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Discrete feedforward and feedback optimal tracking control for offshore steel jacket platforms

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ABSTRACT

This paper is concerned with discrete feedforward and feedback optimal tracking control schemes for an offshore steel jacket platform subject to irregular wave force. By discretizing a dynamic model of the offshore steel jacket platform system, a discrete feedforward and feedback optimal tracking controller is developed first to attenuate the wave-induced vibration of the offshore platform. Then, for the case of the offshore platform with control delays, a discrete feedforward and feedback optimal tracking controller with memory is presented. The controllers can be designed by solving an algebraic Riccati equation and a Stein equation, respectively. It is found through simulation results that compared with the classic state feedback optimal tracking control schemes, the proposed control schemes are more efficient in attenuating the vibration of the offshore platform. In addition, compared with the feedforward and feedback optimal control schemes, the proposed control schemes require less control cost.

1. Introduction

In ocean engineering, offshore steel jacket platform plays an important role in oil and gas exploration, drilling operations and transportation in ocean environment. As is well known, the offshore platform is generally exposed to various loads, such as earthquake, wave, and current (Patel, 1989; Abdel-Rohman, 1996). In the last few decades, the active control for the offshore platform subject to earthquake, ice and wave force has been received considerable attention and much effort has been devoted to the development of control schemes. For example, to reduce the oscillation amplitudes of the offshore platform subject to the nonlinear self-excited wave force, a multi-loop feedback-control method (Terro et al., 1999), a nonlinear controller and a robust state feedback controller (Zribi et al., 2004) have been developed, respectively. Recently, delayed feedback control schemes (Zhang et al., 2011, 2014, 2013a) have been developed to improve the performance of the offshore platform. By taking the parameter uncertainties and control delay into account, integral sliding mode control schemes (Zhang et al., 2012a, 2014, 2013b,) and a delay-dependent state feedback control scheme (Zhang et al., 2012b) were investigated, respectively.

Notice that optimal control is an efficient scheme to improve the performance of a system with the least control cost. Optimal-based control strategies are applied to control the offshore platform. For example, a nonlinear stochastic optimal control strategy for wave-excited jacket-type offshore platforms has been proposed by Luo and Zhu (2006). For a simplified offshore steel jacket platform with active mass damper mechanisms, Li et al. (2003) have presented an H_2 control scheme to reduce the wave-induced oscillation of the offshore platform with an active mass damper (AMD). By modelling the wave force as the output of a linear exogenous system, Ma et al. (2006) have developed a discrete feedforward and feedback optimal controller to compensate for the performance of the offshore platform. Further, a discrete feedforward and feedback optimal control scheme with memory has been developed for the offshore steel jacket platform with control delays (Ma et al., 2009).

The control schemes mentioned above can improve the control performance of the offshore platform to some different levels. Specifically, note the fact that the discrete control schemes (Ma et al., 2006, 2009) are easy to implement for computer control systems. Inspired by Ma et al. (2006, 2009), in this paper, a discrete feedforward and feedback optimal tracking control scheme is developed to make the output of the offshore platform asymptotically track the desired trajectory, and thereby improve the

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control performance of the offshore platform and reduce the control cost required. In addition, for the offshore steel jacket platform with time-delays in control input, a discrete feedforward and feedback optimal tracking control scheme with memory is presented. The optimal tracking controllers can be obtained by solving algebraic Riccati equations and Stein equations, respectively. To demonstrate the effectiveness of the control methods, the response of a simplified offshore steel jacket platform is investigated. Simulation results show that the vibration amplitudes of the offshore platform with the feedforward and feedback optimal tracking control scheme are smaller than those with the traditional optimal tracking control scheme. Moreover, the control force required by the former is smaller than the one by the latter. It is also shown that the responses of the offshore platform with the feedforward and feedback optimal tracking control scheme are almost the same as those with the feedforward and feedback optimal control scheme (Ma et al., 2006, 2009), while the control force by the former is smaller than the one by the latter.

2. Problem formulation

In this paper, we consider a simplified offshore steel jacket platform with an AMD mechanism presented in Fig. 1 (Li et al., 2003; Ma et al., 2006, 2009). The dynamic equation of the offshore platform can be formulated as

$$\begin{cases} m_1\ddot{z}_1(t) = -(m_1\omega_1^2 + m_2\omega_2^2)z_1(t) - 2(m_1\xi_1\omega_1 + m_2\xi_2\omega_2)\dot{z}_1(t) \\ \qquad + m_2\omega_2^2 z_2(t) + 2m_2\xi_2\omega_2\dot{z}_2(t) + f(t) - u(t) \\ m_2\ddot{z}_2(t) = m_2\omega_2^2[z_1(t) - z_2(t)] + 2m_2\xi_2\omega_2[\dot{z}_1(t) - \dot{z}_2(t)] + u(t) \end{cases} \tag{1}$$

where z_1 denotes the modal coordinate which refers to the deck motion of the offshore structure, z_2 denotes the displacement of the AMD. m_1, ω_1 and ξ_1 are the modal mass, frequency, and damping ratio of the offshore platform, respectively. m_2, ω_2 and ξ_2 are the mass, frequency, and damping ratio of the AMD, respectively. u is the active control force, and f is the irregular wave force acting on the offshore platform.

