Theoretical and Applied Mechanics Letters 11 (2021) 100295

Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

journal homepage: www.elsevier.com/locate/taml

Letter

Platform motion minimization using model predictive control of a floating offshore wind turbine

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ARTICLE INFO

Article history:
Received 16 August 2021
Revised 8 September 2021
Accepted 9 September 2021
Available online 21 September 2021

Keywords:
Wind energy
Floating offshore wind turbine
Platform motion
Model predictive control

ABSTRACT

Wind turbines are installed offshore with the assistance of a floating platform to help meet the world's increasing energy needs. However, the incident wind and extra incident wave disturbances have an impact on the performance and operation of the floating offshore wind turbine (FOWT) in comparison to bottom-fixed wind turbines. In this paper, model predictive control (MPC) is utilized to overcome the limitation caused by platform motion. Due to the ease of control synthesis, the MPC is developed using a simplified model instead of high fidelity simulation model. The performance of the controller is verified in the presence of realistic wind and wave disturbances. The study demonstrates the effectiveness of MPC in reducing platform motions and rotor/generator speed regulation of FOWTs.

The vast majority of offshore wind energy potential is found in deep offshore areas with more than 60 m of water depths. Because of their exorbitant cost, traditional near-shore bottom-fixed wind turbines cannot be operated at deep-sea with a fixed bottom structure based on cost-benefit analysis [1,2]. Offshore wind turbines on a floating platform in deep-water seas are gaining global popularity owing to their prospective advantages of superior offshore wind power collection and low environmental effects. However, with the addition of the floating platform, further problems have emerged.

In comparison to bottom-fixed offshore wind turbines, floating offshore wind turbines (FOWTs) are prone to 6 degrees of platform motion, as illustrated in Fig. 1. Horizontal axis wind turbines are considered for this study; for vertical axis wind turbines readers may refer to Ref.[3]. Even if an FOWT is tied to the bottom of sea with mooring lines, incident waves together with wind would lead to a platform motion. These movements will affect the power generation, structural life, operation and maintenance of FOWT, thus a control mechanism becomes essential to reduce platform movements [4,5]. It was observed that an FOWT undergoes negative damping phenomena when operating at a wind speed greater than the rated wind speed region, called Region III [6,7]. In the case of FOWTs, this means that, compared to onshore turbines, the bandwidth of frequencies where the controller is useful is substantially reduced. Skaare et al. [7] observed this phenomenon while utilizing a controller borrowed from the traditional bottom-fixed wind turbines. Later, Jonkman et al. [8] utilized the detuned gains based on the gain scheduled algorithm; however, the controller was designed based on the single-input single-output (SISO) mechanism and missed out on the advantages offered by the multiple-input multiple-output (MIMO) controller.

Additionally, various MIMO control techniques are used to overcome FOWT's shortcomings that are exacerbated by the floating platform. Namik et al. utilized MIMO control techniques to address the FOWT's limitations, including the utilization of the individual blade pitch phenomenon blade pitch control mechanism in which blades are pitched individually, rather than collectively, as is the case with conventional collective blade pitch mechanisms [9,10]. Similarly, there are tuned-mass damper (TMD) based control algorithms used for the platform motion mitigation [11–13]. However, increased is cost and model complexity are significant issues to be addressed before consideration.

MIMO controllers generally provide improved performance in better rotor speed regulation, power generation, and platform motion suppression compared with the baseline FOWT controllers. However, these improvements fail to compete with the counterpart bottom-fixed wind turbines. One major drawback is that control algorithms are designed based on complex FOWT models such as fa-

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https://doi.org/10.1016/j.taml.2021.100295

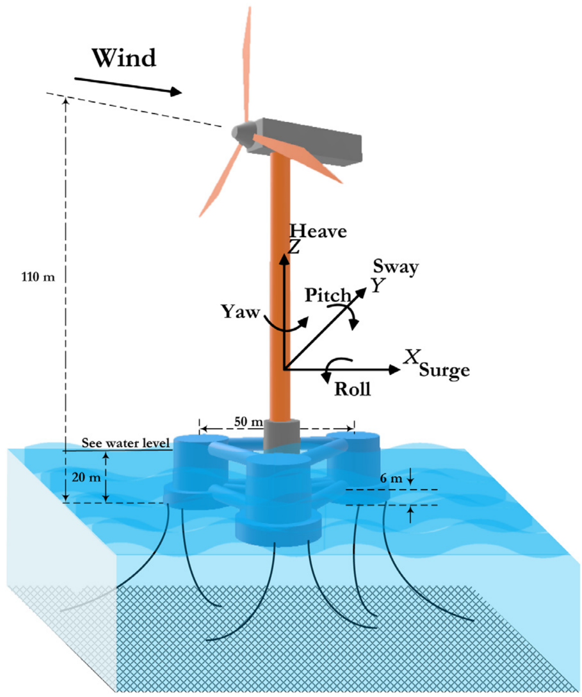


Fig. 1. Floating offshore wind turbine.

