Floating Wind Turbine Motion Suppression Using an Active Wave Energy Converter

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Abstract: This paper proposes a new concept of an actively-controlled wave energy converter for suppressing the pitch and roll motions of floating offshore wind turbines. The wave energy converter consists of several floating bodies that receive the wave energy, actuators that convert the wave energy into electrical energy and generate the mechanical forces, and rigid bars that connect the floating bodies and the wind turbine platform and deliver the actuator forces to the platform. The rotational torques that are required to minimize the platform pitch and roll motions are determined using a linear quadratic regulator. The torques determined in this manner are realized through the actuator forces that maximize the wave power capture as well. The performance of the proposed wave energy converter in simultaneously suppressing the platform pitch and roll motions and extracting the wave energy is validated through simulations.

Key words: Floating Wind Turbine, Wave Energy Converter, Platform Motion Suppression, Linear Quadratic Regulator, Power Capture Maximization.

1 Introduction

Development and improvement of the modern society, as well as the population growth, come with a continuously growing demand for energy[1]. Every automated process and improvement on the personal comfort require the utilization of energy. Due to concerns of climate changes, it is necessary to meet this growing energy demand through increased amounts of clean and renewable energy, such as solar and wind power, while decreasing the dependency on the traditional fossil fuel-based energy. A clean and sustainable energy source that is showing very fast growth in the last few decades is the wind energy[2]. Nowadays, wind turbines are seen everywhere.

A recent trend in wind energy sector is to build wind turbines and wind farms offshore, far from the coast. Such locations are suitable for wind energy harvesting due to various advantages. For example, the wind blowing over the ocean is stronger and steadier than the onshore wind[3]. Besides, offshore wind turbines will have much less, if any, visual and noise impact on human residents. Additionally, the energy is mostly needed in coastal areas where large cities are situated.

However, if a wind turbine is located at the deep water ocean, it needs to be placed on a floating platform[4], because it is not economically feasible to mount the turbine on the seabed. This platform requirement increases the cost of energy, due to the platform cost, the increased cost related to the difficulty in installation and maintenance, and the structural load increase during the operation in a harsh environment. Concerning the last point, it should be noted that when the wave hits the platform, the platform tends to oscillate, and this oscillation can cause premature fatigue in the turbine structure. Many strategies have been proposed to address this issue[5-7], but in general, it comes with some compromise on the wind energy capture. It would be better to have a mechanism to suppress the oscillatory motion of the floating platform without sacrificing the amount of wind energy that would be captured, and this is the motivation of the research in the present paper.

In the area of mechanical vibrations, it is a well-known and natural concept to attach passive vibration absorbers[8] to the vibrating objects to suppress their vibration. Although some previous work has attached small bodies to offshore wind turbines to suppress the platform vibration[9-13], none of these studies aim at maximizing the energy converted during the process. In general, this class of existing research merely tries to match the natural frequency of the floating body oscillation with the dominant wave period, and transfer the oscillation to the attached small bodies. On the other hand, the present work sees this platform oscillation as potentially additional energy to be harvested. For the vibration suppression of the platform and the collection of extra energy from the wave, a wave energy converter has to be attached to the wind turbine platform.

This paper proposes a new concept of an actively-controlled wave energy converter for suppressing the pitch and roll motions, to be attached to the floating offshore wind turbines. The proposed wave energy converter consists of several floating bodies that receive the wave energy, actuators that convert the wave energy into electrical energy and generate the mechanical forces, and rigid bars that connect the floating bodies with the wind turbine platform and deliver the actuator forces to the platform to suppress the platform vibrations. The rotational torques that minimize the platform pitch and roll motions are determined through a linear quadratic regulator. These rotational torques are realized by the actuator forces such that the wave power captured by the wave energy converter is maximized at each time instant. The performance of the proposed wave energy converter in simultaneously suppressing the platform pitch and roll motions and extracting the wave energy is validated through simulations with a realistic wave profile.

The paper is organized as follows. In Section 2, the proposed wave energy converter is explained in detail, and the control objectives for the wave energy converter are stated. To achieve the control objectives, Section 3 presents the feedback control structure and the controller design. The designed controller is validated by simulation studies in Section 4, where the platform vibration and the wave energy harvested amount are compared between the cases with and without the proposed wave energy converter.

2 WECs for Vibration Suppression of Offshore Platforms

Vibration of offshore platforms is a challenging issue that needs to be carefully taken into consideration. Such vibration is inevitable due to the lack of fixed points that are able to provide an external force to the platform. Especially, in the ocean with the water depth more than 50 meters, it is not feasible to make a rigid connection between the platform and the seabed.

