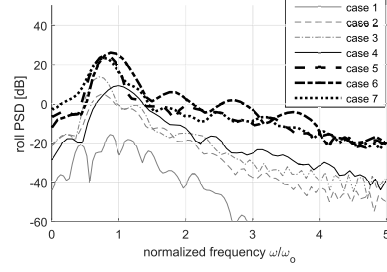
(a) Surge.



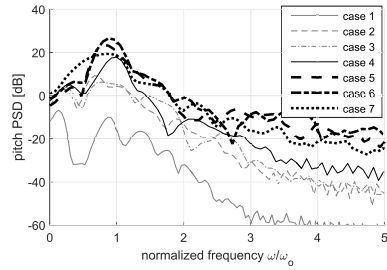
(b) Sway.



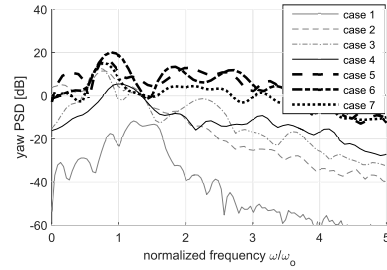
(c) Heave.



(d) Roll.



(e) Pitch.



(f) Yaw.

Figure 21: Power spectral density of the floater motion (Mean values are removed). The x -axis shows the frequencies normalized by the modal wave frequencies.

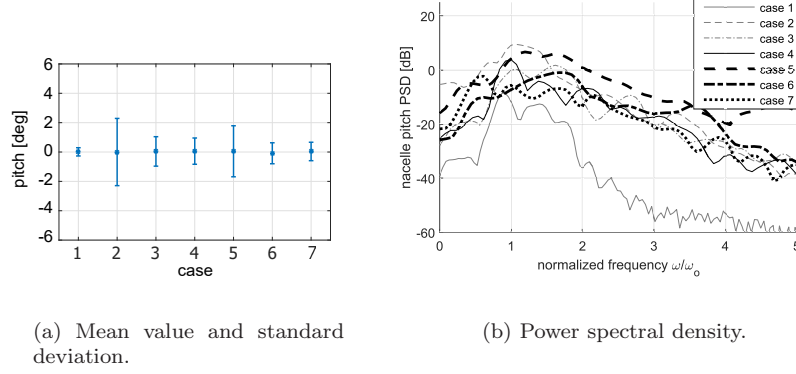


Figure 22: Motion properties of the pitch motion of the nacelle.

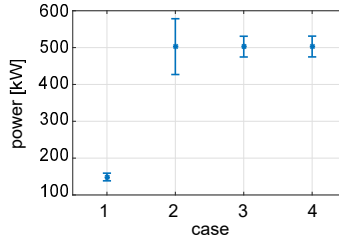


Figure 23: Mean values and stand deviations of the power under operational cases.

are dominated by the waves. It should be mentioned that resonant frequencies appear in the yaw motion of the floater due to the large restoring force induced by the shroud thrust. The resonant frequencies also play an important role in the yaw dynamic response.

The generated power in the operational cases is illustrated in Fig. 23. Because of the low sensitivity of the aerodynamics to the blade pitch, the power variation in case 2 is large compared to other cases. The standard deviations of all the four cases are within 15%.

The passive yawing system, which is important for the availability of the present system, is evaluated in the following. The cut-in wind speed is applied and the wind turbine is placed back to the wind, say, the initial yaw angle is set as 180 deg. The yaw motion of the nacelle is measured and plotted in Fig. 24. The wind turbine is not stable at its initial position and starts to swing at the beginning. The drag force on the shroud assists the floater to rotate back to the nominal orientation in 300 s. Therefore, the wind turbine is able to yaw to the wind direction automatically by the shroud with the self-stabilization feature.

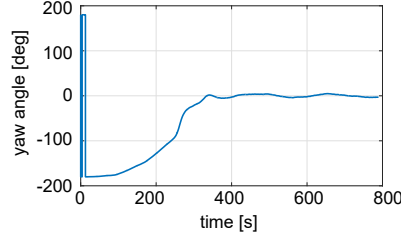


Figure 24: Yaw motion of the floater when wind flows from the opposite direction.