tigue, aerodynamics, structures, and turbulence (FAST) [14], which has 40/42 degree of freedoms (DOFs). A complex FOWT model may be reasonable for the load analysis but higher DOFs make the control synthesis complicated and prone to inadequate control design. Simplified designs of FOWT may solve this issue, where carefully chosen DOFs are considered to make control synthesis relatively easy without giving up essential system dynamics [15,16].

This paper proposes a state-feedback model-based predictive control (MPC) based on a nonlinear simplified 3D model [16] to minimize the platform oscillations and rotor/generator speed regulations. Linear state-space model is obtained based on the simplified nonlinear model at an operating point in Region III. A quadratic cost function-based MPC solver computes the output at every interval in the presence of incident and wave. Results are compared with the baseline traditional gain-scheduling proportional integral (GS-PI) [17] and a linear quadratic integral (LQI) controller using FAST.

We first provide a description of the baseline FOWT examined in this study and the simplified FOWT utilized for controller synthesis. Then, the details are given to formulating a linear state-space model based on a simplified nonlinear model used to devise MPC. A virtual utility-scale FOWT designed by National Renewable Energy Laboratory (NREL) is used in this paper for validation purposes, referred to as baseline wind turbine in the paper. The baseline wind turbine is supported by semi-submersible platform as shown in Fig. 1. The baseline FOWT is widely used for validation of newly designed control methods. Below is a brief introduction of the features of the baseline wind turbine related to the controller desgin.

The wind turbine under consideration is erected in the ocean based on a semi-submersible platform. The platform is made up of three stabilizing offset columns, whereas the tower is attached the main column in the center. The platform is anchored to the sea bottom using mooring lines.

The available input actuators ($\boldsymbol{u}$) for the wind turbine are:

$$\boldsymbol{uu} = [\beta, \tau_g, \gamma]^{\mathrm{T}}, \tag{1}$$

where β is the collective blade pitch angle, τ_g is the generator torque and γ is the nacelle yaw.

In this paper, the input vector $\boldsymbol{u}$ is used for the MPC control formulation and no additional actuators are considered in controller synthesis.

The FAST model has 40/42 DOFs, which leads to a complex wind turbine system from the perspective of control design. There is a need for simplified models for control design, simple enough to be used for control synthesis without compromising essential wind turbine dynamics. Therefore we refer to a simplified nonlinear 3D FOWT model that has been compared and validated using the FAST model for its usefulness for control synthesis [16]. We can describe the simplified nonlinear model by following expression.

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w}), \tag{2}$$

where x represents the states of the system states which includes the platform motion i.e., surge (X), sway (Y), heave (Z), roll (θ_x), pitch (θ_y), yaw (θ_z), their derivatives, rotor speed (ω_r), generator speed (ω_g) and elastic deformation of the gearbox transmission ($\Delta\theta$). $\boldsymbol{u}$ contains the input actuators, defined in Eq. (1), whereas $\boldsymbol{v}$ and $\boldsymbol{w}$ are incident wind and wave disturbances.

In order to design MPC, a linear state-space model is calculated by linearizing the nonlinear model Eq. (2) at an operating point $\boldsymbol{x}_0$ in Region III. We get the following linearized model,

$$\delta\dot{\boldsymbol{x}} = A\delta\boldsymbol{x} + B\delta\boldsymbol{u} + B_v\delta\boldsymbol{v} + B_w\delta\boldsymbol{w}, \tag{3}$$

here, the δ represents the deviation from the operating point.

Wind turbine control objectives vary based on wind speed which results in region dependent control strategies [4]. The scope of this paper is limited to the control of wind turbine operating in Region III. In Region III, control objectives include the rotor/generator speed regulation in the presence of excessive wind at minimal platform motions.

Generated power is regulated using ω_g based on following equation,

$$P = T_g \times \omega_g \times \eta, \tag{4}$$

here, T_g is the generator torque and η is the generator efficiency.

For the platform motion suppression, we have considered the surge (X), sway (Y), roll (θ_x) and pitch (θ_y) states.

