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DELAYED FUZZY H_∞ CONTROL OF OFFSHORE STEEL JACKET PLATFORMS

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Abstract

We study a delayed fuzzy H_∞ control problem for an offshore platform under external wave forces. First, by considering perturbations of the masses of the platform and an active mass damper, a Takagi–Sugeno fuzzy model is established. Then, by introducing time delays into the control channel, a delayed fuzzy state feedback H_∞ controller is designed. Simulation results show that the delayed fuzzy state feedback H_∞ controller can reduce vibration amplitudes of the offshore platform and can save control cost significantly.

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Keywords and phrases: offshore platform, fuzzy control, active control, time delay, delayed feedback control.

1. Introduction

Excessive environmental loadings including waves, ice, and earthquakes acting on offshore platforms may lead to large vibrations and thereby affect structural safety and reliability [2, 9]. In the last few decades, in order to mitigate vibration of the offshore platform, active control has been paid considerable attention and a large number of control strategies, such as optimal control [5, 13], robust control [14, 17], sliding mode control [11, 14], and network-based control [10], have been reported. More recently, delayed feedback control schemes have been developed to suppress vibration of the offshore platform [12]. It is known that the aforesaid methods are effective to mitigate vibration of the platform. However, most of the results are based on the fact that system models are almost exactly known. Specifically, from the real application point of view, the masses of the offshore structure are not always invariant.

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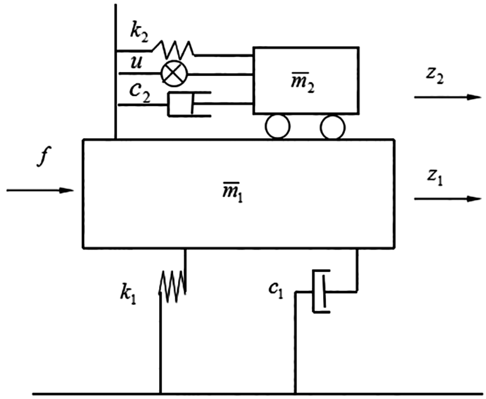

FIGURE 1. An offshore platform with an AMD mechanism [2].

As an effective method dealing with nonlinear, complex dynamic uncertain systems, fuzzy control has been extensively investigated [3, 4, 6–8, 15, 16]. In this paper, by taking into account perturbations of masses of the offshore platform and active mass damper mechanisms, we intend to establish a Takagi–Sugeno fuzzy model of the offshore platform. Then, by artificially introducing a time delay into the control channel, we address the delayed fuzzy state feedback H_∞ control problem of the offshore platform, and investigate the design approaches and effectiveness of the delayed fuzzy control scheme. Our simulation results show that the proposed fuzzy control scheme is better than the traditional fuzzy control scheme.

2. Problem formulation

An offshore steel jacket platform subject to wave forces is presented in Figure 1 [2], where only the most dominant vibration modes of the platform and an active mass damper (AMD) mechanism are considered. Taking perturbations of masses of the first vibration mode and the AMD into account yields the motion equation of the system as

$$\begin{cases} \bar{m}_1(t)\ddot{z}_1(t) = -[\bar{m}_1(t)\omega_1^2 + \bar{m}_2(t)\omega_2^2]z_1(t) + \bar{m}_2(t)\omega_2^2 z_2(t) \\ \qquad\qquad - 2[\bar{m}_1(t)\xi_1\omega_1 + \bar{m}_2(t)\xi_2\omega_2]\dot{z}_1(t) \\ \qquad\qquad + 2\bar{m}_2(t)\xi_2\omega_2\dot{z}_2(t) - u(t) + f(t), \\ \bar{m}_2(t)\ddot{z}_2(t) = \bar{m}_2(t)\omega_2^2 z_1(t) + 2\bar{m}_2(t)\xi_2\omega_2\dot{z}_1(t) + u(t) \\ \qquad\qquad - \bar{m}_2(t)\omega_2^2 z_2(t) - 2\bar{m}_2(t)\xi_2\omega_2\dot{z}_2(t), \end{cases} \tag{2.1}$$

where ξ_1 and ω_1 are the damping ratio and frequency of the offshore platform, respectively; ξ_2 and ω_2 are the damping ratio and frequency of the AMD, respectively; z_1 and z_2 denote displacements of the platform and the AMD, respectively; $f(t)$ is the external wave force, and $u(t)$ denotes the active control. The time-varying masses of the platform and the AMD are denoted by $\bar{m}_1(t)$ and $\bar{m}_2(t)$, respectively.