For this reason, techniques to suppress platform vibration need to rely on the forces generated by the interaction with water or wind. In this study, extra floating bodies will be attached to the floating platform of the wind turbine in order to generate the external force from the wave. Once these floating bodies are subjected to the wave forces, they tend to oscillate vertically. This kinetic energy can be converted into electrical energy if these bodies are parts of a Wave Energy Converter (WEC) system.

In this section, the WEC proposed in this paper are presented in detail, with the delineation of the function of its components. The mechanism of how the WEC is used to suppress the angular vibration is described, with some layout suggestions of the floating bodies in the WEC system that is attached to the platform. Finally, the WEC system combined with a 5MW floating wind turbine is presented.

2.1 WEC System Description

This paper considers the WEC system depicted in Fig. 1. This WEC system mainly consists of three components: a rigid bar to be connected to the platform; an actuator that can work as a motor or an electrical energy generator; and the floating body.

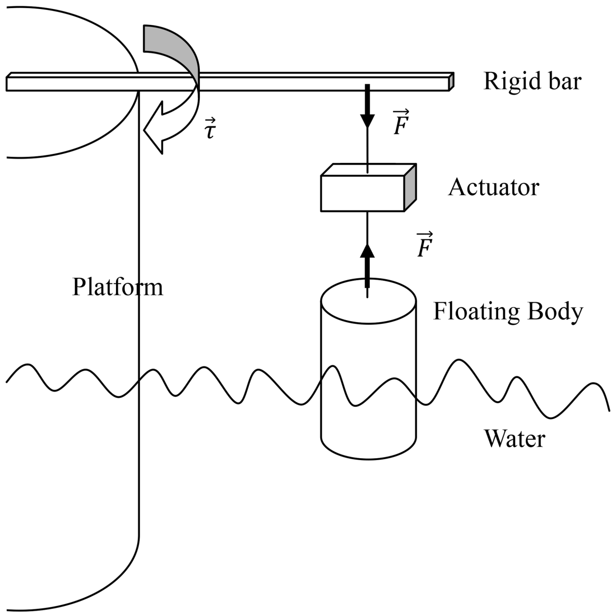

Fig. 1 WEC system.

2.1.1 Floating body

As shown in Fig. 1, the floating body is partially submerged in the water, and subjected to the action of waves. These waves excite the body and generate the vertical motion. The resulting kinetic energy can be converted into electrical energy by the actuator connected to it.

There is a secondary function of the floating body. Namely, the floating body is responsible for providing the external forces to the WEC system, and thus to the floating platform, due to its interaction with the water.

2.1.2 Actuator

The actuator, shown in Fig. 1 between the floating body and the rigid bar, is responsible for providing a force to both rigid bar and floating body. This actuator is a regular electric generator, which can also act as a motor. Depending on the direction of the force and the relative motion between the rigid bar and the floating body, the actuator will act as a motor or an electrical generator.

The actuator acts as a motor if the direction of the applied force is the same as the relative motion between the rigid bar and the floating body. This means that the actuator force "assists" the relative motion between the rigid bar and the floating body. If the actuator is acting as a motor, it consumes electrical energy and increases the kinetic energy of the other two components.

On the other hand, the actuator acts as an electrical generator when the applied force is in the opposite direction of the relative motion between the rigid bar and the floating body. This means that the actuator force "resists" the relative motion between the rigid bar and the floating body. If the actuator is acting as a generator, it harvests the energy by converting the kinetic energy into electrical energy.

2.1.3 Rigid bar

The rigid bar is the component of the WEC that transmits a torque to the platform from the actuator force. The rigid bar dimensions are important from the system design point of view. To generate a sufficient amount of torque to suppress the platform vibration, a short rigid bar would require a significant force from the actuator. Besides, if the rigid bar is short, the influence of the radiation wave from the oscillating floating body on the platform vibration becomes dominant. On the other hand, a long bar would require a small force from the actuator to generate the required torque for platform vibration suppression, but such a small force will make the generated energy small when the actuator acts as an electrical generator. Therefore, a careful trade-off has to be struck in designing the rigid bar length.

2.2 WEC Set for Platform Vibration Suppression

Vibration on the offshore platform can constitute different motions, such as the vibration on its structure due to flexibility, the translational movement, and the angular motion. The present study aims at suppressing the angular vibration of the platform; specifically, roll and pitch motions. This is because the angular vibration will cause fatigue loading on the tower of the wind turbine, especially the tower base. In addition, such angular vibration of the platform deteriorates the power capture of the wind turbine. Thus, the WEC attached to the platform is designed to provide torques in roll and pitch directions for vibration reduction.

2.2.1 Torque from an individual WEC

In order to provide the platform with the torque that is needed for its stabilization, the actuator interacts with the rigid bar, making a force that results in the specified torque. The actuator needs a support to provide this force. This support comes from the floating body.