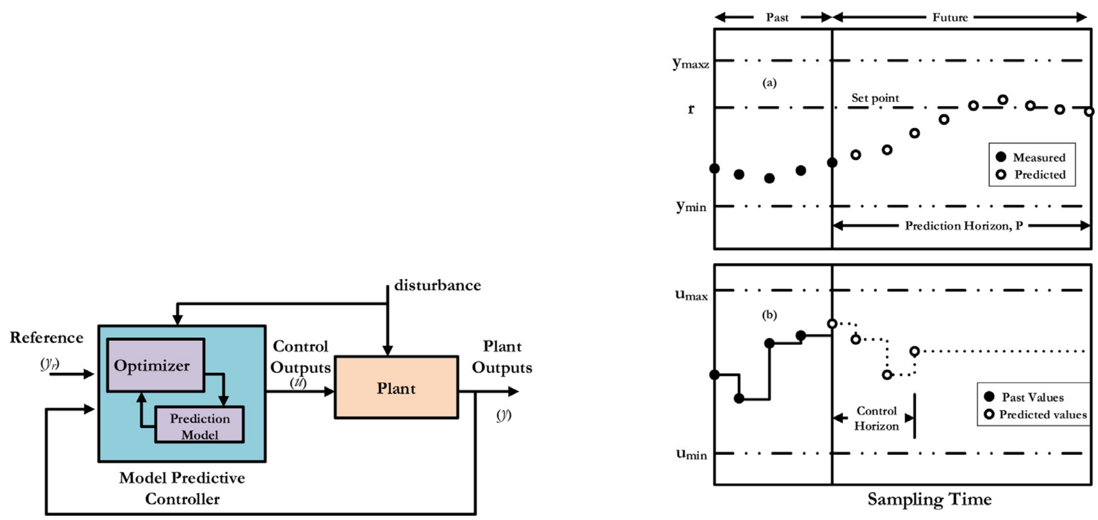
After discussing the baseline FOWT, simplified FOWT model and the procedure to linearize it, now we discuss the controllers that were developed for this research. To begin, we will quickly discuss the controllers with which MPC will be compared, namely the baseline controller and the linear quadratic integral (LQI) controller. Then, we provide an MPC controller based on a simplified FOWT model and demonstrate its application to the baseline wind turbine.

For validation, we utilized two controllers. The first is a gain-scheduled proportional-integral controller called the baseline controller that was taken from [8]. It is generally regarded as a reference controller for the purpose of comparing and validating newly developed FOWT controllers. The second controller is the LQI controller, which is a linear quadratic controller extension that is used to regulate system states and reduce output steady-state error [18]. The cost function to be minimized using LQI is given as,

$$J_{\mathrm{LQI}} = \int_0^\infty \left(\mathbf{z}^{\mathrm{T}} Q_{\mathrm{LQI}} \mathbf{z} + \mathbf{u}^{\mathrm{T}} R_{\mathrm{LQI}} \mathbf{u}\right) \mathrm{d}t, \tag{5}$$

here, Q_{LQI} and R_{LQI} are the diagonal weight matrices of augmented states and inputs. z and u are the augmented states and inputs of system.

MPC is a discrete-time control method in which the control action is computed at each step, rather than pre-calculated across the whole horizon [19]. The controller takes the current state of the systems as the starting state for the following interval and



(a) MPC generic system (b) MPC schematic

Fig. 2. Model predictive control.

calculates the next series of control inputs. MPC controllers have many significant advantages, including the incorporation of input-output actuator constraints into the control law, the avoidance of saturation and an excessive rate of change, which makes them a feasible option for multi-variable systems such as FOWT. In this paper, the MPC method is based on a linear wind turbine model at a given operating point. The suggested MPC for FOWT control is designed to reduce platform movements while regulating the generated power. The MPC control system is shown in Fig. 2a, where we have a tracking reference value y_r, u being the control input of FOWT, and y is the state-output.