Let $x_1 = z_1$, $x_2 = z_2$, $x_3 = \dot{z}_1$, $x_4 = \dot{z}_2$, $x^T = [x_1 \quad x_2 \quad x_3 \quad x_4]$, and

$$\begin{aligned} a_{31}(t) &= -\omega_1^2 - \omega_2^2 \bar{m}_2(t)/\bar{m}_1(t), \\ a_{32}(t) &= \omega_2^2 \bar{m}_2(t)/\bar{m}_1(t), \\ a_{33}(t) &= -2\xi_1\omega_1 - 2\xi_2\omega_2\bar{m}_2(t)/\bar{m}_1(t), \\ a_{34}(t) &= 2\xi_2\omega_2\bar{m}_2(t)/\bar{m}_1(t). \end{aligned}$$

Then, from (2.1),

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + D(t)f(t), \quad x(0) = x_0, \tag{2.2}$$

where

$$\begin{aligned} A(t) &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ a_{31}(t) & a_{32}(t) & a_{33}(t) & a_{34}(t) \\ \omega_2^2 & -\omega_2^2 & 2\xi_2\omega_2 & -2\xi_2\omega_2 \end{bmatrix}, \\ B(t) &= \begin{bmatrix} 0 & 0 & -1/\bar{m}_1(t) & 1/\bar{m}_2(t) \end{bmatrix}^T, \\ D(t) &= \begin{bmatrix} 0 & 0 & 1/\bar{m}_1(t) & 0 \end{bmatrix}^T. \end{aligned}$$

We assume that the time-varying mass $\bar{m}_i(t)$ satisfies $0 < m_i \le \bar{m}_i(t) \le M_i, i = 1, 2$. We denote the membership functions as

$$\begin{cases} \phi_i^m(\bar{m}_i(t)) = [M_i - \bar{m}_i(t)]/(M_i - m_i), \\ \phi_i^M(\bar{m}_i(t)) = [\bar{m}_i(t) - m_i]/(M_i - m_i), \quad i = 1, 2. \end{cases}$$

It is clear that $\phi_i^M(\bar{m}_i(t)) + \phi_i^m(\bar{m}_i(t)) = 1, i = 1, 2$. Then

$$\bar{m}_i(t) = \phi_i^m(\bar{m}_i(t))m_i + \phi_i^M(\bar{m}_i(t))M_i, \quad i = 1, 2.$$

Suppose that the fuzzy sets of $\bar{m}_i(t), i = 1, 2$, are set as 'S' and 'B'. Then one can define fuzzy variables as

$$\begin{aligned} &\text{Case 1:} \quad \bar{m}_1(t) \in B,\ \bar{m}_2(t) \in B; \quad \text{Case 2:} \quad \bar{m}_1(t) \in B,\ \bar{m}_2(t) \in S; \\ &\text{Case 3:} \quad \bar{m}_1(t) \in S,\ \bar{m}_2(t) \in B; \quad \text{Case 4:} \quad \bar{m}_1(t) \in S,\ \bar{m}_2(t) \in S. \end{aligned}$$

Then the dynamic model (2.2) can be represented by the following Takagi–Sugeno fuzzy model rules.

Model rule k: If case k, then

$$\dot{x}(t) = A_k x(t) + B_k u(t) + D_k f(t), \tag{2.3}$$

where matrices A_k, B_k, and D_k $(k = 1, 2, 3, 4)$ can be obtained by replacing the pair $(\bar{m}_1(t), \bar{m}_2(t))$ in time-varying matrices $A(t)$, $B(t)$, and $D(t)$ with the constant matrix pairs (M_1, M_2), (M_1, m_2), (m_1, M_2), and (m_1, m_2), respectively.

