Journal of Institute of Control, Robotics and Systems (2014) 20(11):1142-1146
http://dx.doi.org/10.5302/J.ICROS.2014.14.8021 ISSN:1976-5622 eISSN:2233-4335

타카기-수게노 퍼지 시스템의 H_∞ 샘플치 제어

H_∞ Sampled-Data Control of Takagi-Sugeno Fuzzy System

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Abstract: This paper addresses on a H_∞ sampled-data stabilization of a Takagi-Sugeno (T-S) fuzzy system. The sampled-data stabilization problem is formulated as a discrete-time stabilization one via a direct discrete-time design approach. It is shown that the sampled-data fuzzy control system is asymptotically stable whenever its exactly discretized model is asymptotically stable. Based on an exact discrete-time model, sufficient design conditions are derived in the format of linear matrix inequalities (LMIs). An example is provided to illustrate the effectiveness of the proposed methodology.

Keywords: T-S (Takagi-Sugeno) fuzzy model, H_∞ control, sampled-data fuzzy control, direct discrete-time design, exact approach, LMI (Linear Matrix Inequality)

I. INTRODUCTION

A direct discrete-time design is one of powerful design methodologies for sampled-data fuzzy controls (see [1-5] and references cited therein). It is to design a sampled-data controller based on the discrete-time model of a sampled-data dynamics. In [1-3], approximately discretized model is presented in the form of the general discrete-time Takagi-Sugeno (T-S) fuzzy model, and thus sampled-data fuzzy controllers are easily designed via the existing discrete-time fuzzy control theories. However, as mentioned in [6,7], the stability of the actual sampled-data closed-loop system may not be guaranteed due to approximation error, although its approximate discrete-time model is stable.

Recently, Kim *et al.* proposed an exact approach to a sampled-data state-feedback control [4]. In their method, there is no approximation error contrary to [1-3], and hence the stability of actual sampled-data control system is well guaranteed. In [5], an extension to observer-based output-feedback control is discussed. However, H_∞ control problem has not yet been fully investigated. It is nontrivial to formulate the problem in a discrete-time scheme due to the time-varying disturbance.

The purpose of this paper is to derive sufficient conditions on the H_∞ sampled-data stabilization of T-S fuzzy system via the direct discrete-time approach. Motivated by [4,5], an exact discrete-time model in an integral form is adopted here. It can be shown that the sampled-data fuzzy control system is asymptotically stable if its exactly discretized model is so. Sufficient conditions for asymptotic stabilization with H_∞ disturbance attenuation performance are derived in the sense of discrete-time Lyapunov theory and given in terms of linear matrix inequalities (LMIs). Finally, an example is given for testifying to the validity of the proposed design methodology.

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Manuscript received July 7, 2014 / revised September 10, 2014 / accepted September 15, 2014
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※ This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2014R1A1A1004610).
※ A draft [11] of this research was presented in ICROS2014.

Notations: The relation $P \succ Q$ ($P \prec Q$) means that the matrix $P - Q$ is positive (negative) definite. For simplicity, we will use x and x_{kT} in place of $x(t)$ and $x(kT)$, respectively, for the continuous-time and discrete-time signal vectors unless otherwise indicated. $\lambda_{max}(A)$ ($\lambda_{min}(A)$) is the maximum (minimum) eigenvalue of matrix A. An ellipsis is adopted for long symmetric matrix expressions, e.g.,

$$K^T \begin{bmatrix} He\{S\} & (*) \\ M & Q^T(*) \end{bmatrix} (*) := K^T \begin{bmatrix} S + S^T & M^T \\ M & Q^T Q \end{bmatrix} K.$$

II. PRELIMINARIES

Consider the T-S fuzzy systems

$$\begin{aligned} \dot{x} &= A(\mu)x + B_w(\mu)w + B_u(\mu)u \\ &=: f(x, w, u) \\ z &= D(\mu)x + E(\mu)u \end{aligned} \tag{1}$$

where $x \in \mathbb{R}^n$ is the state, $w \in \mathbb{R}^s$ is the disturbance belonging to $w \in L_2[0, t_f]$, $t_f \in \mathbb{R}_{>0}$, $u \in \mathbb{R}^m$ is the control input, $z \in \mathbb{R}^q$ is the controlled output, and