The force acting on the floating body from the actuator is complemented by the other forces acting on the floating body, specifically, the gravitational force, the buoyancy and the wave force. The net force will result in acceleration or deceleration of the floating body. When the WEC system harvests energy, the floating body will decelerate because its kinetic energy will be converted into electrical energy.

2.2.2 Multiple WEC to suppress platform vibration

With the WEC structure in Fig. 1, a single WEC is just able to provide a torque in one single direction. Since we desire to suppress the angular motion in both roll and pitch directions, a minimum of two WECs should be attached to the platform.

The functions of the attached WEC system are not only to suppress the platform vibration, but also to convert wave energy into electrical energy as much as possible. In order to accomplish this second function, any WEC added after the second one will increase the degree of freedom that is available to choose each individual force in a way that the summation of all torques is able to suppress the angular motion and maximize the total energy converted by the actuators.

This study suggests that, for each side of the platform, two WECs are attached, one at each end of the platform side. In this way, the symmetry of the WEC structure will be preserved, making the WEC setup invariable with a frame rotation due to changes in wind or wave direction. Figure 2 exemplifies this concept for square and triangular platforms. The triangular platforms are commonly used and popular in the offshore wind energy sector.

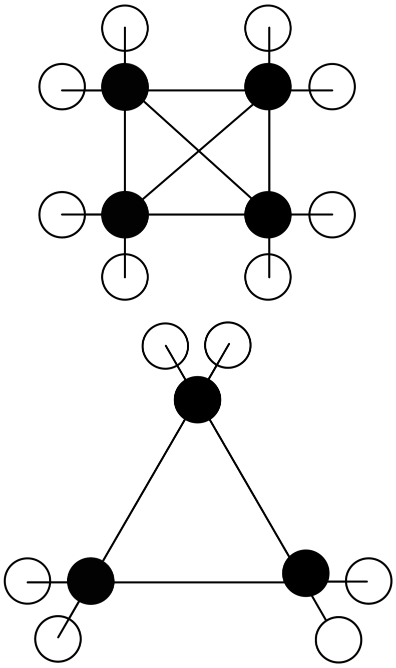

Fig. 2 Example of WEC attachment (Top view). Black disks and white disks indicate the platform columns and the WECs, respectively.

2.3 5MW Offshore Wind Turbine

The concept of attaching a set of WECs to the floating offshore wind turbine can be employed to suppress the vibration of floating platforms. This paper demonstrates the underlying concept with a semisubmersible platform that supports a utility-scale 5-megawatt wind turbine system, as illustrated in Fig. 3[14].

The virtual offshore wind turbine system in Fig. 3 was developed by the National Renewable Energy Laboratory (NREL) in the United States, and it is frequently used in offshore wind turbine control studies, with open source medium-fidelity simulation software developed by NREL called Fatigue, aerodynamics, structures and turbulence (FAST).

Six WECs will be attached to this platform (two in each column), as in the lower figure of Fig. 2. Those WECs will provide the torque that is required to suppress the angular movement of the platform.

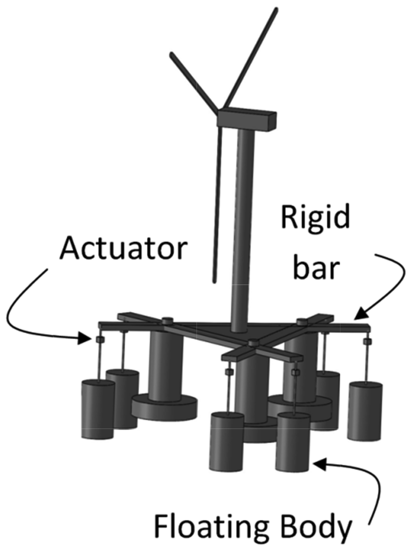

Fig. 3 5MW offshore wind turbine.

2.4 Control Objective

There are many features to be controlled in an offshore wind turbine, such as the nacelle yaw to follow the wind direction, the blade pitch angle to regulate the rotor speed over high wind speed region, and the generator torque to maximize the power capture below the rated wind speed region. Control methods for these control objectives have been thoroughly addressed in many wind turbines studies for both onshore and offshore applications[15].

The particular issue of floating offshore wind turbines that the present study addresses is the angular oscillation of the platform. The wind turbine nacelle is a heavy device located on top of a tall tower. Repeated angular motions can accelerate fatigue failure, increasing the cost of maintenance or worse, causing collapse. Based on that, the control goal of the present research can be divided into two separate objectives:

Objective 1 - Suppress the angular platform motion (pitch and roll) by attaching wave energy converters, which will be responsible for providing the external force that is needed to avoid these undesirable motions.

Objective 2 - Maximize the conversion of energy from the waves into electrical energy.