6. Conclusion

In this paper, the design aspects of a novel floating type shrouded wind turbine was presented, and a method of quick modeling and aero-hydro-servo integrated simulation were proposed for the static/dynamic analysis. From this study, it can be obtained that:

- The hinge structure between the tower and the nacelle can help on maintaining the nacelle to be horizontal even in large tower inclination. The wind drag on the rotor and shroud provides proper damping effect on the nacelle motion in roll, pitch and yaw.
- Since the mooring lines are connected far above the center of mass of the floating wind turbine and the mooring force points toward horizontal, restoring stability of the system is enhanced. The mooring system can help on reducing the size of floater.
- The passive yaw system is effective thanks to the slewing bearing set between the floater and the mooring cables and the self-stabilization property of the shroud. The settling time that the wind turbine rotates from the opposite position to the nominal orientation is about 300 s under the cut-in condition.

In addition, from the results of this analysis, several great attention should be paid for next optimized design stage:

- The specification of floater and tower is highly determined by the thrust on the shroud. Owing to the large shroud thrust in extreme wind conditions, large loads would apply on the supporting mechanical components, and therefore their material and strength have to be carefully designed.
- Both the resonant response and the wave-induced response have significant influence the system response in operational conditions. In survival cases, however, wave-induced response becomes domination. Optimal design of the floater to reduce the wave-induced response would be necessary. In addition, the resonant frequencies in pitch and yaw motion are highly dependent on the wind conditions, which is not a preferred situation. The

resonant frequencies have to be designed outside the wave frequencies with enough margin to avoid the resonance.

- The motion of wind turbine disturbs the power generation and decreases the power quality. Advanced controller design for collective blade pitch would be necessary. Besides, battery sets and super-capacitors would be required to help on smoothing the power output. In this case, the collaborative control between the wind turbine and the power conversion system is preferred.
- The nacelle can maintain its position in horizontal level even under large tower inclination. However, tower height should be large enough to prevent the shroud from water exposure.

In general, the studies performed in this paper provide an initial evaluation on the floating type shrouded wind turbines. More studies including the water tank test will be performed in future to investigate the nonlinear hydrodynamic/aerodynamic effects on the system.

References

- [1] IEA., Renewables 2017, <http://www.iea.org>, [accessed on 26/April/2018] (2017).
- [2] IEA., Technology roadmap: Wind energy-2013 edition, <http://www.iea.org>, [accessed on 26/April/2018] (2013).
- [3] M. Karimirad, C. Michailides, V-shaped semisubmersible offshore wind turbine: An alternative concept for offshore wind technology, *Renewable Energy* 83 (2015) 126–143.
- [4] J. Chen, Z. Hu, G. Liu, D. Wan, Coupled aero-hydro-servo-elastic methods for floating wind turbines, *Renewable Energy* 130 (2019) 139–153.
- [5] H. Kakuya, T. Shiraishi, S. Yoshida, T. Utsunomiya, I. Sato, Experimental results of floating platform vibration control with mode change function using full-scale spar-type floating offshore wind turbine, *Wind Engineering* 42 (3) (2018) 230–242.
- [6] <http://www.amsc.com>, [accessed on 18/June/2018] (2018).
- [7] G. Sieros, P. Chaviaropoulos, J. D. Sørensen, B. Bulder, P. Jamieson, Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy, *Wind energy* 15 (1) (2012) 3–17.
- [8] O. Igra, Research and development for shrouded wind turbines, *Energy Conversion and Management* 21 (1) (1981) 13–48.

