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A Study on Control of Wave Energy Converter for Motion Suppression of Semisubmersible

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Abstract: With the development of ocean energy exploration, reliable floating platforms with very small motion are expected to develop. For instance, the maximum pitching amplitude of a floater for floating offshore wind turbine is required to be less than a few degrees. On the other hand, ocean waves contain abundance of untapped renewable energy with very high power density. Integration of floating platform with wave energy converters while reducing the structure interaction becomes significant for offshore development. In this paper, control of wave energy converters on reducing the pitch motion of a floating platform is studied. Firstly, mathematical model of the whole system is proposed. The control of wave energy converters leads to solve a constrained optimization problem. Secondly, hybrid model predictive control is presented to synthesize the controller. Finally, numerical examples are given to verify the effectiveness of the proposed controller. It is shown that the reduction of pitch motion of the platform and the wave energy extraction are compatible.

Keywords: wave energy converter, floating platform, hybrid model predictive control, constrained optimization, pitching reduction

1. INTRODUCTION

A floating platform is a specialised marine vessel used in a number of offshore applications such as offshore drilling rigs and heavy lift cranes. As the development of offshore wind energy exploration, reliable and low cost floating platforms are increasingly required (Ishihara et al., 2007). Although the platforms are designed with good sea-keeping performance and good stability, environmental forces induced by wind, waves and ocean currents can, however, induce undesired heave and pitch motion, which would induce large external loads on structure and reduce the fatigue life of devices on the platforms (Henderson and Patel, 2003; Faltinsen, 1993). Suzuki and Sato (2007) have performed some pioneering work on investigating the effects of motion of floating platform on the strength of offshore wind turbine blades, and they come to the result that pitching with amplitude of 5 degrees will lead to a 50% increase of sectional modulus of a blade to avoid fatigue failure. Thus, anti-motion of the floating platform becomes a very important issue in many practical situations.

In the last decade there have been some floating platforms built for full scale experimentation like GustosMSC Tri-Floater (Huijs et al., 2013), WindFloat (Roddier et al., 2010), and the V-shape semi-submersible floater (Karimirad and Michailides, 2015). Most of them are designed with three or four rigidly-connected columns having a small waterplane area to decrease the effects of waves. Even by sophisticated analysis and design, Huijs et al. (2013) have reported that the maximum inclination of the floaters would also reach to 10 degrees according to model tests. In order to further reduce the motions, various methods and state-of-art structures were proposed in the literature. In (Aubault et al., 2006) and (Zhu et al., 2012), novel water-entrapment plates with large horizontal skirts were designed to increase the added-mass and viscous loads to semi-submersible platform. In the methods, the natural periods of the platform in heave, pitch and roll can be adjusted to avoid the resonance with the environmental forces. Though the water-entrapment plates can be systematically designed considering strength analysis and fatigue loads, the fabrication cost and maintenance, however, would limit its applications. In addition, Roddier and Cermelli (2013) have proposed an interesting concept of structure consisting of three column tubes which are partly filled with water. The water can be pumped between the three columns to balance out the environment forces so that the inclination of platform could be controlled. A major advantage of the concept is that the pitch motion can be controlled by pumping the water from some columns to the others. However, the response may be too slow to non-regular waves in addition to the requirement of external power supply.

On the other hand, ocean waves contain abundance of untapped energy with very high power density. Recent studies also put effort in combining wave energy converters (WEC) with floating offshore wind turbine (FOWT) for a better utilization of marine space and lower installa-

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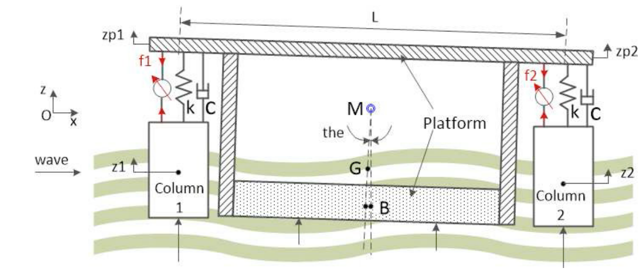

Fig. 1. Schematic of conceptual design.

tion cost owing to the shared electrical grid connections and mooring systems (Borg et al., 2013; Chandrasekaran et al., 2014; Perez et al., 2015). Though there are many advantages, the combination also introduces the inter-influence between WEC and FOWT that makes the whole system complex. Perez and Iglesias (2012) reported that particular attention should be paid to the wind turbine foundation affected by the installation of the WEC since the inclination of foundation may exceed the design limit.