$$\begin{aligned} A(\mu) &:= \sum_{i=1}^{r} \theta_i(\mu)\, A_i \\ B_w(\mu) &:= \sum_{i=1}^{r} \theta_i(\mu)\, B_{w_i} \\ B_u(\mu) &:= \sum_{i=1}^{r} \theta_i(\mu)\, B_{u_i} \\ D(\mu) &:= \sum_{i=1}^{r} \theta_i(\mu)\, D_i \\ E(\mu) &:= \sum_{i=1}^{r} \theta_i(\mu)\, E_i \end{aligned}$$

in which $\theta_i(\mu)$ the firing strength satisfying two properties

$$\theta_i(\mu) \in \mathbb{R}_{[0,1]}$$
$$\sum_{i=1}^{r} \theta_i(\mu) = 1$$

and μ the vector containing premise variables.

Throughout this paper, we assume the following.

Assumption 1: The vector-valued function f in (1) is locally Lipschitz in x on $\mathcal{B}_x := \{x \in \mathbb{R}^n | \|x\| \le \Delta_x\}$ with Lipschitz constant $l \in \mathbb{R}_{>0}$.

Our concerned problem is formulated as follows.

Problem 1: Given the sampling time $T \in \mathbb{R}_{>0}$, find the control gains K_i and X_i such that

i) when $w = 0$, (1) closed by the sampled-data fuzzy controller

$$u = u_{kT} := K(\mu_{kT}) X(\mu_{kT})^{-1} x_{kT} \tag{2}$$

for $t \in [kT, kT+T), k \in \mathbb{Z}_{\ge 0}$, is asymptotically stable, where

$$K(\mu_{kT}) := \sum_{i=1}^{r} \theta_i(\mu_{kT}) K_i$$

and

$$X(\mu_{kT}) := \sum_{i=1}^{r} \theta_i(\mu_{kT}) X_i$$

ii) when $w \in L_2[0, NT]$ and $x_0 = 0$, it has γ-disturbance-attenuation performance defined by

$$\int_0^{NT} \|z(\tau)\|^2 d\tau \le \gamma^2 \int_0^{NT} \|w(\tau)\|^2 d\tau \tag{3}$$

for the given attenuation level $\gamma \in \mathbb{R}_{>0}$ and some $N \in \mathbb{N}$.

III. MAIN RESULTS

Before proceeding next, the following lemmas and propositions will be needed in proving the main results:

Lemma 1 [8]**:** Given any vector function x, and $P = \mathrm{P}^{\mathrm{T}} \succ 0$ 0 of appropriate dimensions, and $t_0, t_f \in \mathbb{R}_{>0}$, it is true that

$$\left(\int_{t_0}^{t_f} x(\tau) d\tau\right)^T P \int_{t_0}^{t_f} x(\tau) d\tau \le (t_f - t_0) \int_{t_0}^{t_f} x(\tau)^T P x(\tau) d\tau$$

Lemma 2 [9]**:** Given any matrices X and $P = P^T \succ 0$, it is true that

$$-X^T P^{-1}(*) \preccurlyeq P - \mathrm{He}\{\mathrm{X}\}$$

Lemma 3 [10]**:** The following matrix inequality

$$\sum_{i=1}^{r}\sum_{j=1}^{r} \theta_i(\mu_{kT})\theta_j(\mu_{kT}) Y_{ij} \prec 0$$

holds if there exist Z_{ij} of appropriate dimension such that

$$Y_{ii} - Z_{ii} \prec 0, i \in I_R$$
$$Y_{ij} + Y_{ji} - He\{Z_{ij}\} \prec 0, (i,j) \in I_J \times I_R$$
$$\begin{bmatrix} Z_{11} & (*) & \cdots & (*) \\ Z_{12} & Z_{22} & & (*) \\ \vdots & & \ddots & \vdots \\ Z_{1r} & Z_{2r} & \cdots & Z_{rr} \end{bmatrix} \prec 0$$

where $I_R := \{1, 2, \ldots, r\}$ and $I_J \times I_R$ means all pairs $(i,j) \in I_R \times I_R$ such that $1 \le i < j \le r$.