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Using a defuzzifier method yields an overall fuzzy model of the system as

$$\dot{x}(t) = \sum_{k=1}^{4} h_k(m(t))[A_k x(t) + B_k u(t) + D_k f(t)], \tag{2.4}$$

where $m(t) = [\bar{m}_1(t) \quad \bar{m}_2(t)]^T$ and

$$h_1(m(t)) = \phi_1^M(\bar{m}_1(t))\phi_2^M(\bar{m}_2(t)), \quad h_2(m(t)) = \phi_1^M(\bar{m}_1(t))\phi_2^m(\bar{m}_2(t)),$$
$$h_3(m(t)) = \phi_1^m(\bar{m}_1(t))\phi_2^M(\bar{m}_2(t)), \quad h_4(m(t)) = \phi_1^m(\bar{m}_1(t))\phi_2^m(\bar{m}_2(t)).$$

It is clear that $h_k(m(t)) \geq 0$ and $\sum_{k=1}^{4} h_k(m(t)) = 1$.

The output equation of the system is given as

$$y(t) = C_1 x(t) + E_1 f(t), \tag{2.5}$$

where

$$C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad E_1 = \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}.$$

The fuzzy control rules are given as follows.

Control rule l: If case l, then

$$u(t) = K_l x(t-\tau), \quad l = 1, 2, 3, 4,$$

where $\tau > 0$ is the artificially introduced delay to be determined. The overall fuzzy control law of the system can be designed as

$$u(t) = \sum_{l=1}^{4} h_l(m(t)) K_l x(t-\tau). \tag{2.6}$$

The aim of this paper is to design the control law (2.6), such that (i) under this law, the system (2.4) is asymptotically stable; and (ii) under the zero initial condition, the H_∞ performance $\|y(t)\| < \gamma \|f(t)\|$ of the system is guaranteed for nonzero $f(t) \in L_2[0, \infty)$ and a prescribed $\gamma > 0$.

3. Controller design

To obtain the main results, the following lemma is needed.

LEMMA 3.1 (Schur complement [1]). *For a given symmetric matrix*

$$\Upsilon = \Upsilon^T = \begin{bmatrix} \Upsilon_{11} & \Upsilon_{12} \\ * & \Upsilon_{22} \end{bmatrix},$$

where $\Upsilon_{11} \in \mathbb{R}^{r \times r}$, the following conditions are equivalent:

(1) $\Upsilon < 0$;
(2) $\Upsilon_{11} < 0,\ \Upsilon_{22} - \Upsilon_{12}^T \Upsilon_{11}^{-1} \Upsilon_{12} < 0$; *and*
(3) $\Upsilon_{22} < 0,\ \Upsilon_{11} - \Upsilon_{12} \Upsilon_{22}^{-1} \Upsilon_{12}^T < 0$.

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Substituting (2.6) into (2.4) yields the closed-loop system

$$\dot{x}(t) = \sum_{k=1}^{4}\sum_{l=1}^{4} h_{kl}(t)[A_k x(t) + B_k K_l x(t-\tau) + D_k f(t)], \tag{3.1}$$

where $h_{kl}(t) = h_k(m(t))h_l(m(t))$.

Proposition 3.2. *For given scalars $\gamma > 0$, $\tau > 0$, assume that there exist 4×4 matrices $\bar{P} > 0$, $\bar{Q} > 0$, $\bar{R} > 0$, and matrices $\bar{M}_1$, $\bar{M}_2$, $\bar{M}_3$ with appropriate dimensions, and 1×4 matrices $\bar{K}_l$ such that the following matrix inequalities simultaneously hold for $k, l = 1, 2, 3, 4$:*

$$\begin{bmatrix} \bar{\Lambda}_{11} & \bar{\Lambda}_{12} & \bar{\Lambda}_{13} & \sqrt{\tau}\bar{P}A_k^T & \bar{P}C_1^T & \sqrt{\tau}\bar{M}_1 \\ * & \bar{\Lambda}_{22} & -\bar{M}_3^T & \sqrt{\tau}\bar{K}_l^T B_k^T & 0 & \sqrt{\tau}\bar{M}_2 \\ * & * & -\gamma^2 I & \sqrt{\tau}D_k^T & E_1^T & \sqrt{\tau}\bar{M}_3 \\ * & * & * & -\bar{R} & 0 & 0 \\ * & * & * & * & -I & 0 \\ * & * & * & * & * & -\bar{P}\bar{R}^{-1}\bar{P} \end{bmatrix} < 0, \tag{3.2}$$