Some studies have used the WECs to stabilize the platform, but no study was found that maximized the wave energy conversion during platform stabilization. Those studies focused only on the suppression of the platform angular vibration.

These objectives are subjected to some constraints based on the nature of the actuators and the movement restriction of the floating bodies. These constraints are indicated below.

Constraint 1 - For four designed actuators, the applied force must be against the floating body velocity.

In order to maximize the energy conversion in the actuators from kinetic energy to electrical energy, four out of the six actuators will act strictly as generators. This means they will only apply forces on the floating body in the opposite direction of their motion. The other two actuators will be able to act as motors or generators in order to guarantee the required torques in pitch and roll directions.

Constraint 2 - A floating body cannot move more than half of its length, up or down.

This constraint is illustrated in Fig. 4, and comes from the motion limitation of the floating bodies. The turbulence caused by a cylinder emerging completely from the water or submerging its entire volume is a phenomenon that is difficult to model and analyze. In order to avoid this situation, the motion of each floating body will be constrained to half of its length, up or down, so that the floating body is always partially submerged.

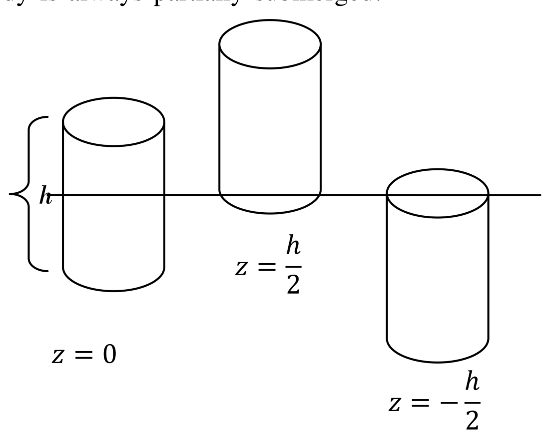

Fig. 4 Floating body motion constraint.

3 Controller Design

This section presents the feedback controller for the actuator in the WEC system described in Section 2, in order to suppress the platform vibration and to optimize the energy capture of the WEC system. First, the proposed controller structure is described, which consists of two sub-controllers. The first sub-controller is a linear quadratic regulator (LQR), which determines the torque signals that are required to minimize the platform vibration through the angular position and velocity feedback signals. To realize the torque signals calculated by the LQR controller in the most efficient manner, the second sub-controller, called the wave energy maximizer, determines the actuator forces that maximize the total captured wave power at each time instant.

3.1 Control Structure

The proposed control structure is illustrated in Fig. 5. Because reducing the angular motion of the platform is the main objective of the controller, an exclusive controller will be designed to comply with this objective, independent of the WEC's states or input. A linear quadratic regulator (LQR) will be designed to determine the amount of torque that is required to suppress the platform angular motion. In this paper, an LQR controller is utilized because it is advantageous to balance the platform vibration performance and the required torque input amplitude.

The needed torque will be carried to the secondary controller where the six forces from each of the actuators will be selected in order to satisfy the torque demand and maximize the energy conversion. This decision will be made by knowing the velocity of each one of the floating bodies.

Figure 5 shows a block diagram of the control structure. In this figure, F is a vector with the forces generated by the 6 actuators, z is a vector of the vertical positions of the 6 floating bodies, $\dot{z}$ is a vector of the vertical velocities of the floating bodies, θ and $\dot{\theta}$ are vectors of roll and pitch angles, and roll and pitch angular velocities, respectively, and τ is a vector of the x and y components of the total torque applied by the actuators on the platform.

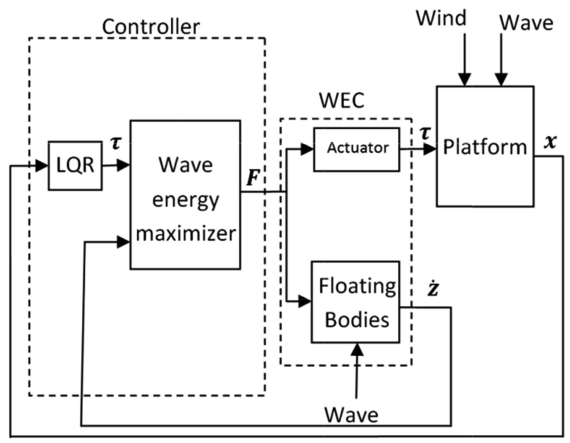

Fig. 5 Control structure block diagram.

3.2 LQR Design

A linear quadratic regulator is an infinite-horizon optimal controller that calculates the necessary input by feeding back the states of the system through constant gains, designed to minimize a cost function. The specific cost function is a weighted sum of the quadratic forms of the state vector and of the input vector. In order to design the LQR controller, it is necessary to model a relationship between states and the inputs (i.e., a dynamic model of the system). This relationship is given by the state equations:

$$\dot{x} = f(x, \tau) \tag{1}$$

where x is the state vector and u is the input vector. The detailed form of the function f is found in [17, 18].