In the discrete-time procedure to generate input, the system iteratively computes the system output over a prediction horizon (N_p). The control horizon (N_m) decides the length of the control input used to minimize the cost function at every step. The whole procedure of cost function minimization is shown in Fig. 2a. The following expression may be used to calculate the objective functions (J) for a N_p and N_m.

$$J = \sum_{k=i+1}^{i+N_p} \|Q[y_k - y_\mathrm{r}]\|^2 + \sum_{k=i}^{i+N_\mathrm{m}-1} \|R[u_k - u_{k-1}]\|^2, \tag{6}$$

subjected to the following of constraints:

$$\begin{cases} u_k = u_{i+N_M-1}, & \forall k = i+N_m, i+N_m+1, \ldots, i+N_p, \\ \mathbf{u}_\mathrm{min} \le u_k \le \mathbf{u}_\mathrm{max}, & \forall k = i, i+1, \ldots, i+N_m-1, \\ |(u_k - u_{k-1})/\Delta t| \le u_\mathrm{max}, & \forall k = i, i+1, \ldots, i+N_m-1, \\ \mathbf{y}_\mathrm{min} \le y_k \le \mathbf{y}_\mathrm{max}, & \forall k = i+1, i+2, \ldots, i+N_p. \end{cases} \tag{7}$$

here, Q relates to the state weight matrices and R contains input variable weights matrices. x_max, x_min, u_max and u_min are the saturation limits for states and inputs, as given in Ref [17].

We examine the performance of the proposed MPC controller. The MPC controller is validated on the nonlinear wind turbine simulator, FAST. For the sake of comparison, we have considered conventional baseline GS-PI and an LQI controller designed to aim at platform motions minimization and rotor/generator speed regulation. All the DOFs in FAST are kept active during these time series validation simulations.

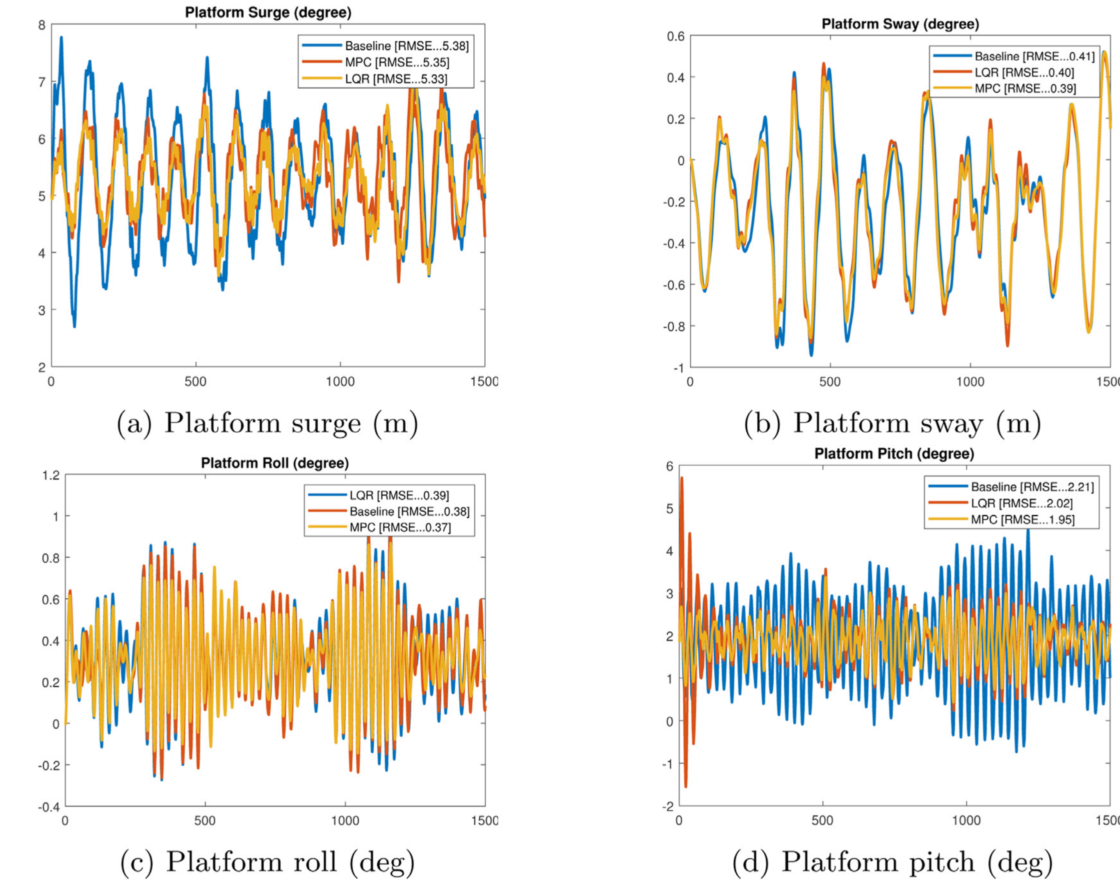
All the validation simulations are conducted using Open-FAST [20] integrated with Matlab/Simulink environment. The realistic turbulent input wind and irregular wave time-series are used for this study, refer to Table 1 for the metocean conditions. Incident turbulent wind is generated using TurbSim v2.00 [21], and incident irregular waves are produced using JONSWAP/Pierson-Moskowitz spectrum. The actuator constraints for input actuators such as blade pitch, generator torque, and yaw are considered according to Ref.[17].