In this paper, to overcome the negative effect of WEC on floating platform, we propose a control law to control the power take-off devices based on the relative motion between the WECs and the platform. Assumed small-amplitude motions, the whole system is linearized to formulate a state-space model. The control on power take-off devices leads to solve a constrained optimization problem. Hybrid model predictive control method is then presented to reduce the pitch motion of the platform while maintaining the passivity of the power take-off devices.

The remainder of this paper is organized as follows. In section 2, the conceptual design of a semi-submersible platform with WECs is introduced. Section 3 the mathematical model of the system and the problem description are presented. Then, hybrid model predictive control for anti-motion of the platform is proposed in section 4. Some numerical examples are finally given in section 5 to demonstrate the effectiveness of the proposed method.

2. SYSTEM DESCRIPTION

The conceptual design of a combined system consisting of a semi-submersible and wave energy converters is shown in Fig. 1. As the first step of the research, a two-dimensional model which is bilaterally symmetric is considered. For simplicity, the mooring system is also disregarded. The semi-submersible is supported both by the pontoon via the pillars and by the vertical columns (work as WEC). The amplitude of motion is assumed to be small and there is enough space between the columns and the semi-submersible to avoid the mechanical crash within the components. In the figure, L is the distance between the two columns, z_1 and z_2 are the displacements of column 1 and column 2, θ is the pitching angle of the main body, and z_{p_1} and z_{p_2} are the displacement of the platform in vertical direction at the ends. The dampers c and the springs k are used to model the mechanical components connecting the platform and WECs. The power take-off devices are supposed to be adjustable, and the resulting counteracting forces are denoted as f_1 and f_2, respectively.

Usually, a power take-off device is represented by a linear spring-damper system (Borg et al., 2013; Zhu et al., 2016). The coefficients of the spring and the damper are chosen to avoid the natural period of floating platform matching the dominant period of the incident waves. However, if the incident waves deviate from the design conditions, motion of the floating platform would be amplified by the WECs. In the following sections, a method is proposed to actively control the power take-off devices to regulate the pitch motion of platform.

3. MATHEMATICAL MODEL AND PROBLEM FORMULATION

3.1 Mathematical Model

Assuming small motions and denoting the displaced motion as $\xi \triangleq [z_1,\, z_2,\, \theta]^T$, the dynamics of the system can be expressed as (Zhu et al., 2016)

$$(\mathbf{M}+\mathbf{A}_\infty)\ddot{\xi} + \mathbf{K} * \dot{\xi} + \mathbf{\Lambda}\dot{\xi} + \mathbf{G}\xi = \tau_{\text{exc}} + \mathbf{\Delta f}, \quad (1)$$

where $\tau_{\text{exc}} \in \mathcal{R}^3$ is the excitation forces due to the incoming waves and wind, $\mathbf{f} = [f_1,\, f_2]^T$ is the adjustable forces generated by power take-off devices of WECs, $\mathbf{M} = \text{diag}(m_c, m_c, J_p)$ is generalized mass matrix, $\mathbf{A}_\infty = \text{diag}(m_\infty, m_\infty, J_\infty)$ is a constant positive-definite matrix called *infinite-frequency added mass*, the convolution term $(\mathbf{K}*\dot{\xi})(t) = \int_0^t \mathbf{K}(t-t')\dot{\xi}(t')dt'$ is *fluid-memory model* that $\mathbf{K}(t)$ represents the matrix of retardation. The matrices $\mathbf{\Lambda}$, $\mathbf{G}$, $\mathbf{\Delta}$ are given as

$$\mathbf{\Lambda} = \begin{bmatrix} c & 0 & -\frac{L}{2}c \\ 0 & c & \frac{L}{2}c \\ -\frac{L}{2}c & \frac{L}{2}c & \frac{L^2}{2}c \end{bmatrix}, \; \mathbf{\Delta} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ \frac{L}{2} & -\frac{L}{2} \end{bmatrix},$$