In what follows, the signals in the state equations are detailed, and the LQR controller is designed based on the dynamic model.

3.2.1 States, Input and Disturbance

Because Objective 1 is to suppress the angular vibration of the platform, the states used in the LQR are the angles in roll and pitch and their angular velocities:

$$x = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \quad (2)$$

where θ_1 and $\dot{\theta}_1$ are the roll angle of the platform and its velocity, and θ_2 and $\dot{\theta}_2$ are the pitch angle of the platform and its velocity, respectively.

The input vector for the LQR consists of the torques in two directions,

$$\tau = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (3)$$

where τ_1 is the torque in the roll direction and τ_2 is the torque in the pitch direction.

The wind interaction with the turbine and the wave incident on the platform and the floating bodies are considered as unmeasurable disturbances. Although they are taken into consideration in the simulation study to validate the designed controller, they are not modeled for the controller design purpose.

3.2.2 Linearization

The LQR controller design requires a linear state space model. The relation $\dot{x} = f(x, \tau)$ will be linearized around an operating point (x_{op} and u_{op}) to get the linear state equation:

$$\dot{x} = Ax + B\tau , \quad (4)$$

where the matrices A and B are obtained by using the Jacobians of f:

$$A = \left.\frac{\partial f}{\partial x}\right|_{x = x_{op}} ; B = \left.\frac{\partial f}{\partial \tau}\right|_{\tau = \tau_{op}} \quad (5)$$

The operating point is selected as a steady state condition that corresponds to a selected wind speed.

3.2.3 LQR Formulation for the Linearized Model

TheLQR controller is designed such that it minimizes a cost function consisting of the integral of the weighted summation of squares of the states and inputs. These squares are weighted by the positive definite matrices Q and R. In this way, the cost function $J(u(\cdot))$, where $u(\cdot)$ is the selected input for each instant, is given by:

$$J(\tau(\cdot)) = \int_0^{\infty} x^T(t) Qx(t) + \tau^T(t) R\tau(t) dt \quad (6)$$

For a linear, time-invariant system, the input that minimizes the cost function is given in a state-feedback form as

$$\tau(t) = -Kx(t) \quad (7)$$

where the constant K is given by:

$$K = R^{-1} BTP . \quad (8)$$

here, the symmetric matrix P is the unique positive definite solution of the algebraic Riccati equation:

$$ATP + PA - PB R^{-1} BTP + Q = 0 \quad (9)$$

3.2.4 Selection Guidelines for Q and R

As stated before, the matrices Q and R are the weights of the states and the inputs in the cost function. Their matrix values depend on the priority in minimizing the state and the input values. For example, the larger the values of R in comparison to Q, the smaller will be the control input.

In this model, Q is selected as a 4-by-4 diagonal matrix where each diagonal element corresponds to each state. For example, the larger the element $Q_{1,1}$ is in comparison to the others, the controller will try to minimize the first state, which is the roll angle θ_1.

Because there is no preference between roll and pitch minimization, $Q_{1,1}$ and $Q_{2,2}$ are set to the same value. The objective of the LQR controller is to minimize the platform oscillation, not its velocity, and thus it will set $Q_{3,3} = Q_{4,4} = 0$. There is no advantage in minimizing the values of torques as long as they are not saturated. Therefore, R will be chosen as small values in comparison to Q.

3.3 Maximizing Energy Converted on WEC

The LQR controller will determine the torques required to suppress the angular vibration of the platform. These torques will be realized and provided by the six actuators located in each WEC. This setup gives the freedom to vary four out of the six actuators. This choice is intended to provide the most possible energy from the WEC, with the generation of the required torques.

3.3.1 Actuators Working as Generators

This freedom will be provided to four actuators. Their role in the system will be to maximize their own energy conversion. In other words, these actuators will convert the kinetic energy in the floating bodies into electrical energy. Hence, these actuators will only act as generators, producing their force only in the opposite direction to their respective relative velocity between the floating bodies and the rigid bars. This condition is given by Constraint 1:

$$F_i \dot{z}_i < 0 . \quad (10)$$

where $\dot{z}_i$ is the vertical relative velocity between i-th floating body and a rigid bar, and F_i is the force applied by the actuator on its respective floating body. Both are stipulated to be positive when pointing up.

