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Robust Synchronization and Fault Detection of Uncertain Master-Slave Systems with Mixed Time-Varying Delays and Nonlinear Perturbations

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Abstract: In this paper, the problem of robust synchronization and fault detection for a class of master-slave systems subjected to some nonlinear perturbations and mixed neutral and discrete time-varying delays is investigated based on an H_∞ performance condition. By introducing a descriptor technique, using Lyapunov-Krasovskii functional and a suitable change of variables, new required sufficient conditions are established in terms of delay-dependent linear matrix inequalities to synthesize the residual generation scheme. The explicit expression of the synchronization law is derived for the fault such that both asymptotic stability and a prescribed level of disturbance attenuation are satisfied for all admissible nonlinear perturbations. A numerical example with simulation results illustrates the effectiveness of the methodology.

Keywords: Fault detection, master-slave systems, nonlinear perturbation, synchronization, time-delay.

1. INTRODUCTION

In the last few years, synchronization in dynamical systems has received a great deal of interest among scientists from various fields [1-5]. In order to better understand the dynamical behaviours of different kind of complex networks, an important and interesting phenomenon to investigate is the synchrony of all dynamical nodes. In fact, synchronization is a basic motion in nature that has been studied for a long time, ever since the discovery of Christian Huygens in 1665 on the synchronization of two pendulum clocks. The results of chaos synchronization are utilized in biology, chemistry, secret communication and cryptography, nonlinear oscillation synchronization and some other nonlinear fields. The first idea of synchronizing two identical chaotic systems with different initial conditions was introduced by Pecora and Carroll [6], and the method was realized in electronic circuits. The methods for synchronization of the chaotic systems have been widely studied in recent years, and many different methods have been applied theoretically and experimentally to synchronize chaotic systems, such as feedback control [7-12], adaptive control [13-17], backstepping [18] and sliding mode control [19,20]. Recently, the theory of incremental input-to-state stability to the problem of synchronization in a complex dynamical network of identical nodes, using chaotic nodes as a typical platform was studied in [21].

There is an increasing demand for dynamic systems to become safer, more reliable and more economical in operation. This requirement extends beyond the normally accepted safety-critical systems e.g., nuclear reactors, aircraft and many chemical processes, to systems such as autonomous vehicles and some process control systems where the system availability is vital [22]. The field of fault diagnosis for dynamic systems (including fault detection and isolation) has become an important topic of research in the past three decades (see for instance [22-26]).

On the other hand, time-delay exists widely in practice. The delay effects on the stability of systems including delays in the state and/or input is a problem of recurring interest since the delay presence may induce complex behaviours (oscillation, instability, bad performances) for the schemes (see for instance [27-30]). Large delays in some reaction processes of chemical industries or time-delays induced by long-distance transportation and communication might cause the closed-loop systems unstable and deteriorate the control performance. Recently, a stability criteria is proposed for neutral systems with mixed time-varying delays and nonlinear perturbations based on Lyapunov functional approach and linear matrix inequality method in [31]. On the contrary to the intensive investigation of robust fault diagnosis for uncertain systems and fault diagnosis for nonlinear systems, which have achieved much progress in recent years [32,33], the works on fault diagnosis for time-delay systems are very few.

On the research of fault diagnosis for linear time-delay systems, Yang and Saif in [34] first proposed a scheme of actuator and sensor fault diagnosis using an unknown input observer and a technique of input estimation for systems with time-delays only in the state. In this work, modeling uncertainties were not considered and some assumptions on the system's structure decomposition were unreasonable. For systems with state and input time-delays, Ding *et al*. in [35] designed a robust fault detection filter that guaranteed both sensitivity to faults and insensitivity to disturbances. In the scheme of the

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reference [36], the influence of disturbances on the residual was further decreased using the idea of integrated design of H_∞ filter and unknown input observer. Based on an adaptive observer, Jiang *et al.* in [37] developed a scheme to estimate abrupt state fault for linear (nonlinear) systems with only state time-delays, and no uncertainties were considered. For systems with constant time-delays in inputs and outputs only, Zhang *et al.*, in [38] presented a state fault detection method based on parity space. Recently, a geometric approach for fault detection and isolation of retarded and neutral time-delay systems was developed in [39]. The time-delays investigated above are either in the state, the derivative of the state or in the input/output, neither in both of them or in the derivative of state. In practice, a system may involve time-delays in states, inputs/outputs and the derivative of states, and the influences of modeling uncertainties, noises and disturbances are perhaps not negligible. Furthermore, from the published results in [23,24,39,40], it appears that general results pertaining to robust fault detection of linear systems with mixed neutral and discrete time-varying delays, some nonlinear perturbations and an H_∞ performance criteria, which are infinite dimensional systems in essence, are few and restricted, despite its practical importance, mainly due to the mathematical difficulties in dealing with such mixed delays and nonlinearities. Hence, it is our intention in this paper to tackle such an important yet challenging problem.