$$\mathbf{G} = \begin{bmatrix} \rho g S + k & 0 & -\frac{L}{2}k \\ 0 & \rho g S + k & \frac{L}{2}k \\ -\frac{L}{2}k & \frac{L}{2}k & \rho g V \overline{\text{GM}} + \frac{L^2}{2}k \end{bmatrix},$$

where ρ is the density of water, g the gravitational acceleration, S the waterplane area of the column, V the displaced volume of water and $\overline{\text{GM}}$ the meta-centric height. In this study, the excitation force τ_{exc} are regarded as a disturbance that can be modeled by

$$\dot{\mathbf{x}}_\tau(t) = \mathbf{\Gamma}\mathbf{x}_\tau(t), \quad (2a)$$
$$\tau_{\text{exc}}(t) = \mathbf{\Pi}\mathbf{x}_\tau(t), \quad (2b)$$

where $\mathbf{x}_\tau \in \mathcal{R}^p$ is the excitation force state, $\mathbf{\Gamma}$ and $\mathbf{\Pi}$ are real matrices with suitable dimensions. Note that step and/or periodic disturbances can be represented by (2).

Note that the pitch motion of the columns as well as the heave motion of the platform is not considered in the models expressed by (1). In practical case, the columns should be designed with high restoring capability in pitch direction while keeping the pitch natural frequency far away from the wave band. Besides, the hydrodynamic horizontal forces on the columns and their effect on the pitch motion of the platform are ignored since the arm of force of the horizontal forces is usually small compared to that of the vertical forces. If this is not the case, pitch motion equations of the columns should also be considered in the models.

Owing to the causality, the fluid-memory model can be approximated by a linear subsystem

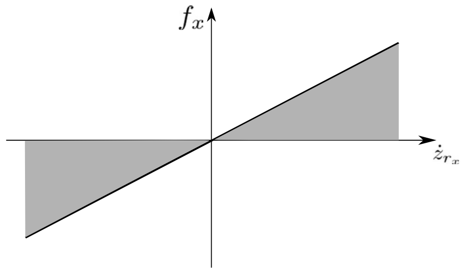

Fig. 2. Adjustable forces are only available in the shadow area expressed by conditions (6) and (7).

$$\dot{\mathbf{x}}_r(t) = \mathbf{A}_r\mathbf{x}_r(t) + \mathbf{B}_r\dot{\xi}(t) \tag{3a}$$
$$(\mathbf{K} * \dot{\xi})(t) = \mathbf{C}_r\mathbf{x}_r(t), \tag{3b}$$

where $\mathbf{x}_r \in \mathcal{R}^n$ is the state vector, the matrices $\mathbf{A}_r$, $\mathbf{B}_r$ and $\mathbf{C}_r$ are system matrices which can be obtained from theory or experiments by system identification. A comprehensive understanding can be referred to (Perez and Fossen, 2009a).

Introducing a new state $\mathbf{x} = [\xi^T, \dot{\xi}^T, \mathbf{x}_r^T, \mathbf{x}_\tau^T]^T$, models (1), (2) and (3) can be integrated by

$$\dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,\mathbf{f}(t) \tag{4}$$

with

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{3\times3} & \mathbf{I}_3 & \mathbf{0}_{3\times n} & \mathbf{0}_{3\times p} \\ -\mathbf{M}_a^{-1}\mathbf{G} & -\mathbf{M}_a^{-1}\boldsymbol{\Lambda} & -\mathbf{M}_a^{-1}\mathbf{C_r} & \mathbf{M}_a^{-1}\boldsymbol{\Pi} \\ \mathbf{0}_{n\times3} & \mathbf{B}_r & \mathbf{A}_r & \mathbf{0}_{n\times p} \\ \mathbf{0}_{p\times3} & \mathbf{0}_{p\times3} & \mathbf{0}_{p\times n} & \boldsymbol{\Gamma} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{0}_{3\times2} \\ \mathbf{M}_a^{-1}\boldsymbol{\Delta} \\ \mathbf{0}_{n\times2} \\ \mathbf{0}_{p\times2} \end{bmatrix}.$$