where

$$\begin{aligned} \bar{\Lambda}_{11} &= A_k\bar{P} + \bar{P}A_k^T + \bar{Q} + \bar{M}_1 + \bar{M}_1^T, \\ \bar{\Lambda}_{12} &= B_k\bar{K}_l + \bar{M}_2^T - \bar{M}_1, \\ \bar{\Lambda}_{22} &= -\bar{Q} - \bar{M}_2 - \bar{M}_2^T, \quad \textit{and} \\ \bar{\Lambda}_{13} &= D_k + \bar{M}_3^T. \end{aligned}$$

Then the system (3.1) is asymptotically stable, and the H_∞ performance is guaranteed; the controller gain matrix is given by $K_l = \bar{K}_l\bar{P}^{-1}$, $l = 1, 2, 3, 4$.

Proof. Choose a Lyapunov–Krasovskii functional candidate [12] as

$$V(t) = x^{\mathrm{T}}(t)Px(t) + \int_{t-\tau}^{t} x^T(s)Qx(s)\,ds + \int_{-\tau}^{0}\int_{t+\theta}^{t} \dot{x}^T(s)R\dot{x}(s)\,ds\,d\theta,$$

where $P > 0$, $Q > 0$, $R > 0$.

Let

$$\xi^T(t) := \begin{bmatrix} x^T(t) & x^T(t-\tau) & f^T(t) \end{bmatrix}, \quad M^T := \begin{bmatrix} M_1^T & M_2^T & M_3^T \end{bmatrix},$$

where $M_1, M_2 \in \mathbb{R}^{4\times4}$, $M_3 \in \mathbb{R}^{1\times4}$.

Taking the derivative of $V(t, x_t)$ along the trajectory of (3.1) yields

$$\begin{aligned} \dot{V}(t) &= 2\dot{x}^T(t)Px(t) + x^T(t)Qx(t) - x^T(t-\tau)Qx(t-\tau) \\ &\quad + \tau\dot{x}^T(t)R\dot{x}(t) - \int_{t-\tau}^{t} \dot{x}^T(s)R\dot{x}(s)\,ds \\ &\quad + 2\xi^T(t)M\Big[x(t) - x(t-\tau) - \int_{t-\tau}^{t} \dot{x}(s)\,ds\Big]. \end{aligned} \tag{3.3}$$

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Denote

$$\Lambda_{11} = PA_k + A_k^T P + Q + M_1 + M_1^T,$$
$$\Lambda_{12} = PB_k K_l + M_2^T - M_1, \quad \Lambda_{22} = -Q - M_2 - M_2^T,$$
$$\Delta_1^T = \begin{bmatrix} A_k & B_k K_l & D_k \end{bmatrix}, \quad \alpha(t) = R\dot{x}(t) + M^T \xi(t).$$

Then, from (3.1) and (3.3),

$$\begin{aligned} \dot{V}(t) \le \sum_{k=1}^{4}\sum_{l=1}^{4} h_{kl}(t)\Big[& x^T(t)\Lambda_{11}x(t) + 2x^T(t)\Lambda_{12}x(t-\tau) \\ & + 2x^T(t)(PD_k + M_3^T)f(t) + x^T(t-\tau)\Lambda_{22}x(t-\tau) \\ & + \xi^T(t)(\tau\Delta_1 R\Delta_1^T + \tau M R^{-1} M^T)\xi(t) - \int_{t-\tau}^{t} \alpha^T(s)R^{-1}\alpha(s)\,ds\Big]. \end{aligned} \quad (3.4)$$