- 430 [9] M. O. L. Hansen, N. N. Sørensen, R. Flay, Effect of placing a diffuser around a wind turbine, *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology* 3 (4) (2000) 207–213.
- [10] F. Bet, H. Grassmann, Upgrading conventional wind turbines, *Renewable Energy* 28 (1) (2003) 71–78.
- 435 [11] Y. Liu, S. Yoshida, An extension of the generalized actuator disc theory for aerodynamic analysis of the diffuser-augmented wind turbines, *Energy* 93 (2015) 1852–1859.
- [12] Y. Ohya, T. Karasudani, A shrouded wind turbine generating high output power with wind-lens technology, *Energies* 3 (4) (2010) 634–649.
- 440 [13] W.-X. Wang, T. Matsubara, J. Hu, S. Odahara, T. Nagai, T. Karasutani, Y. Ohya, Experimental investigation into the influence of the flanged diffuser on the dynamic behavior of cfrp blade of a shrouded wind turbine, *Renewable Energy* 78 (2015) 386–397.
- 445 [14] J. Bukala, K. Damaziak, H. R. Karimi, K. Kroszczynski, M. Krzeszowiec, J. Malachowski, Modern small wind turbine design solutions comparison in terms of estimated cost to energy output ratio, *Renewable Energy* 83 (2015) 1166–1173.
- [15] M. J. Werle, W. M. Presz, Ducted wind/water turbines and propellers revisited, *Journal of Propulsion and Power* 24 (5) (2008) 1146–1150.
- 450 [16] H. Zhu, M. Sueyoshi, C. Hu, S. Yoshida, Modelling and attitude control of a shrouded floating offshore wind turbine with hinged structure in extreme conditions, in: *Proceedings of the IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, San Diego, 2017.
- 455 [17] A. C. Aranake, V. K. Lakshminarayan, K. Duraisamy, Computational analysis of shrouded wind turbine configurations using a 3-dimensional rans solver, *Renewable Energy* 75 (2015) 818–832.
- [18] A. Aranake, K. Duraisamy, Aerodynamic optimization of shrouded wind turbines, *Wind Energy* 20 (5) (2017) 877–889.
- [19] M. Hepperle, *JavaFoil users guide* (2011).
- 460 [20] D. M. Somers, Design and experimental results for the s825 airfoil, Tech. rep., National Renewable Energy Lab., Golden, CO (United States) (2005).
- [21] T. Burton, N. Jenkins, D. Sharpe, E. Bossanyi, *Wind energy handbook*, John Wiley & Sons, 2011.
- 465 [22] F. Blaabjerg, M. Liserre, K. Ma, Power electronics converters for wind turbine systems, *IEEE Transactions on industry applications* 48 (2) (2012) 708–719.

- [23] Q. Li, Y. Kamada, T. Maeda, J. Murata, K. Iida, Y. Okumura, Fundamental study on aerodynamic force of floating offshore wind turbine with cyclic pitch mechanism, *Energy* 99 (2016) 20–31.
- 470 [24] S. Yamanaka, T. Hirai, Y. Nihei, A. Sou, Interaction between advanced spar and regular waves, in: ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers, 2017, pp. V006T05A024–V006T05A024.
- [25] C. Lee, J. Newman, WAMIT user manual, version 7.2, WAMIT, Inc., Chestnut Hill, MA.
- 475 [26] M. Karimirad, T. Moan, Wave-and wind-induced dynamic response of a spar-type offshore wind turbine, *Journal of waterway, port, coastal, and ocean engineering* 138 (1) (2011) 9–20.
- [27] T. I. Fossen, Handbook of marine craft hydrodynamics and motion control, John Wiley & Sons, Ltd, UK, 2011.
- 480 [28] T. Perez, T. Fossen, Identification of dynamic models of marine structures from frequency-domain data enforcing model structure and parameter constraints, Tech. rep., ARC Centre of Excellence for Complex Dynamic Systems and Control (2009).
- 485 [29] H. Zhu, C. Hu, Y. Liu, Optimum design of a passive suspension system of a semi-submersible for pitching reduction, *Journal of Dynamic Systems, Measurement, and Control* (2016) doi:10.1115/1.4033948.
- [30] S. A. Ning, A simple solution method for the blade element momentum equations with guaranteed convergence, *Wind Energy* 17 (9) (2014) 1327–1345.
- 490 [31] H. Glauert, Airplane propellers, in: *Aerodynamic theory*, Springer, 1935, pp. 169–360.
- [32] M. Yin, G. Li, M. Zhou, C. Zhao, Modeling of the wind turbine with a permanent magnet synchronous generator for integration, in: *Power Engineering Society General Meeting*, IEEE, 2007, pp. 1–6.
- 495 [33] H. Zhu, H. Fujimoto, Suppression of current quantization effects for precise current control of spmsm using dithering techniques and kalman filter, *Industrial Informatics*, *IEEE Transactions on* 10 (2) (2014) 1361–1371.
- [34] C. Nichita, D. Luca, B. Dakyo, E. Ceanga, Large band simulation of the wind speed for real time wind turbine simulators, *IEEE Transactions on energy conversion* 17 (4) (2002) 523–529.
- 500 [35] D. N. Veritas, Structural design of offshore units (wsd method), DNV Offshore Standard C 201.