In this paper, we are concerned to develop a new delay-dependent stability criterion for robust synchronization and fault detection filter problem of linear systems subjected to mixed neutral and discrete time-varying delays and some nonlinear perturbations which satisfy the Lipschitz conditions. The contribution of this paper is three-fold: first, this paper extends previous works on synchronization and fault detection problem and derives some new theoretical results; second, this paper shows how the synchronization and fault detection problem can be reduced to a convex problem with additional degrees of freedom to design a synchronization law; third, by introducing a descriptor technique, using Lyapunov-Krasovskii functional and a suitable change of variables, we establish new required sufficient conditions in terms of delay-dependent linear matrix inequalities (LMIs) under which the desired synchronization law exist, and derive the explicit expression of these salve systems to satisfy both asymptotic stability and an H_∞ performance condition. A numerical example is given to illustrate the use of our results.

Notations: The notations used throughout the paper are fairly standard. I and 0 represent identity matrix and zero matrix; symbols J and $\hat{J}$ represent, respectively, [I, 0]and $[0, I]$; the superscript $'T'$ stands for matrix transposition and. ||.|| refers to the Euclidean vector norm or the induced matrix 2-norm. diag$\{\cdots\}$ represents a block diagonal matrix and the operator sym(A) represents $A+A^T$. $\varepsilon\{.\}$ denotes the expectation operator with respect to some probability measure P. The notation $P>0$ means that P is real symmetric and positive definite; the symbol * denotes the elements below the main diagonal of a symmetric block matrix.

2. PROBLEM DESCRIPTION

We consider a class of continuous linear systems with some nonlinear perturbations and mixed neutral and discrete time-varying delays described by

$$\begin{aligned}\dot{x}_m(t) &= A\,x_m(t) + A_1\,x_m(t-\tau(t)) + A_2\,\dot{x}_m(t-d(t)) \\ &\quad + E_{h_1}\,h_1(t,x_m(t)) + E_{h_2}\,h_2(t,x_m(t-\tau(t))) \\ &\quad + E_{h_3}\,h_3(t,\dot{x}_m(t-d(t))) + E_f\,f(t),\end{aligned} \tag{1a}$$

$$x_m(t) = \phi(t) \qquad t\in[-\kappa,\,0], \tag{1b}$$

$$z_m(t) = C_1\,x_m(t), \tag{1c}$$

$$y_m(t) = C_2\,x_m(t) + C_h\,h_4(t,x_m(t)) + C_f\,f(t) \tag{1d}$$

with $x_m(t)=[x_{m1}(t),x_{m2}(t),\cdots,x_{mn}(t)]^n\in\Re^n$ where $x_{mi}(t)$ are the master system's state vector associated with the i-th state, $z_m(t)\in\Re^z$ and $y_m(t)\in\Re^p$ are, respectively, the controlled- and the measured- output of the master system. The term $f(t)\in\Re^l$ corresponds to fault modes and E_f is called fault signature which is assumed known. $h_1(t,x(t))$, $h_2(t,x(t-\tau(t)))$, $h_3(t,\dot{x}(t-d(t)))$ and $h_4(t,x(t))$ are time-varying vector-valued functions which are unknown and present the nonlinear parameter perturbations. The time-varying function $\phi(t)$ is continuous vector valued initial function and the parameters $\tau(t)$ and $d(t)$ are time-varying delays satisfying

$$0\le\tau(t)\le\tau_1,\qquad \dot{\tau}(t)\le\tau_2, \tag{2a}$$

$$0\le d(t)\le d_1,\qquad \dot{d}(t)\le d_2<1 \tag{2b}$$

with $\kappa=\max\{\tau_1,d_1\}$. One can define a difference operator $D:C([-\kappa,0],\Re^n)\to\Re^n$ such that

$$Dx_t = x(t) - A_2\,x(t-d(t)). \tag{3}$$

Definition 1 [27]**:** The difference operator D is said to be stable if the zero solution of the homogeneous difference equation

$$Dx_t = 0,\, t\ge 0,\, x_0=\Psi\in\{\Phi\in C([-\kappa,0]):\nabla\Phi=0\}$$

is uniformly asymptotically stable.