First, let $f(t) = 0$; we consider asymptotic stability of the system (3.1). From (3.4),

$$\dot{V}(t) \le \sum_{k=1}^{4}\sum_{l=1}^{4} h_{kl}(t)\upsilon^T(t)[\tilde{\Omega} + \tau\tilde{\Delta}_1 R\tilde{\Delta}_1^T + \tau\tilde{M}R^{-1}\tilde{M}^T]\upsilon(t), \quad (3.5)$$

where $\upsilon^T(t) = [x^T(t) \quad x^T(t-\tau)]$ and

$$\tilde{\Omega} = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ * & \Lambda_{22} \end{bmatrix}, \quad \tilde{\Delta}_1^T = \begin{bmatrix} A_k & B_k K_l \end{bmatrix}, \quad \tilde{M} = \begin{bmatrix} M_1 \\ M_2 \end{bmatrix}.$$

Note the fact that pre- and post-multiplying the matrix on the left-hand side of the inequality (3.2) by a matrix $\mathrm{diag}\{\bar{P}^{-1}, \bar{P}^{-1}, I, \bar{R}^{-1}, I, \bar{P}^{-1}\}$ and its transpose, respectively, and setting $P = \bar{P}^{-1}, Q = \bar{P}^{-1}Q\bar{P}^{-1}, R = \bar{R}^{-1}, K_l = \bar{K}_l P^{-1}$,

$$\begin{bmatrix} \Lambda_{11} & \Lambda_{12} & PD_k + M_3^T & \sqrt{\tau}A_k^T R & C_1^T & \sqrt{\tau}M_1 \\ * & \Lambda_{22} & -M_3^T & \sqrt{\tau}K_l^T B_k^T R & 0 & \sqrt{\tau}M_2 \\ * & * & -\gamma^2 I & \sqrt{\tau}D_k^T R & E_1^T & \sqrt{\tau}M_3 \\ * & * & * & -R & 0 & 0 \\ * & * & * & * & -I & 0 \\ * & * & * & * & * & -R \end{bmatrix} < 0, \quad (3.6)$$

which indicates that

$$\begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \sqrt{\tau}A_k^T R & \sqrt{\tau}M_1 \\ * & \Lambda_{22} & \sqrt{\tau}K_l^T B_k^T R & \sqrt{\tau}M_2 \\ * & * & -R & 0 \\ * & * & * & -R \end{bmatrix} < 0. \quad (3.7)$$

By Schur complement [1], (3.7) means that

$$\tilde{\Omega} + \tau\tilde{\Delta}_1 R\tilde{\Delta}_1^T + \tau\tilde{M}R^{-1}\tilde{M}^T < 0. \quad (3.8)$$

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From (3.5), if inequality (3.8) holds for $k, l = 1, 2, 3, 4$, then $\dot{V}(t) \le \lambda x^T(t)x(t)$ for a scalar $\lambda > 0$. Therefore, the system (3.1) is asymptotically stable.

Let

$$\Omega = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} & \Lambda_{13} \\ * & \Lambda_{22} & -M_3^T \\ * & * & -\gamma^2 I \end{bmatrix} \quad \text{and} \quad \Delta_2 = \begin{bmatrix} C_1 & 0 & E_1 \end{bmatrix}.$$

Then, from (2.5), (3.1), and (3.4),

$$\dot{V}(t) + y^T(t)y(t) - \gamma^2 f^T(t)f(t) \le \sum_{k=1}^{4}\sum_{l=1}^{4} h_{kl}\xi^T(t)\Pi\xi(t),$$

where $\Pi = \Omega + \tau\Delta_1 R\Delta_1^T + \Delta_2^T\Delta_2 + \tau M R^{-1} M^T$.

By Schur complement, (3.6) guarantees that $\Pi < 0$, which leads to

$$\dot{V}(t) + y^T(t)y(t) - \gamma^2 f^T(t)f(t) < 0. \tag{3.9}$$

Integrating both sides of (3.9) from 0 to ∞, and noting the zero initial condition, $\|y(t)\| < \gamma\|f(t)\|$ holds for nonzero $f(t) \in L_2[0, \infty)$. This completes the proof. □

Remark 3.3. Note that (3.2) is not a linear matrix inequality; one cannot solve it directly by using Matlab LMI Toolbox. In this case, to compute controller gain matrices $K_l, l = 1, 2, 3, 4$, we can transform it into a linear matrix inequality by using $-\bar{P}\bar{R}^{-1}\bar{P} \le \bar{R} - 2\bar{P}$.