The control objectives of MPC control method is to minimize the platform translatory motions (surge and sway), rotatory motions (roll and pitch), rotor and generator speed regulation while operating in Region III. The qualitative evaluation of these signals is achieved with the use root-mean-square error (RMSE) function. Respective RMSE values are provided in the legends in each figure. Figure 3a and 3b illustrate the time-domain simulation results of platform surge and sway motion of FOWT under the effect of incident wind and wave. While the baseline and LQI controllers have almost identical platform sway performance, the MPC controller has better surge motion performance. The comparison of platform roll and pitch motion of FOWT in the time domain simulation considering incident wind and wave is presented in Fig. 3c and 3d. It can be observed, that the MPC outnumbers the baseline and LQI in dealing with the platform pitch motion. However, these controllers have almost similar performance dealing with the roll the motion. The comparison of the generator and speed tracking in time domain simulations under the influence of incident wind and wave is illustrated in Fig. 4. MPC has a better performance in comparison with the baseline and LQI controller.

For floating offshore wind turbines, it is critical to mitigate platform movements in order to expand the lifespan and reduce the levelized cost of energy as compared to bottom-fixed wind turbines. In this article, we have presented platform stability and rotor/generator speed regulation strategy for a floating offshore wind turbine based on MPC. We have used baseline and LQI controllers for performance comparison. It was shown that MPC controller successfully reduces platform motions while regulating rotor/generator speed operating in Region III, compared to baseline PI and LQI control. Although the sway and roll motions have similar improvements for these controllers, the deviation is already small enough, and thus it has a minor impact on energy generation from unidirectional wind speed. Additionally, MPC cost function integrates the system's constraints into controller contrary to

Table 1
Met-ocean conditions.

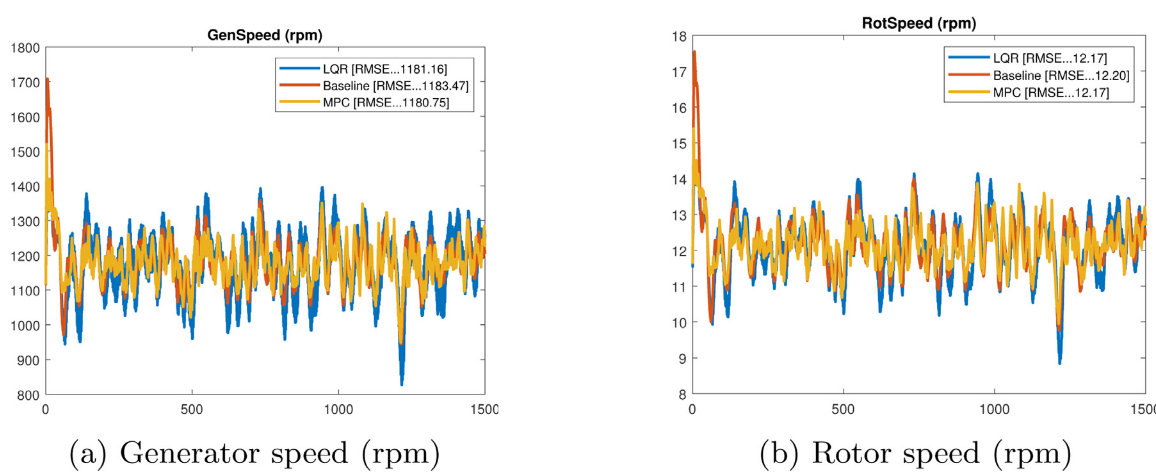
Average wind speed (m/s)	Significant wave height (m)	Peak spectral period (s)
18	1.2646	10



(a) Platform surge (m) (b) Platform sway (m)

(c) Platform roll (deg) (d) Platform pitch (deg)

Fig. 3. FOWT translatory and rotatory motion.



(a) Generator speed (rpm) (b) Rotor speed (rpm)

Fig. 4. FOWT generator and rotor speed regulation.

physical constraints imposed on the system while using baseline and LQI controllers. Our research focused on developing an MPC controller using a simplified FOWT model operating at a single operational point; the performance may be enhanced by constructing the MPC control over the entire Region III.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by Ministry of Science and Technology of China (No. 2017YFE0132000).

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