The stability of the difference operator D is necessary for the stability of the system (1). Therefore, throughout the paper, the following assumption is needed to enable the application of Lyapunov's method for the stability of neutral systems.

Assumption 1: It follows from [27] that a delay-independent sufficient condition for the asymptotic stability of the system (1) is that all the eigenvalues of the matrix A_2 are inside the unit circle, i.e., $\lambda_{\max}(A_2)<1$.

Furthermore, we make the following assumption for the nonlinear perturbation functions in (1).

Assumption 2: The nonlinear function $h_i : \Re \times \Re^n \to \Re^n$ are continuous and satisfy $h_i(t, 0)=0$ and the Lipschitz condition, i.e., $\|h_i(t,x_0) - h_i(t,y_0)\| \le \|U_i(x_0 - y_0)\|$ for all $x_0, y_0 \in \Re^n$ and U_i are known matrices.

Remark 1: The model (1) can describe a large amount of well-known dynamical systems with time-delays, such as the delayed Logistic model, the chaotic models with time-delays, the artificial neural network models with time-delays, and the predator-prey model with delays.

Now, given the master signal $x_m(t)$, we are to design a feasible coupling technique to realize the synchronization between two identical systems with different initial conditions. Actually, the slave system is described as follows:

$$\begin{aligned}\dot{x}_s(t) &= A x_s(t) + A_1 x_s(t-\tau(t)) + A_2 \dot{x}_s(t-d(t)) \\ &\quad + E_{h_1} h_1(t, x_s(t)) + E_{h_2} h_2(t, x_s(t-\tau(t))) \\ &\quad + E_{h_3} h_3(t, \dot{x}_s(t-d(t))) + B u(t) + D w(t),\end{aligned} \tag{4a}$$

$$x_s(t) = \varphi(t) \qquad t \in [-\kappa, 0], \tag{4b}$$

$$z_s(t) = C_1 x_s(t), \tag{4c}$$

$$y_s(t) = C_2 x_s(t) + C_h h_4(t, x_s(t)), \tag{4d}$$

$$r(t) = V(y_m(t) - y_s(t)) \tag{4e}$$

with $x_s(t) = [x_{s1}(t), x_{s2}(t), \cdots, x_{sn}(t)]^n \in \Re^n$ where $x_{si}(t)$ are the slave system's state vector associated with the ith state; $u(t) \in \Re^m$ is a coupled term which is considered as the control input; $w(t) \in L_2^s[0, \infty)$ is the disturbance, $z_s(t) \in \Re^z$ and $y_s(t) \in \Re^p$ are corresponded to the controlled- and the measured output of the slave system, respectively. $\varphi(t)$ is a continuously differentiable functional. $r(t)$ is the so-called *generated residual signal* and is associate with a matrix V.
In the absence of $w(t)$ and $f(t)$, it is required that

$$\|x_m(t) - x_s(t)\|_2 \to 0 \quad as \quad t \to \infty, \tag{5}$$

where $e(t) = [e_1(t), e_2(t), \ldots, e_n(t)]^T = x_m(t) - x_s(t)$ is the synchronization error. Then, the synchronization error system between (1) and (4) can be expressed by

$$\begin{aligned}\dot{e}(t) &= Ae(t) + A_1 e(t-\tau(t)) + A_2 \dot{e}(t-d(t)) \\ &\quad + E_{h_1} \psi_1(t, e(t)) + E_{h_2} \psi_2(t, e(t-\tau(t))) \\ &\quad + E_{h_3} \psi_3(t, \dot{e}(t-d(t))) - B u(t) - \hat{D} \hat{w}(t),\end{aligned} \tag{6a}$$