3.3.2 Actuators Working as Generators and Motors

The two remaining actuators will generate the necessary forces to provide the total torques required by the LQR controller. Each WEC is located on the x-y plane (parallel to the water surface) at the coordinates (x_i, y_i). The torques provided by each WEC around x and y axes are given by:

$$\tau_{xi} = F'_i y_i \qquad \text{and} \qquad \tau_{yi} = -F'_i x_i \quad (11)$$

here, F'_i is the force applied by the actuator on the rigid bar, stipulated to be positive if it is pointing down. This force selection leads to the total torques provided by the six actuators as:

$$\tau = [yx]^T F' , \quad (12)$$

where x is the a column vector with the x-coordinates of the floating bodies and y is the a column vector with the y-coordinates of the floating bodies.

Defining the fifth and sixth WECs as the ones whose actuators also work as motors, these equations can be rewritten in a way that F'_5 and F'_6 are functions of the required torque and the other 4 forces:

$$F'_5 = \frac{x_6 \Delta\tau_x + y_6 \Delta\tau_y}{x_6 y_5 - x_5 y_6} \quad F'_6 = \frac{x_5 \Delta\tau_x + y_5 \Delta\tau_y}{x_5 y_6 - x_6 y_5} \quad (13)$$

where

$$\Delta\tau_x = \tau_x - \sum_{i=1}^{4} F'_i y_i \quad \Delta\tau_y = \tau_y + \sum_{i=1}^{4} F'_i x_i \quad (14)$$

The forces applied on the rigid body by the actuator (F'_i) are positive pointing down, in equations (11) to (14). Based on Newton´s third law, F'_i and F_i have the same magnitude but opposite directions. As F'_i is positive pointing down and F_i is pointing down, they have to be equal, and thus, from now on F'_i will be replaced by F_i.

3.3.3 Energy Maximization Method

The total power converted from the kinetic energy of the floating body into electrical energy is given by:

$$P = -F^T \dot{z} . \quad (15)$$

In order to select the force that maximizes this power, it is convenient to express power as a function of F_1, F_2, F_3 and F_4. Substituting the equations (13) into equation (15), the power can be expressed as

$$P = -\sum_{i=1}^{4} F_i \delta_i - \frac{x_6 \tau_x + y_6 \tau_y}{x_6 y_5 - x_5 y_6} \dot{z}_5 - \frac{x_5 \Delta\tau_x + y_5 \Delta\tau_y}{x_5 y_6 - x_6 y_5} \dot{z}_6 \quad (16)$$

where

$$\delta_i = \dot{z}_i - \frac{x_6 y_i - y_6 x_i}{x_6 y_5 - x_5 y_6} \dot{z}_5 - \frac{x_5 y_i - y_5 x_i}{x_5 y_6 - x_6 y_5} \dot{z}_6 . \quad (17)$$

The relationbetween F_1, F_2, F_3, F_4 and P is linear and independent, which means the values of F_1, F_2, F_3 and F_4 that maximize P must be on the limit of the allowed ranges. The maximum value of a force depends on the type of the actuator that is used. This value will be denoted by F_{max}. In this way, the possible value that maximizes the power for each force is F_{max} in the opposite direction to δ_i. Note that F_i also has to satisfy Constraint 1. That leads to the value of zero if $\dot{z}_i$ has the opposite sign of δ_i and F_{max} in the opposite direction of $\dot{z}_i$ if they have the same sign. To summarize, the force can be obtained by

$$\underset{F_i}{\operatorname{argmax}} P = \begin{cases} -sgn(\dot{z}_i) F_{max}, & if\ sgn(\dot{z}_i) = sgn(\delta_i) \\ 0, & otherwise \end{cases} . \quad (18)$$

4 Simulation Results

In order to demonstrate the efficiency of the designed controller, a simulation study is carried out and the angular vibration and the energy converted by the WECs are determined in Matlab/Simulink environment. In this section, details of the simulation settings, information on the simulation tool, and the simulation results are given.

4.1 Simulation Setting

4.1.1 Wind

The wind provided for the wind turbine is at the constant speed 18m/s[12]. Some studies utilize a more realistic wind information where its speed and direction change with time. That is required if those studies deal with the nacelle yaw control and the blade pitch control. In the present work, the wind is treated as an unknown disturbance, and its small variations do not considerably affect the roll and pitch motions.

4.1.2 Wave

Because of the role played by the wave in the present model, a realistic wave profile is used. An irregular wave is provided to the system. This irregular wave is designed as a sum of regular waves with different wave frequencies[19]. Each of those waves has a frequency (ω_i), an amplitude (A_i) and a random phase angle (φ_i). Significant wave height (H_s) and peak or modal frequency (ω_0) are the proprieties that characterize the irregular wave. Significant is the wave height defined by the mean value of the wave height (measured from trough to crest) of the one-third cycles with the highest wave height[20], while peak frequency is the frequency of the wave that carries more energy among the regular waves that compose the irregular wave. The wave height can easily be found in oceanography reports, and the peak frequency is related to the significant wave height by:

$$\omega_0 = 0.4 \sqrt{\frac{g}{H_s}} , \tag{19}$$

where g is the gravitational acceleration.