Proposition 1: An exact discrete-time model of (1) is given by

$$\begin{aligned} x_{kT+T} = x_{kT} + \int_{kT}^{kT+T} & (A(\mu_{kT}) x_{kT} + B_w(\mu_{kT}) w \\ & + B_u(\mu_{kT}) u_{kT} + p) d\tau \end{aligned} \tag{4}$$

Then, the discrete-time model of (4) together with (3) becomes

$$\begin{aligned} x_{kT+T} = \int_{kT}^{kT+T} & \left[\frac{1}{T} I + G(\mu_{kT}) X(\mu_{kT})^{-1} \quad B_w(\mu_{kT})\right] \\ & \times \begin{bmatrix} x_{kT} \\ w \\ p \end{bmatrix} d\tau \end{aligned} \tag{5}$$

where

$$p = f(x, w, u_{kT}) - f(x_{kT}, w, u_{kT})$$
$$G(\mu_{kT}) = A(\mu_{kT}) X(\mu_{kT}) + B_u(\mu_{kT}) K(\mu_{kT}).$$

Proof: Integrating both sides in (1) under $u = u_{kT}$ over $[kT, t]$ and replacing t by $kT + T$ yields (4). ■

Proposition 2: Assume that $w = 0$. Then, whenever (5) is asymptotically stable, the closed-loop system of (1) and (2) is also asymptotically stable.

Proof: It follows from (1) and (2) that $t \in [kT, kT+T), k \in \mathbb{Z}_{\ge 0}$,

$$\begin{aligned} \|x\| \le \|x_{kT}\| + \int_{kT}^{t} \sum_{i=1}^{r}\sum_{j=1}^{r} & \theta_i(\mu_\tau)\theta_j(\mu_{kT}) \left(\|A_i\| \|x(\tau)\|\right. \\ & \left. + \|B_{u_i} K_j\| \|X(\mu_{kT})^{-1}\| \|x_{kT}\|\right) d\tau \\ \le \sup_{(g,h,i,j) \in I_R \times I_R \times I_R \times I_R} & \left(\left(1 + \frac{T(\|B_{u_i} K_j\|)}{\sqrt{\lambda_{min}(X_g X_h^T)}}\right) \|x_{kT}\| \right. \\ & \left. + \int_{kT}^{t} \|A_i\| \|x(\tau)\| d\tau \right) \end{aligned}$$

Applying the Grownwall-Bellman inequality to $\|x\|$ yields

$$\|x\| \le c_1 \mathrm{e}^{c_2 T} \|x_{kT}\| =: \mathrm{c}_3 \|x_{kT}\|$$

where

$$c_1 = \sup_{(g,h,i,j) \in I_R \times I_R \times I_R \times I_R} \left(1 + \frac{T(\|B_{u_i} K_j\|)}{\sqrt{\lambda_{min}(X_g X_h^T)}}\right)$$
$$c_2 = \sup_{i \in I_R} \|A_i\|.$$

It is obvious that c_3 is independent of $k \in \mathbb{Z}_{\ge 0}$. Hence, we can conclude that $\|x\|$ is uniformly bounded by $\|x_{kT}\|$. ■

Theorem 1: The sampled-data fuzzy controller (2) asymptotically stabilizes (1) with γ-disturbance- attenuation performance if there exist $P_i = P_i^T \succ 0$, K_i, X_i, and Z_{ij} such that

$$Y_{ghii} - Z_{ii} \prec 0, (g,h,i) \in I_R \times I_R \times I_R \quad (6)$$

$$Y_{ghij} + Y_{ghji} - He\{Z_{ij}\} \prec 0, (g,h,i,j) \in I_R \times I_R \times I_J \times I_R \quad (7)$$

$$\begin{bmatrix} Z_{11} & (*) & \cdots & (*) \\ Z_{12} & Z_{22} & & (*) \\ \vdots & & \ddots & \vdots \\ Z_{1r} & Z_{2r} & \cdots & Z_{rr} \end{bmatrix} \prec 0 \quad (8)$$

where

$$Y_{ghij} = \begin{bmatrix} \frac{1}{T}P_i - He\{X_i\} & (*) & (*) & (*) & (*) & (*) & (*) \\ 0 & -\gamma I & (*) & (*) & (*) & (*) & (*) \\ 0 & 0 & -I & (*) & (*) & (*) & (*) \\ 0 & 0 & 0 & -I & (*) & (*) & (*) \\ \frac{1}{T}X_i + A_i X_j + B_{u_i} K_j & B_{w_i} & I & 0 & -\frac{1}{T}P_h & (*) & (*) \\ D_g X_i + E_g K_i & 0 & 0 & D_g & 0 & -\gamma I & (*) \\ A_i X_j + B_{u_i} K_j & B_{w_i} & I & 0 & 0 & 0 & -\frac{2}{(l^2+1)T^2} I \end{bmatrix}$$