Here $\mathbf{0}_{i\times j}$ is zeros matrix with size of $i\times j$, $\mathbf{I}_l$ is unit matrix with size of l. The term $\mathbf{M}_a$ represents $(\mathbf{M}+\mathbf{A}_\infty)$. For discrete-time implementation with fixed sampling period T_s, system equation (4) can be written as

$$\mathbf{x}(k+1) = \mathbf{A}_d\mathbf{x}(k) + \mathbf{B}_d\mathbf{f}(k), \tag{5}$$

where k is the discrete-time index, $\mathbf{A}_d = e^{\mathbf{A}T_s}$, $\mathbf{B}_d = \int_0^{T_s} e^{\mathbf{A}(T_s-t)}\mathbf{B}dt$.

3.2 Constrained Optimization Problem

For conserving the passivity of the power take-off devices, the following constraints

$$\begin{cases} f_1\dot{z}_{r_1} \geq 0, \\ f_2\dot{z}_{r_2} \geq 0, \end{cases} \tag{6}$$

where $z_{r_1} = z_x - z_{p_x}$ ($x = 1$ or 2), have to be imposed on the model (4). From practical situations, the maximum forces would be limited and proportional to the motion velocities. For simplicity, the following constraints

$$\begin{cases} |f_1| \leq d_c|\dot{z}_{r_1}|, \\ |f_2| \leq d_c|\dot{z}_{r_2}|, \end{cases} \tag{7}$$

where d_c is a constant coefficient, are applied in our study. The force domain determined by (6) and (7) is shown in Fig. 2.

The objective of our problem is to control the constrained adjustable forces $\mathbf{f}$ to minimize the pitch motion of the platform defined as

$$J = \int \left(q_1\theta^2 + q_2\dot{\theta}^2 + r(f_1^2+f_2^2)\right)dt$$
$$= \int (\mathbf{x}^T\mathbf{Q}\mathbf{x} + \mathbf{f}^T\mathbf{R}\mathbf{f})dt \tag{8}$$

with $Q = \text{diag}(0,\,0,\,q_1,\,0,\,0,\,q_2,\,\mathbf{0}_{1\times n})$ and $R = \text{diag}(r,\,r)$. Performance index (8) is a combination of the Euclidean norm of pitching displacement and velocity, and adjustable inputs. The parameters q_1, q_2 and r are weighting factors. In the next section, we will show that the linear system (4) under constraints (6) and (7) can be modelled within the framework of the mixed logical dynamical (MLD) systems.

4. HYBRID MODEL PREDICTIVE CONTROL

4.1 Hybrid Dynamical Model

According to Giorgetti et al. (2007), the passive conditions (6) can be translated into a set of thresholds and logic conditions by introducing binary variables $\delta_{\dot{z}_x}$, δ_{f_x} ($x = 1$ or 2) such that

$$[\delta_{\dot{z}_x} = 1] \leftrightarrow [\dot{z}_{r_x} \leq 0], \tag{9a}$$
$$[\delta_{f_x} = 1] \leftrightarrow [f_x \leq 0], \tag{9b}$$
$$[\delta_{\dot{z}_x} = 1] \rightarrow [\delta_{f_x} = 1], \tag{9c}$$
$$[\delta_{\dot{z}_x} = 0] \rightarrow [\delta_{f_x} = 0], \tag{9d}$$

where '↔' means 'if and only if' and '→' means 'implies', see for comprehensive understanding. Besides, the conditions (7) can be rewritten as

$$\sigma_1 = \begin{cases} f_1 - d_c\dot{z}_{r_1} & \text{if } \dot{z}_{r_1} \leq 0 \\ -f_1 + d_c\dot{z}_{r_1} & \text{otherwise.} \end{cases} \tag{10a}$$

$$\sigma_2 = \begin{cases} f_2 - d_c\dot{z}_{r_2} & \text{if } \dot{z}_{r_2} \leq 0 \\ -f_2 + d_c\dot{z}_{r_2} & \text{otherwise.} \end{cases} \tag{10b}$$