4. Simulation results

A simulation example is given in this section to show the effectiveness of the delayed fuzzy state feedback H_∞ control scheme. In system (2.1), let $\omega_1 = 2.0466$ revolutions per second (rps), $\xi_1 = 2\%$, $\omega_2 = 2.0074$ rps, and $\xi_2 = 20\%$. The masses of platform and AMD are set as $\bar{m}_1(t) = 7825\,307 + 500\sin(t)$ kg and $\bar{m}_2(t) = 78\,253 + 50\cos(t)$ kg. The wave force $f(t)$ acting on the offshore structure can be computed as in the work of Zhang et al. [13]. Let $\gamma = 15$ and $\tau = 0.002$ s. Then, by numerically solving the matrix inequality (3.2), we obtain the gain matrices of a delayed fuzzy state feedback H_∞ controller (DFSFHC) as

$$K_l = 10^7 \times \begin{bmatrix} -0.4313 & 0.0175 & 2.1324 & 0.0015 \end{bmatrix}, \quad l = 1, 2, 3, 4.$$

Under the control of DFSFHC, the responses of displacement, velocity, and acceleration of the platform and the control force are depicted in Figure 2, which show that the designed delayed fuzzy controller can reduce vibrations of the platform significantly.

To further demonstrate the superiority of DFSFHC over the traditional fuzzy state feedback H_∞ controller (FSFHC), the peak to peak amplitudes of displacement, velocity, and acceleration of the platform and control force with DFSFHC and FSFHC are computed and listed in Table 1. From the table, it is evident that both control force

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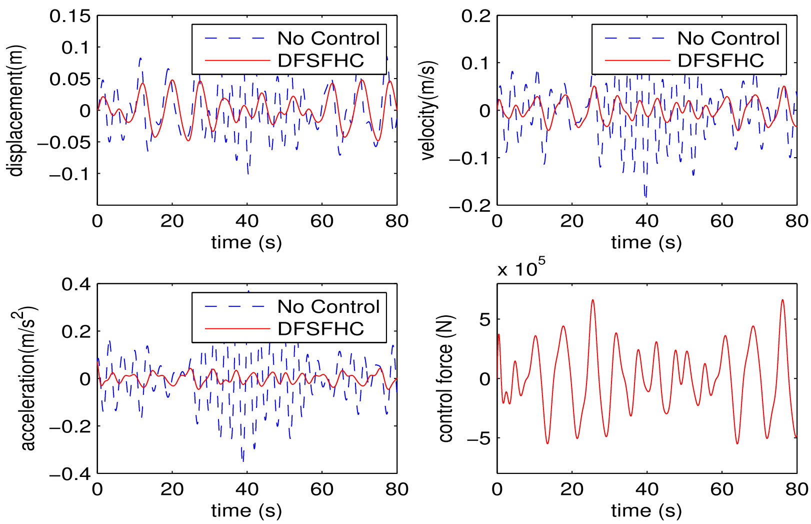

FIGURE 2. Responses of offshore platform and control force. (Colour available online).

TABLE 1. Vibration amplitudes of the offshore platform and control force.

Controller	x_1 (m)	$\dot{x}_1$ (m s^{-1})	$\ddot{x}_1$ (m s^{-2})	u (10^6 N)
No control	0.1998	0.3743	0.7384	–
FSFHC	0.1063	0.1042	0.1249	1.3031
DFSFHC	0.0963	0.0936	0.1179	1.2150

and oscillation amplitudes of displacement, velocity, and acceleration of the system with DFSFHC are smaller than the ones with FSFHC. It indicates that by artificially introducing a proper time delay into the control channel, both vibration amplitudes of the offshore platform and control force can be reduced.

5. Conclusions

A Takagi–Sugeno fuzzy dynamical model has been established for an offshore steel jacket platform under wave forces. By artificially introducing time delays into the control channel, a delayed fuzzy state feedback H_∞ control scheme has been developed. Simulation results show that compared to the traditional fuzzy state feedback H_∞ control scheme, the delayed fuzzy state feedback H_∞ control scheme is more effective in improving the control performance of the offshore platform.

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