Proof: Define

$$J_{kT} := \Delta V(x_{kT}) + \gamma^{-1} \int_{kT}^{kT+T} z^T z \, d\tau - \gamma \int_{kT}^{kT+T} w^T w \, d\tau \quad (9)$$

where

$$\Delta V(x_{kT}) = V(x_{kT+T}) - V(x_{kT})$$
$$V(x_{kT}) = x_{kT}^T P(\mu_{kT})^{-1} x_{kT}$$
$$P(\mu_{kT}) = \sum_{i=1}^{r} \theta_i(\mu_{kT}) P_i.$$

We observed that

i) in the case that $w = 0$,

$$J_{kT} < 0 \Rightarrow \Delta V(x_{kT}) < 0$$

since

$$\gamma^{-1} \int_{kT}^{kT+T} z^T z \, d\tau > 0$$

ii) in the case that $w \in L_2[0, NT]$ and $x_0 = 0$,

$$\begin{aligned} J_{kT} < 0 &\Rightarrow \Delta V(x_{kT}) + \gamma^{-1} \int_{kT}^{kT+T} z^T z \, d\tau - \gamma \int_{kT}^{kT+T} w^T w \, d\tau < 0 \\ &\Rightarrow V(x_{NT}) - V(x_0) + \gamma^{-1} \int_0^{NT} z^T z \, d\tau - \gamma \int_0^{NT} w^T w \, d\tau < 0 \\ &\Rightarrow (3) \end{aligned}$$

since $V(x_{NT}) > 0$ and $V(x_0) = 0$.

It follows from (5) in Proposition 1, (9), Lemmas 1-3, Assumption 1, the congruence transformation, and the Schur complement, and the definitions

$$H(\mu, \mu_{kT}) := D(\mu) X(\mu_{kT}) + E(\mu) K(\mu_{kT})$$
$$\tilde{x} := [x_{kT}^T \quad w^T \quad p^T \quad x(\tau)^T - x_{kT}^T]^T$$

that

$$\begin{aligned} & J_{kT} < 0 \\ \Leftarrow\ & T \int_{kT}^{kT+T} \begin{bmatrix} x_{kT} \\ w \\ p \end{bmatrix}^T \begin{bmatrix} \frac{1}{T} I + G(\mu_{kT}) X(\mu_{kT})^{-1} & B_w(\mu_{kT}) & I \end{bmatrix}^T \\ & + \gamma^{-1} \int_0^{NT} \begin{bmatrix} x_{kT} \\ x(\tau) - x_{kT} \end{bmatrix}^T [H(\mu, \mu_{kT}) X(\mu_{kT})^{-1} \quad D(\mu)]^T (*) \\ & \times \begin{bmatrix} x_{kT} \\ x(\tau) - x_{kT} \end{bmatrix} d\tau - \gamma \int_{kT}^{kT+T} w^T w \, d\tau - x_{kT}^T P(\mu_{kT})^{-1} x_{kT} \\ & < 0 \end{aligned}$$

$\Leftarrow$

$$T \int_{kT}^{kT+T} \tilde{x}^T \left(\begin{bmatrix} \frac{1}{T} I + G(\mu_{kT}) X(\mu_{kT})^{-1} & B_w(\mu_{kT}) & I & 0 \\ H(\mu, \mu_{kT}) X(\mu_{kT})^{-1} & 0 & 0 & D(\mu) \\ G(\mu_{kT}) X(\mu_{kT})^{-1} & B_w(\mu_{kT}) & I & 0 \end{bmatrix}^T \times \begin{bmatrix} \frac{1}{T} P(\mu_{kT+T}) & 0 & 0 \\ 0 & \gamma I & 0 \\ 0 & 0 & \frac{2}{(l^2+1)T^2} I \end{bmatrix}^{-1} (*) - \begin{bmatrix} \frac{1}{T} P(\mu_{kT})^{-1} & 0 & 0 & 0 \\ 0 & \gamma I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{bmatrix} \right) \tilde{x} d\tau < 0$$