$$z_m(t) - z_s(t) = C_1 e(t), \tag{6b}$$

$$r(t) = V(C_2 e(t) - C_h \psi_4(t, e(t)) + C_f \hat{J} \hat{w}(t)), \tag{6c}$$

where $\hat{w}(t) := col\{w(t), f(t)\}$, $\hat{D} := [D, -E_f]$ and

$$\begin{aligned}\psi_1(t, e(t)) &= h_1(t, x_m(t)) - h_1(t, x_m(t) - e(t)), \\ \psi_2(t, e(t-\tau(t))) &= h_2(t, x_m(t-\tau(t))) \\ &\quad - h_2(t, x_m(t-\tau(t)) - e(t-\tau(t))), \\ \psi_3(t, \dot{e}(t-d(t))) &= h_3(t, \dot{x}_m(t-d(t))) \\ &\quad - h_3(t, \dot{x}_m(t-d(t)) - \dot{e}(t-d(t))), \\ \psi_4(t, e(t)) &= h_4(t, x_m(t)) - h_4(t, x_m(t) - e(t)).\end{aligned}$$

From Assumption 2, the Mean Value theorem and the Leibniz-Newton formula, i.e., $e(t) - e(t-\tau(t)) = \int_{t-\tau(t)}^{t} \dot{e}(s) ds$, it is easy to see

$$\begin{aligned}&\psi_2(t, e(t)) - \psi_2(t, e(t-\tau(t))) \\ &\quad = \dot{\psi}_2(\xi)(e(t) - e(t-\tau(t))) \\ &\quad = \dot{\psi}_2(\xi) \int_{t-\tau(t)}^{t} \dot{e}(s) ds,\end{aligned} \tag{7}$$

where ξ is a point on the straight line between $e(t)$ and $e(t-\tau(t))$, which may be different for different rows of $\dot{\psi}_2(\xi)$.

Remark 2: It is noting that, from the equation (7), one can obtain

$$\begin{aligned}&\|\psi_2(t, e(t)) - \psi_2(t, e(t-\tau(t)))\| \\ &\quad = \|\dot{\psi}_2(\xi)(e(t) - e(t-\tau(t)))\| \\ &\quad \le \|\dot{\psi}_2(\xi)\| \|e(t) - e(t-\tau(t))\|\end{aligned} \tag{8}$$

thus, the Lipschitz constant of $\psi_2(.)$can be estimated by $\max_{\xi} \|\dot{\psi}_2(\xi)\|$.

Therefore, from the equation (7), the synchronization error system can be represented in a descriptor model form as

$$\dot{e}(t) = \eta(t), \tag{9a}$$

$$\begin{aligned}\eta(t) &= (A + A_1)e(t) - A_1 \int_{t-\tau(t)}^{t} \eta(s) ds + A_2 \eta(t-d(t)) \\ &\quad + E_{h_1} \psi_1(t, e(t)) + E_{h_2} \psi_2(t, e(t-\tau(t))) \\ &\quad + E_{h_3} \psi_3(t, \eta(t-d(t))) - B u(t) - \hat{D} \hat{w}(t),\end{aligned} \tag{9b}$$

where $S := \dot{\psi}_2(\xi)$.

Remark 3: In general, an equivalent descriptor form is employed to include information about static as well as dynamic constraints. In particular, applying inequalities to descriptor systems augmented from a state-space system also generates some freedom as shown in the next section.

Definition 2: The salve system (6) is said

1) to achieve asymptotic stability in the Lyapunov sense for $\hat{w}(t) = 0$ if the synchronization error system (6) is asymptotically stable for all admissible nonlinear perturbations.
2) to guarantee H_∞ performance condition if under zero initial conditions,

$$\sup_{\|\hat{w}\|_2 \neq 0} \frac{\left\| \begin{bmatrix} z(t) - \hat{z}(t) \\ r(t) \end{bmatrix} \right\|_2}{\|\hat{w}(t)\|_2} \le \gamma \tag{10}$$

holds for all bounded energy disturbances and a prescribed positive value γ.

The problem of synchronization with the fault detection we address here is as follows:
Given a prescribed level of disturbance attenuation $\gamma > 0$, *find a driving signal* $u(t)$ *of the form*

$$u(t) = K_1 e(t)$$

where the matrices K_1 *and* V *are to be determined in the sense of Definition 2.*

Furthermore, as commonly adopted in literature [23,24], the fault f(t) can be detected by the following steps.

Step 1: Select a residual evaluation function

$$J(r_{\varpi}(t)) := (\int_{t_1}^{t_2} r(t)^T r(t)dt)^{0.5},$$

where the length of the time window $\varpi = t_2 - t_1$ is finite and t_1 denotes the initial evaluation time instant.

