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Robust mixed H_∞/passive vibration control of offshore steel jacket platforms with structured uncertainty

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ABSTRACT

This paper focuses on the problems associated with designing a robust mixed H_∞/passive controller for offshore steel jacket platforms with structured uncertainty. The objective of this paper is to design a controller that is meant to stabilize the offshore platform dynamic when exposed to structured uncertainties. This designation must also satisfy a mixed H_∞/passive performance index. In order to design such a controller, at first, the instantaneous state feedback controller ought to be considered. Then, mixed time-delayed states and instantaneous states are to be considered in such a way that the control law covers various kinds of practical situations. Based on the Lyapunov-Krasovskii Functional (LKF), some stability criteria are obtained and expressed in the form of Linear Matrix Inequalities (LMIs). According to these stability criteria, some sufficient conditions for the existence of the state feedback controller gain are to be met. At the end, the designed controllers are applied to the model of the offshore platform with uncertainty before numerically simulating the effectiveness of the proposed methods.

1. Introduction

Offshore steel jacket platforms are the main workstations for oil and gas extraction activities in the ocean. Such platforms contain a lot of equipment including drilling derrick, cranes, pad for helicopter landing, and some offices which make them very heavy. These structures are often located in adverse environments that exposing them to sea waves continuously beat their bodies. Furthermore, some other phenomena such as the earthquake, wind, and water currents can be occurred in these environments (Park et al., 2011; Raheem, 2014; Wilson, 2003). Structural vibration caused by the mentioned forces can give rise to an unsafe environment, where all the personnel working off a platform are put at risk. In a worst case scenario, these forces could conspire to upend the platforms or wreak havoc with their structures. Therefore, many researchers have gravitated toward the field of stability in such structures as they have focused on finding ways to attenuate the structural vibrations on the platforms by resorting to passive and active control methods.

In passive control methods, energy dissipation devices are used to mitigate the vibration effect (Li and Hu, 2002). Despite having some advantages such as not needing external energy, such methods often fall short of their projected performance and prove to be inadmissible in most design cases (El-Reedy, 2012). Similarly, these devices can affect only a narrow structural frequency and manage to attenuate its effects (Yang, 2014). Unfortunately, the environment of the ocean happens to be affected by numerous forces and the sea wave frequency spectrum is a wide band. In order to overcome this defect, active control methods should be used, since they can improve control performances over a wide frequency range (Zhang et al., 2012, 2014a, 2016b). In this way, Terro et al. (1999) designed a multi-loop feedback control for offshore steel jacket platforms, which include both an inner loop and an outer loop for regulating the linear part and overcoming the self-excited hydrodynamic forces of the platform dynamics, respectively. Li et al. (2003) and Luo and Zhu (2006) introduced H_2 active control and nonlinear stochastic optimal control, respectively, to attenuate the vibrations for offshore platforms which are subjected to wave loading. Also, Zhang et al. (2013) used sliding mode H_∞ control for offshore steel jacket platforms being subjected to nonlinear self-excited wave force and external disturbance.

From a practical point of view, it is a well-known fact that time-delays are unavoidable in closed-loop control systems due to finiteness of signal computation and transmission (Muoi et al., 2016). The existence of time-delay will result in poor performance, stability margin reduction, and also increases the complexity in most cases (Rajchakit and Saravanakumar, 2016; Rajchakit et al., 2017). In some problematic areas such as stabilization of oscillatory systems (Abdallah et al., 1993) and vibration control of resonators (Filipović and Olgac, 2002), it has been shown that introducing time-delay intentionally in to the control system could improve the control performance. Zhang et al. (2011) showed that intentionally introducing small time-delays into state

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feedback control structure, will cause the corresponding control force to be smaller. After the publication of this paper, several research papers have been published which have considered the time-delay in the control structure (Yang, 2014; Zhang and Han, 2014; Zhang et al., 2014b). Zhang and Tang (2013) used H_∞ control to attenuate the vibration for offshore steel jacket platforms when time-delay is a contributing factor. Similarly, Zhang et al. (2016a) introduced an event-triggered H_∞ reliable control for offshore structures into network environments.

Although most published papers present different control design methods for offshore platform, they fail to make allowance for any uncertainty in the platform model. On the one hand, not all the elements of the model are exactly known, as the considered models are only linearized models of the real systems. On the other hand, the platform model parameters are likely to undergo some variations in their working lifetime. Mass changes are often accrued by the helicopter landing and equipment transportations. Therefore, this paper investigates the problem of designing a robust mixed H_∞/passive control of offshore steel jacket platforms with structured uncertainty. The controller is designed in a way as to stabilize the offshore platform dynamic which is affected by structured uncertainties, and also to satisfy a mixed H_∞/passive performance index. Based on the Lyapunov-Krasovskii functional, some stability criteria are obtained and expressed in the form of linear matrix inequalities. According to these stability criteria, some sufficient conditions for the existence of the state feedback controller gain are obtained.

The organization of this paper is as follows. In Section 2, offshore steel jacket platform model is given and then some preliminary lemmas are introduced which will help us to drive the main results. In Section 3, based on a LKF, some criteria are given to design a robust mixed H_∞/passive controller for the offshore steel jacket plat-forms with structured uncertainty. Section 4 provides the simulation results. Finally, Section 5 concludes the paper.

Notations. Throughout this paper, $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ represents the set of real $n \times m$ matrices. $\mathbf{P} > 0$ is intended to mean $\mathbf{P}$ is a real positive definite and symmetric matrix. $\mathbf{I}$ is the identity matrix with appropriate dimensions and $\mathrm{diag}\{\mathbf{W}_1, \ldots, \mathbf{W}_m\}$ refers to a real matrix with diagonal elements $\mathbf{W}_1, \ldots, \mathbf{W}_m$. $\mathbf{A}^T$ denotes the transpose of the real matrix $\mathbf{A}$. Symmetric terms in a symmetric matrix are denoted by *.