The elevation of the irregular wave is modeled as a sum of several regular waves. The frequencies of these regular waves are equally distributed between zero and a maximum frequency ($\omega_n \gg \omega_0$) with a difference of $\triangle\omega$. Each regular wave has the energy associated to its frequency ($S(\omega_i)$). The distribution of this energy among the frequencies is the spectrum. The spectrum model used in the present work is called the Pierson - Moskowitz[21] spectrum, and the energy distribution is given by

$$S(\omega_i) = \frac{\alpha g^2}{\omega_i^5} e^{-\beta\left(\frac{\omega_0}{\omega_i}\right)^4} , \tag{20}$$

where α and β are calibration constants of this empirical model ($\alpha = 0.0081$ and $\beta = 0.74$).

The phase of each wave is chosen randomly and the amplitude of each regular wave is given by:

$$A_i = \sqrt{2S(\omega_i)\triangle\omega} . \tag{21}$$

The elevation contribution of each wave (η_i) is given by[16]:

$$\eta_i(x,t) = A_i cos \left[\frac{\omega_i 2}{g}x + \omega_i t + \varphi_i\right] , \tag{22}$$

where x is the point coordinate in the axis that aligns with the wave propagation direction (same as wind direction) and t is the time from the beginning of the simulation. Finally, the observed wave elevation is given by the sum of the elevations of all regular waves:

$$\eta(x,t) = \sum_{i=1}^{n} \eta_i(x,t). \tag{23}$$

For the implementation, a significant wave height of 3.77m and its equivalent peak frequency of 0.64rad/s are selected. The profile of the wave at a specific instant is shown in Fig. 6. A sample of the wave profile for a particular point on time is given by Fig. 7.

4.2 Simulation Tool

The simulation is performed using the mathematical model developed at the Control Engineering Laboratory, the University of British Columbia[20, 21].

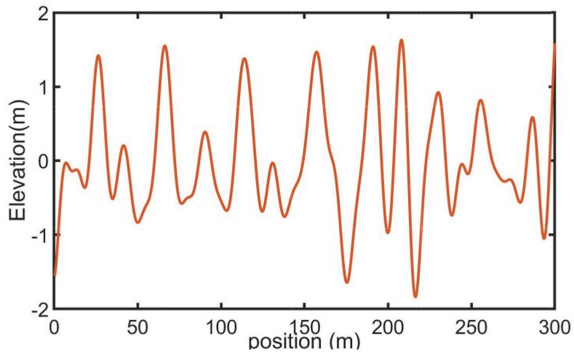

Fig. 6 Elevation as a function of position.

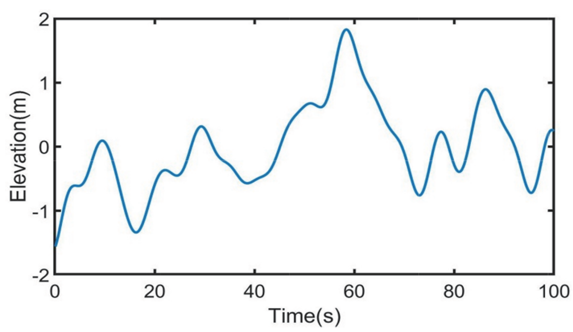

Fig. 7 Elevation as a function of time.

The most popular simulation tool for offshore wind turbines is called FAST (Fatigue, Aerodynamics, Structures, and Turbulence), an open-source simulator developed by National Renewable Energy Laboratory (NREL) in the United States, which has been validated on many wind turbines. Unfortunately, it would not be possible to use this tool in the present study, due to the complexity of the code modifications to incorporate the torque inputs; this will be considered in a future work.

The model utilized in the simulation study is validated on FAST in a rigorous manner. The results demonstrate that it is an accurate tool for predicting the major dynamics of an offshore wind turbine[18]. The fact that it is an open system allows the attachment of the six WECs, essential for the implementation of the method proposed in this present work.

Table 1 summarizes the parameters of the simulated disturbance and the dimensions of WEC components. This is the first proposed dimensions of the WEC system. Future studies will optimize these dimensions.

Table 1 Simulation Parameters.