where $\sigma_x \in \mathcal{R}$ ($x = 1$ or 2) are auxiliary continuous variables on which

$$\sigma_x \geq 0. \tag{10c}$$

System (5) with the constraints (9) and (10) can be modelled as a hybrid system using the hybrid systems description language (HYSDEL) developed in . The HYSDEL compiler translates differences equations and constraints into the MLD system

$$\mathbf{x}(k+1) = \mathbf{A}_d\mathbf{x}(k) + \mathbf{B}_d\mathbf{f}(k) + \mathbf{B}_\delta\boldsymbol{\delta}(k) + \mathbf{B}_\sigma\boldsymbol{\sigma}(k), \tag{11a}$$
$$\mathbf{E}_\delta\boldsymbol{\delta}(k) + \mathbf{E}_\sigma\boldsymbol{\sigma}(k) \leq \mathbf{E}_f\mathbf{f}(k) + \mathbf{E}_x\mathbf{x}(k) + \mathbf{E}_0. \tag{11b}$$

In our case, $\boldsymbol{\delta} = [\delta_{\dot{z}_1},\ \delta_{\dot{z}_2},\ \delta_{f_1},\ \delta_{f_2}]^T \in \{0,1\}^4$ and the continuous vector is $\boldsymbol{\sigma} = [\sigma_1,\ \sigma_2]^T \in \mathcal{R}^2$.

4.2 Model Predictive Control

In model predictive control (MPC), minimizing the cost function (8) for the system (11) at each time step k is relaxed to the optimization problem

$$\min_{\eta}\ J(\eta,\mathbf{x}) \equiv \mathbf{x}_N^T\mathbf{P}\mathbf{x}_N + \sum_{s=1}^{N-1}\mathbf{x}_s^T\mathbf{Q}\mathbf{x}_s + \sum_{s=0}^{N-1}\mathbf{f}_s^T\mathbf{R}\mathbf{f}_s \tag{12}$$

$$\text{s.t.} \begin{cases} \mathbf{x}_{s+1} = \mathbf{A}_d\mathbf{x}_s + \mathbf{B}_d\mathbf{f}_s + \mathbf{B}_\delta\boldsymbol{\delta}_s + \mathbf{B}_\sigma\boldsymbol{\sigma}_s, \\ \mathbf{E}_\delta\boldsymbol{\delta}_s + \mathbf{E}_\sigma\boldsymbol{\sigma}_s \leq \mathbf{E}_f\mathbf{f}_s + \mathbf{E}_x\mathbf{x}_s + \mathbf{E}_0, \\ \mathbf{x}_0 = \mathbf{x}(k) \end{cases} \quad s \geq 0$$

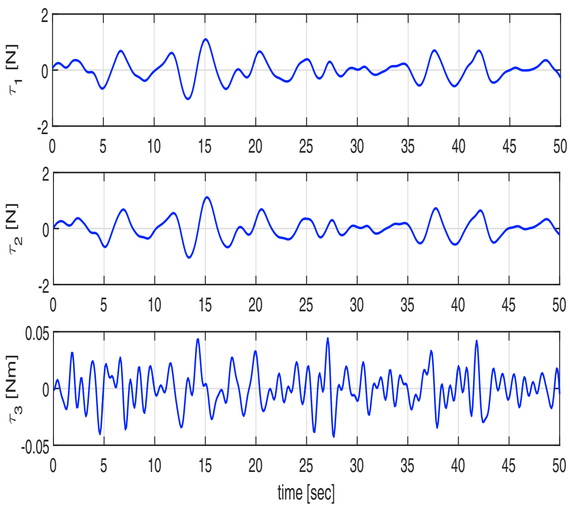

Fig. 3. Forces induced by the incident waves.