Let

$$x_1(t) = z_1(t), \quad x_2(t) = z_2(t), \quad x_3(t) = \dot{z}_1(t), \quad x_4(t) = \dot{z}_2(t) \tag{2}$$

and denote

$$x(t) := [x_1(t)\ \ x_2(t)\ \ x_3(t)\ \ x_4(t)]^T$$

Then, the motion equation (1) can be written as

$$\dot{x}(t) = Ax(t) + Bu(t) + Df(t), \quad x(0) = x_0 \tag{3}$$

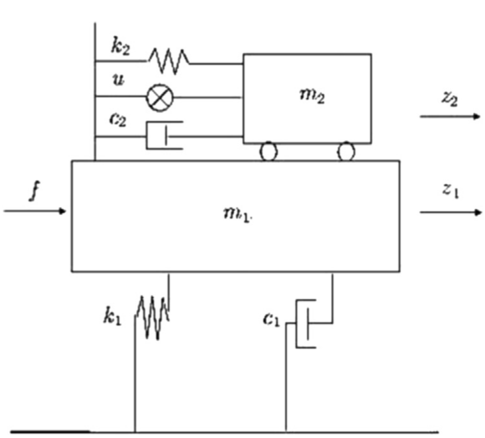

Fig. 1. An idealized offshore platform with AMD.

where x_0 is the initial state, and

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ A_{31} & A_{32} & A_{33} & A_{34} \\ \omega_2^2 & -\omega_2^2 & A_{43} & A_{44} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ -1/m_1 \\ 1/m_2 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 0 \\ 1/m_1 \\ 0 \end{bmatrix} \tag{4}$$

with

$$A_{31} = -(\omega_1^2 + m_2\omega_2^2/m_1), \quad A_{32} = m_2\omega_2^2/m_1,$$
$$A_{33} = -2(\xi_1\omega_1 + m_2\xi_2\omega_2/m_1)$$
$$A_{34} = 2m_2\xi_2\omega_2/m_1, \quad A_{43} = 2\xi_2\omega_2, \quad A_{44} = -2\xi_2\omega_2$$

It is assumed that the offshore platform is idealized as a monopod structure, and the propagation is the direction of x-axis. Then, as stated in Ma et al. (2006), based on wave theory, the wave force term $f(t)$ can be formulated as the output of a linear exogenous system:

$$\begin{cases} \dot{w}(t) = Gw(t) \\ f(t) = Hw(t) \end{cases} \tag{5}$$

where $w \in \mathbb{R}^p$ is the state vector of the exogenous system, $G \in \mathbb{R}^{p\times p}$ and $H \in \mathbb{R}^{1\times p}$ are known constant matrices.

Let T denote the sampling period, then system (3) can be discretized as

$$x(k+1) = \overline{A}x(k) + \overline{B}u(k) + \overline{D}f(k), \quad k = 0, 1, 2, \ldots, x(0) = x_0 \tag{6}$$

where

$$\overline{A} = e^{AT}, \quad \overline{B} = \int_0^T e^{At}B\,dt, \quad \overline{D} = \int_0^T e^{At}D\,dt \tag{7}$$

The exogenous system (5) can be discretized as

$$\begin{cases} w(k+1) = \overline{G}w(k) \\ f(k) = Hw(k), \quad k = 0, 1, 2, \ldots \end{cases} \tag{8}$$

where $\overline{G} = e^{GT}$.

The output equation is given as

$$y(k) = Cx(k) \tag{9}$$

where C is a problem-dependent constant matrix with appropriate dimensions.

The desired input y_r is the output of the following exogenous system:

$$\begin{cases} \eta(k+1) = \overline{M}\eta(k) \\ y_r(k) = \overline{N}\eta(k), \eta(0) = \eta_0, \quad k = 0, 1, 2, \ldots \end{cases} \tag{10}$$

where $\overline{M}$ and $\overline{N}$ are known constant matrices with appropriate dimensions.

The quadratic average performance index is given as

$$J = \lim_{N\to\infty} \frac{1}{N} \sum_{k=0}^{N} [e^{\mathrm{T}}(k)\overline{Q}e(k) + \overline{R}u^2(k)]\,dt \tag{11}$$

where $e(k)$ is the tracking error given as

$$e(k) = y_r(k) - y(k) \tag{12}$$

$\overline{Q} \in \mathbb{R}^{4\times 4}$ is a positive semi-definite matrix, and $\overline{R} > 0$ is a constant.

In what follows, we will design a feedforward and feedback optimal tracking control law $u^*(k)$ for system (6) such that the output $y(k)$ can asymptotically track the desired output $y_r(k)$ and the performance index (11) is minimized, and thereby to improve the control performance of the offshore platform.

To obtain the main results, the following assumptions and lemma are needed.