$$\Leftarrow \begin{bmatrix} -\frac{1}{T} P(\mu_{kT})^{-1} & (*) & (*) & (*) & (*) & (*) & (*) \\ 0 & -\gamma I & (*) & (*) & (*) & (*) & (*) \\ 0 & 0 & -I & (*) & (*) & (*) & (*) \\ 0 & 0 & 0 & -I & (*) & (*) & (*) \\ \frac{1}{T} I + G(\mu_{kT}) X(\mu_{kT})^{-1} & B_w(\mu_{kT}) & I & 0 & -\frac{1}{T} P(\mu_{kT+T}) & (*) & (*) \\ H(\mu, \mu_{kT}) X(\mu_{kT})^{-1} & 0 & 0 & D(\mu) & 0 & -\gamma I & (*) \\ G(\mu_{kT}) X(\mu_{kT})^{-1} & B_w(\mu_{kT}) & I & 0 & 0 & 0 & -\frac{2}{(l^2+1)T^2} I \end{bmatrix} \prec 0$$

$$\Leftarrow \sum_{g=1}^{r} \sum_{h=1}^{r} \sum_{i=1}^{r} \sum_{j=1}^{r} \theta_g(\mu_\tau) \theta_h(\mu_{kT+T}) \theta_i(\mu_{kT}) \theta_j(\mu_{kT}) Y_{ghij} \prec 0$$

$\Leftarrow$ LMIs (6), (7), and (8).

Therefore, from Proposition 2, we can conclude that the closed-loop system of (1) and (2) is asymptotically stable with γ-disturbance- attenuation performance. ■

Remark 1: Theorem 1 are based on the non-quadratic Lyapunov functions with $\boldsymbol{P_i}$, $\boldsymbol{i} \in \boldsymbol{I_R}$, which leads to a less conservative result than previous results [1-3] based on the usage of the quadratic Lyapunov functions with common $\boldsymbol{P_1} = \boldsymbol{P_2} = \cdots = \boldsymbol{P_r} = \boldsymbol{P}$.

IV. A NUMERICAL EXAMPLE

Consider the simply modified Moore–Greitzer model of a jet engine with the assumption of no stall taken from [10]

$$f(x,w,u) = \begin{bmatrix} -\frac{3}{2}x_1^2 - \frac{1}{2}x_1^3 - x_2 \\ -u + w \end{bmatrix}$$
$$z = 0.1x_2 + 0.1w$$

in which we see that $l = \frac{71}{8}$ from

$$\left\|\frac{\partial f}{\partial x}\right\| = \max\left\{\left|-3x_1 - \frac{3}{2}x_1^2\right| + 1, 0\right\}.$$
$$x_1 \in \left\{x_1 \in \mathbb{R} \mid |x_1| \le \frac{3}{2}\right\}$$

By consulting the fuzzy modeling [4], its T-S fuzzy model is given by

$$A_1 = \begin{bmatrix} \frac{9}{8} & -1 \\ 0 & 0 \end{bmatrix},\ A_2 = \begin{bmatrix} -\frac{27}{8} & -1 \\ 0 & 0 \end{bmatrix},$$
$$B_{u_1 1} = B_{u_2} = \begin{bmatrix} 0 \\ -1 \end{bmatrix},\ B_{w_1} = B_{w_2} = \begin{bmatrix} 0 \\ -1 \end{bmatrix},$$
$$D_1 = D_2 = [0 \quad 0.1],\ E_1 = E_2 = 0.1.$$
$$\theta_1(\mu) = \theta_1(x_1) \frac{-\frac{3}{2}x_1 - \frac{1}{2}x_1^2 + \frac{27}{8}}{\frac{36}{8}},\ \theta_2(\mu) = 1 - \theta_1(\mu)$$

Solving LMIs (6), (7), and (8) in Theorem 1 for the given $T = 0.02$ and $\gamma = 0.1992$, we have the following control gains:

$$K_1 = [-0.0141 \quad 0.2667],\ K_2 = [-0.0141 \quad 0.2676]$$
$$X_1 = \begin{bmatrix} 0.0145 & 0.0266 \\ 0.0267 & 0.0555 \end{bmatrix},\ X_2 = \begin{bmatrix} 0.0162 & 0.0271 \\ 0.0270 & 0.0533 \end{bmatrix}.$$

When $x_0 = 0$, $w = \cos 30t$, $t \in \mathbb{R}_{[0,10]}$, and $w = 0$, $t \in \mathbb{R}_{>10}$, Figs. 1-4 depict show time responses of the closed-loop states, the sampled-data control input, and controlled output. From this simulation results, we see that all claims in Theorem 1 is true.