Table 1. Characteristics of floating platform

Property	Value
distance between columns [mm]	600
diameter of columns [mm]	100
thickness×width of pillar [mm×mm]	10×100
draft [mm]	170
mass of one column [kg]	1.0
mass of platform [kg]	5.385
moment of inertia of platform [kg·m^2	0.62
$Z_{\rm CoG}$ [mm]	-95
$Z_{\rm CoB}$ [mm]	-104
GM of main body [mm]	20
GM of system (rigidly connected) [mm]	225

where N is control horizon, $\eta \equiv [\mathbf{f}_0^T, \cdots, \mathbf{f}_{N-1}^T, \delta_0^T, \cdots, \delta_{N-1}^T, \sigma_0^T, \cdots, \sigma_{N-1}^T]^T$. The terminal weight $\mathbf{P}$ is defined as the solution of the Riccati equation

$$\mathbf{P} = \mathbf{A}_d^T\mathbf{P}\mathbf{A}_d - (\mathbf{A}_d^T\mathbf{P}\mathbf{B})(\mathbf{R} + \mathbf{B}_d^T\mathbf{P}\mathbf{B}_d)^{-1}(\mathbf{B}_d^T\mathbf{P}\mathbf{A}_d) + \mathbf{Q}. \quad (13)$$

In (12), a full measurement of the state $\mathbf{x}(k)$ at the current step k is required. For our case, state observer based on Kalman filter (Zhu and Fujimoto, 2014) can be adopted to obtain the current state.

According to the MPC control law, at time step k, the minimization (12) is solved to obtain the optimal solution $\eta^* = [\mathbf{f}_0^{*T}, \cdots, \mathbf{f}_{N-1}^{*T}, \delta_0^{*T}, \cdots, \delta_{N-1}^{*T}, \sigma_0^{*T}, \cdots, \sigma_{N-1}^{*T}]^T$, and the first move $\mathbf{f}_0^*$ is applied as the current control input

$$\mathbf{f}(k) = \mathbf{f}_0^* \quad (14)$$

to the system (5). Then, the minimization (12) is repeated at time step $k+1$ based on the new state $\mathbf{x}(k+1)$.

In the following, numerical simulation using a scaled down model is presented to verify the effectiveness of the Hybrid MPC method.

5. NUMERICAL EXAMPLES

Let us consider a conceptual model shown in Fig. 1. The characteristics of the system are summarized in Table 1, which is a 1:100 scale model. The parameters k and c are properly given as $k = 10$ N/m and $c = 0.1$ N·s/m, respectively. Hydrodynamic codes based on potential theory (Liu et al., 2015) are applied to compute the frequency-dependent added mass, the potential damping and wave excitation forces. Owing to the limitation of our research codes on calculating multibody structures, hydrodynamic interaction between the different bodies is neglected. Whilst the inclusion of the hydrodynamic interaction would affect the final results, the proposed method applied here would still be valid once the models is updated. The data are then applied to identify the fluid-memory model in (3) using the toolbox developed in (Perez and Fossen, 2009b).

In the setup, the sampling period is $T_s = 0.1$ s and the control horizon $N = 5$. The coefficient d_c in (7) is assigned by $d_c = 10$ N·s/m. Assuming the excitation forces are with no obvious change in the control horizon, $\tau_{\rm exc}$ is treated as a step disturbance so that $\mathbf{\Gamma}$ and $\mathbf{\Pi}$ in (2) are set as $\mathbf{\Gamma} = 0$ and $\mathbf{\Pi} = \mathbf{1}_{3\times1}$, respectively. By the conditions, the system has natural frequencies of 9.33 rad/s, 8.35 rad/s, 4.84 rad/s and 1.73 rad/s. The weight factors in (8) are set as $q_1 = 1$, $q_2 = 10$ and $r = 0.1$ where the pitching velocity is considered to be the highest priority.

Assuming the semi-submersible in this study is applied for non-fully developed sea with large depth, the modified Pierson-Moskowitz (MPM) Spectrum is applied to describe the sea state:

$$S(\omega) = \mathcal{A}\omega^{-5}\exp(-\mathcal{B}\omega^{-4}), \quad (15)$$

where $\mathcal{A}$ and $\mathcal{B}$ are parameters assigned by $\mathcal{A} = \frac{4\pi^3 H_s^2}{T_z^4}$, $\mathcal{B} = \frac{16\pi^3}{T_z^4}$ (H_s is the significant wave height and T_z is the average zero-crossing wave period). In this study, H_s and T_z are set as $H_s = 0.02$ m and $T_z = 3.55$ s so that the dominating wave period is $T = 4$ s. Note that the period is close to a natural period of the system. The induced excitation forces are shown in Fig. 3.