	Propriety	Value
Wind	Speed	18m/s
Wave	Significant Height	3.77m
	Dominant Frequency	0.64rad/s
WEC	Rigid Bar Length	50m
	Floating Bodies Length	20m
	Floating Bodies Radius	12m
	Floating Bodies Mass	4.53x10^6kg

4.3 Control Parameters

The weighting parameters Q and R are selected to prioritize the suppression of the angular motion, without distinguishing roll from pitch ($Q_{1,1} = Q_{2,2}$). The angular velocity is not a concern ($Q_{3,3} = Q_{4,4} = 0$). Minimizing the input torque is not a priority ($r \ll Q_{1,1}$) where $R = r\, I_2$. The state-space parameters are normalized to achieve a better comparison between Q and R. After these considerations, the selected values for normalized Q and R are:

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},\ R = \begin{bmatrix} 0.02 & 0 \\ 0 & 0.02 \end{bmatrix} \quad (24)$$

For the wave energy converter maximizer, the only parameter to be selected would be the F_{max} for the four generators. This parameter is related mainly to the electrical generators to be used in the real application. The selection of these electrical generators is not in the scope of the present study. For the simulation purpose, a maximum force is selected that does not exceed one quarter of the floating body weight, in order to avoid high acceleration on the floating bodies and abrupt changes on the floating body motion.

4.4 Vibration Response

To check whether the first control objective is achieved, a comparison between the platform angular response for the open loop case and the controlled case is shown in Fig. 8. In the figure, "Open Loop" corresponds to the case when no WECs are attached to the platform, while "Feedback" corresponds to the case when the proposed WECs and control algorithm are applied. In Fig. 8, a considerable suppression of the angular vibration, in both pitch and roll motions, can be observed. This improvement will result in a significant increase of the life span of the wind turbine tower, thereby reducing the maintenance cost.

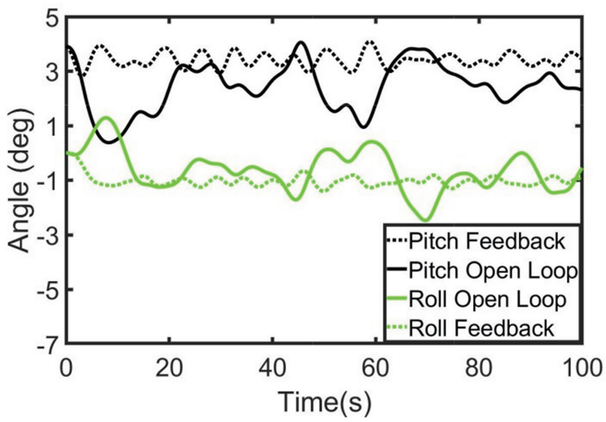

Fig. 8 Pitch and roll angular response comparing open loop and feedback control.

4.5 Energy Converted

An important benefit of utilizing the proposed WECs and control algorithm is the extra energy conversion, in addition to the wind energy harvested by the wind turbine. To evaluate this harvested additional energy, the power converted on the WECs is plotted in Fig. 9.

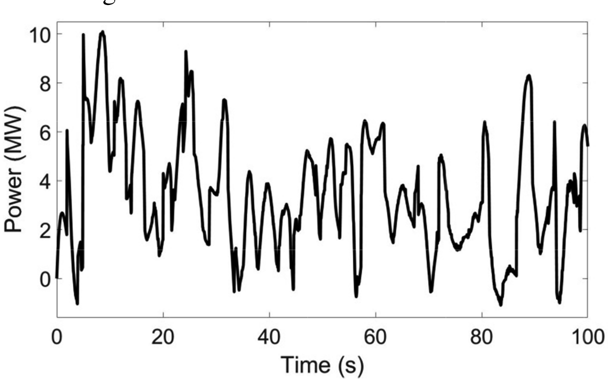

Fig. 9 Converted wave power.

The system shows a mean extra power production of about 3MW, which amounts to more than half of the wind turbine's nominal power (5MW). Another important aspect is that the power is positive most of the time during the simulation. This means that the designed WEC system produces energy while suppressing the platform vibration.

5 Conclusions

This paper proposed a new concept to suppress the platform vibration of a floating offshore wind turbine by attaching actively-controlled wave energy converters. The proposed wave energy converters consist of floating bodies and actuators. A method was proposed to control the actuators for the force generation, in order to decrease the platform motion while maximizing the conversion of the kinetic energy of the floating bodies into electrical energy. The simulation results demonstrated that the control objectives were achieved, in the sense that the angular vibration of the platform was significantly reduced, and at the same time, the energy converted on the WEC system was, on average, over half of the wind turbine production.

The future research will include the optimization on the WEC structure (such as the length of the rigid bar and the size of the floating bodies), the comparison with a passive spring damper system, which would also able to suppress vibration and convert energy, simulations with high fidelity software and small-scale experimental verification, and evaluation of the benefits of the present method on the life span of a floating offshore wind turbine.

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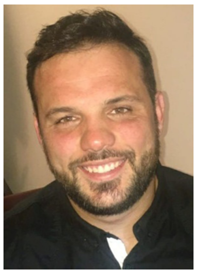

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