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IFAC-PapersOnLine 49-23 (2016) 380–385

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

Hongzhong Zhu * **Changhong Hu** **

* *Research and Education Center for Advanced Energy Materials, Devices, and Systems, Kyushu University, Kasuga 816-8580, Japan (e-mail: zhuhongzhong@riam.kyushu-u.ac.jp)*
** *Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan (e-mail: hu@riam.kyushu-u.ac.jp)*

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-

2405-8963
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.434

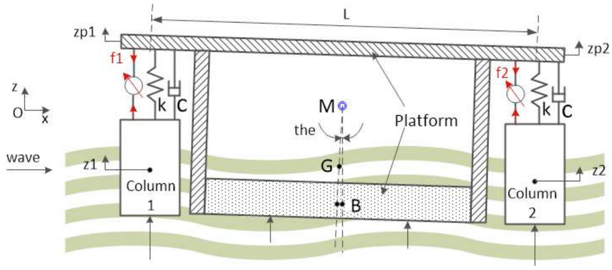

Fig. 1. Schematic of conceptual design.

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)

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

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 $\boldsymbol{\Lambda}$, $\mathbf{G}$, $\boldsymbol{\Delta}$ are given as

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

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

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

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

where $\mathbf{x}_\tau \in \mathcal{R}^p$ is the excitation force state, $\boldsymbol{\Gamma}$ and $\boldsymbol{\Pi}$ 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