For comparison, the following three cases are considered:

- **Case 1**: Power take-off devices are inactive so that $\mathbf{f} = \mathbf{0}$;
- **Case 2**: Power take-off devices are represented by linear dampers having coefficient of d_c;
- **Case 3**: Power take-off devices are controlled by MPC.

The numerical results are shown in Figs. 4∼6. In Fig. 4, the comparison of pitch angles of the three cases are plotted. Their root-mean-square (RMS) values as well as the maximum values are concluded in Table. 2. It is observed that though the pitch motion can be remarkably reduced by power take-off devices working as linear damper, it can furthermore be reduced about 50% by MPC from the maximum pitching angle 0.72 deg to 0.36 deg. The relative velocities between the columns and the platform versus the corresponding control inputs are plotted in Fig. 5. From the figure, The forces and the relative velocities behave in the same directions so that the conditions (6) and (7) are guaranteed. Besides, the energy converted by power take-off devices are compared in Fig. 6. Owing to the control, the power take-off devices also decrease their capability of extracting wave energy. The trade-off between the pitching

Table 2. Comparison of pitching angles

Case	Case 1	Case 2	Case 3
$\theta_{\max}$ [deg]	5.07	0.72	0.34
θ_{RMS} [deg]	2.26	0.23	0.12

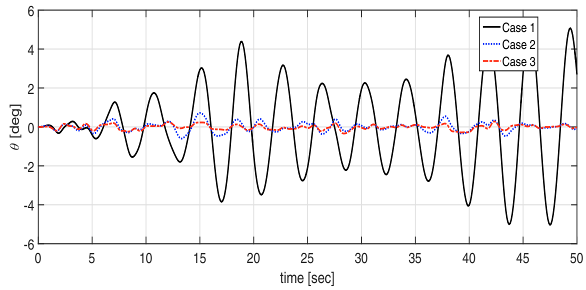

Fig. 4. Comparison of pitch motion.

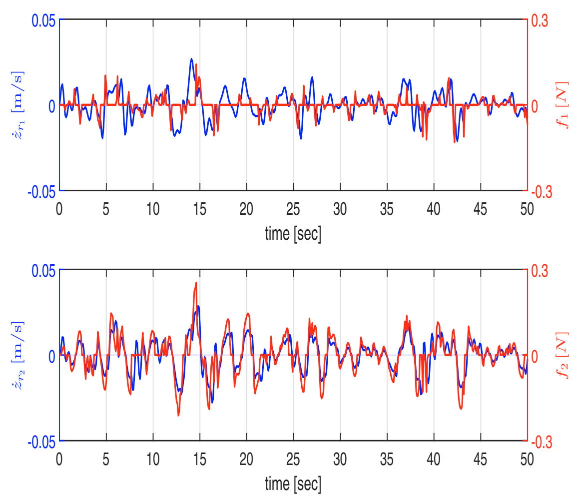

Fig. 5. Input generated by the controller.

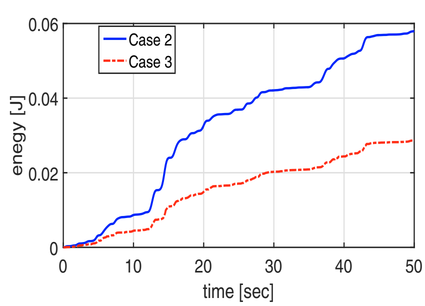

Fig. 6. Comparison of converted energy.

reduction of platform and the efficiency of WECs need be further studied.

6. CONCLUSION

This paper studied the control of a combined system consisting of a floating platform and wave energy converters. Wave energy converters are implemented to capture wave induced energy as well as to reduce the pitch motion of floating platform. The control was based on hybrid model predictive control method taking advantage of the dynamical system model which has the predictive ability. The numerical examples are given to confirm the effectiveness of the proposed controller. It is shown that the pitch motion of platform can be reduced by 50% when control is performed. In future work,the trade-off between the pitching reduction of platform and the efficiency of WECs will be studied. Besides, model test will be performed and the comparison with our numerical results will be given.

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