2. Offshore steel jacket platform model and preliminaries

Consider an offshore steel jacket platform which has been equipped with an active mass damper (AMD) mechanism and shown in Fig. 1. If we were to take the first dominant vibration mode of the structure into consideration, the dynamic equations of the structure could be described as follows (Zhang and Tang, 2013):

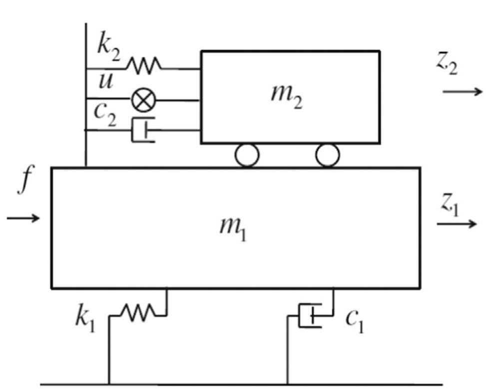

Fig. 1. A reduced model of offshore steel jacket platform with AMD mechanism (Yang, 2014).

$$\begin{aligned} m_1\ddot{z}_1(t) &= -(m_1\omega_1^2 + m_2\omega_2^2)z_1(t) + 2m_2\xi_2\omega_2\dot{z}_2(t) \\ &\quad -2(m_1\xi_1\omega_1 + m_2\xi_2\omega_2)\dot{z}_1(t) + m_2\omega_2^2 z_2(t) \\ &\quad +f(t) - u(t), \\ m_2\ddot{z}_2(t) &= m_2\omega_2^2 z_1(t) + 2m_2\xi_2\omega_2\dot{z}_1(t) - m_2\omega_2^2 z_2(t) \\ &\quad -2m_2\xi_2\omega_2\dot{z}_2(t) + u(t), \end{aligned} \tag{1}$$

where $z_1(t)$ and $z_2(t)$ represent displacements of the platform deck and the AMD, respectively; m_i, ω_i, and ξ_i, $i = 1, 2$, are the mass, natural frequency, and the damping ratio of the platform, $i = 1$, and the AMD, $i = 2$,

respectively; $u(t)$ is the active control signal and $f(t) \in \mathcal{L}_2[0, \infty)$ is the external wave force acting on the offshore structure and has limited energy.

The model of generalized wave force $f(t)$ has been presented and utilized in (Li et al., 2003; Ma et al., 2009; Yang, 2014) and references therein.

Let define the state vector as

$$\mathbf{x}(t) = [x_1(t)\ \ x_2(t)\ \ x_3(t)\ \ x_4(t)]^T = [z_1(t)\ \ z_2(t)\ \ \dot{z}_1(t)\ \ \dot{z}_2(t)]^T,$$

then the Eq. (1) can be written as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) + \mathbf{D}f(t), \tag{2}$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\left(\omega_1^2 + \omega_2^2\frac{m_2}{m_1}\right) & \omega_2^2\frac{m_2}{m_1} & -2\left(\xi_1\omega_1 + \xi_2\omega_2\frac{m_2}{m_1}\right) & 2\xi_2\omega_2\frac{m_2}{m_1} \\ \omega_2^2 & -\omega_2^2 & 2\xi_2\omega_2 & -2\xi_2\omega_2 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{m_1} \\ \frac{1}{m_2} \end{bmatrix},\ \mathbf{D} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{m_1} \\ 0 \end{bmatrix}.$$

In order to specify a performance index and design a controller to reduce the platform oscillation, it is needed to determine the controlled outputs. That is to say, a reasonable control output, with the wave forces influence it, in the following manner:

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{F}f(t), \tag{3}$$

where

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

and $\mathbf{F} \in \mathbb{R}^2$ is a real known matrix.

If parametric uncertainties were to be considered, the dynamic equations of the offshore structure could be rewritten as follows:

$$\begin{cases} \dot{\mathbf{x}}(t) = \overline{\mathbf{A}}\mathbf{x}(t) + \overline{\mathbf{B}}u(t) + \overline{\mathbf{D}}f(t), \\ \mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{F}f(t), \end{cases} \tag{4}$$

where

$$\overline{\mathbf{A}} = \mathbf{A} + \Delta\mathbf{A}(t),\ \ \overline{\mathbf{B}} = \mathbf{B} + \Delta\mathbf{B}(t),\ \ \overline{\mathbf{D}} = \mathbf{D} + \Delta\mathbf{D}(t), \tag{5}$$

and $\Delta\mathbf{A}(t)$, $\Delta\mathbf{B}(t)$, $\Delta\mathbf{D}(t)$ are norm-bounded parameter uncertainties and are assumed to be of the following form:

$$[\Delta\mathbf{A}(t)\ \ \Delta\mathbf{B}(t)\ \ \Delta\mathbf{D}(t)] = \mathbf{L}\Lambda(t)[\mathbf{E}_A\ \ \mathbf{E}_B\ \ \mathbf{E}_D]. \tag{6}$$

The matrices $\mathbf{L}$, $\mathbf{E}_A$, $\mathbf{E}_B$, and $\mathbf{E}_D$ are known real constant matrices with appropriate dimensions and $\Lambda(t)$ is an unknown time-varying real matrix satisfying

$$\Lambda^T(t)\Lambda(t) \le \mathbf{I}. \tag{7}$$

Remark 1: In the uncertainty structure, given by Eq. (6), matrices $\mathbf{L}$,