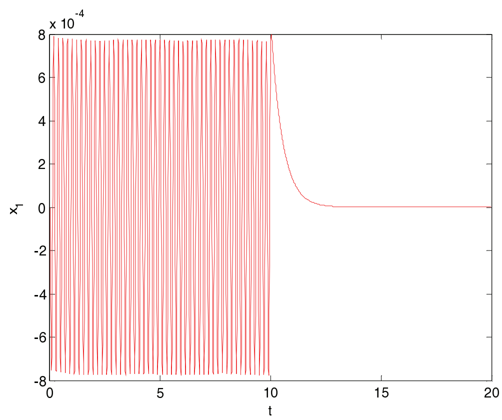

그림 1. x_1의 시간응답.

Fig. 1. Time response of x_1.

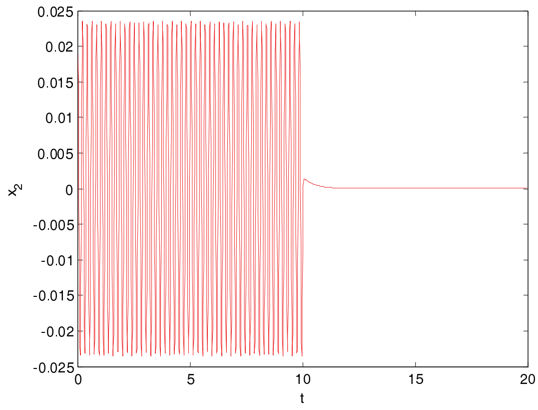

그림 2. x_2의 시간응답.

Fig. 2. Time response of x_2.

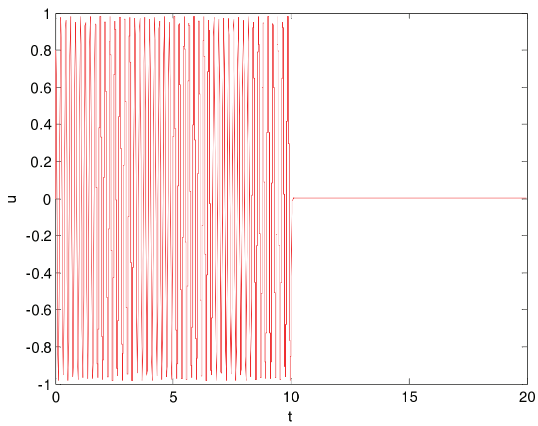

그림 3. u의 시간응답.

Fig. 3. Time response of u

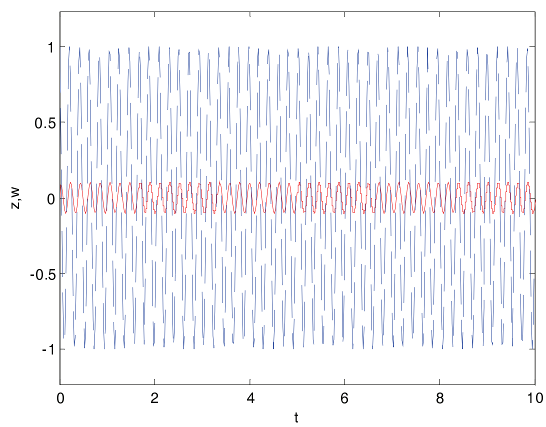

그림 4. z (실선)와 w(파선)의 시간응답.

Fig. 4. Time response of z(solid) and w(dashed).

V. CONCLUSIONS

This paper has derived sufficient design conditions for H_∞ sampled-data stabilization of a Takagi-Sugeno (T-S) fuzzy system. The theoretical results are based on the exactly, rather than approximately, discretized model of a class of nonlinear systems. Numerical simulation has successfully verified all of theoretical claims.

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