Step 2: Select a threshold $J_{th} := \sup_{w \in L_2, t_1 \geq 0} J(r_{\varpi}(t))$.

Step 3: Test:

$$\begin{aligned} &J(r_{\varpi}(t)) > J_{th} \Rightarrow with\ faults \Rightarrow alarm \\ &J(r_{\varpi}(t)) \leq J_{th} \Rightarrow no\ faults. \end{aligned} \tag{11}$$

This test is a decision making process that always comes down to a threshold logic of a decision function.

Remark 4: The fault can be detected according to the logical relationship (11). In the fault-free case, the generated residual $r(t)$ is only affected by the disturbance input $w(t)$.

Before ending this section, we recall a well-known lemma, which will be used in the proof of our main results.

Lemma 1 [29]**:** For any arbitrary column vectors $a(t)$, $b(t)$, matrices $\Phi(t)$, H, U and W the following inequality holds:

$$-2\int_{t-r}^{t} a(s)^T \Phi(s) b(s)\, ds \leq \int_{t-r}^{t} \begin{bmatrix} a(s) \\ b(s) \end{bmatrix}^T \begin{bmatrix} H & U-\Phi(s) \\ * & W \end{bmatrix} \begin{bmatrix} a(s) \\ b(s) \end{bmatrix} ds,$$

where

$$\begin{bmatrix} H & U \\ * & W \end{bmatrix} \geq 0.$$

3. MAIN RESULTS

In this section, we present our new sufficient conditions for the solvability of the problem of the synchronization and fault detection using the Lyapunov method and an LMI approach.

Firstly, we choose a Lyapunov-Krasovskii functional candidate for the synchronization error system (6a) as

$$V(t) = V_1(t) + V_2(t) + V_3(t), \tag{12}$$

where

$$\begin{aligned} V_1(t) &= e(t)^T P_1 e(t) = \overline{\eta}(t)^T T P \overline{\eta}(t), \\ V_2(t) &= \int_{t-\tau(t)}^{t} e(s)^T Q_1 e(s)ds + \int_{t-d(t)}^{t} e(s)^T Q_2 e(s)ds \\ &\quad + \int_{t-d(t)}^{t} \eta(s)^T Q_3 \eta(s)ds, \\ V_3(t) &= \int_{t-\tau(t)}^{t}\int_{s}^{t} \eta(\xi)^T R_1 \eta(\xi)d\xi ds, \\ V_4(t) &= \int_{t-d(t)}^{t}\int_{s}^{t} \eta(\xi)^T R_2 \eta(\xi)d\xi ds \end{aligned}$$

with $\overline{\eta}(t) := col\{e(t), \eta(t)\}$, $T := diag\{I, 0\}$ and

$$P := \begin{bmatrix} P_1 & 0 \\ P_3 & P_2 \end{bmatrix}, \quad P_1 = P_1^T > 0. \tag{13}$$

In the following theorem, we state our main results.

Theorem 1: Under Assumptions 1 and 2, consider master-slave systems (1) and (4) and let the scalars γ, τ_1, $d_1 > 0$, τ_2, d_2, ε be given. If there exist the matrices P_2, V, U, M_1, $\cdots$, M_9 and the positive definite matrices P_1, H_1, Q_1, Q_2, Q_3, R_1, R_2, satisfying the following LMIs

$$Q_3 - (1-\tau_2)R_1 < 0, \tag{14a}$$

$$\begin{bmatrix} H_1 & U \\ * & Q_3 \end{bmatrix} \geq 0, \tag{14b}$$

$$\begin{bmatrix} \tilde{\Pi} & \overline{d}_{12}\begin{bmatrix} M \\ 0 \end{bmatrix} \\ * & -\overline{d}_{12}R_2 \end{bmatrix} < 0 \tag{14c}$$

with $\overline{d}_{12} := d_1/1-d_2$, $M := col\{M_1, M_2, \cdots, M_9\}$ and

$$\tilde{\Pi} = \begin{bmatrix} \tilde{\Pi}_{11} & \tilde{\Pi}_{12} & J^T M_3 - M_1 & \tilde{\Pi}_{14} & \tilde{\Pi}_{15} & \tilde{\Pi}_{16} & \tilde{\Pi}_{17} & \tilde{\Pi}_{18} & \tilde{\Pi}_{19} & J^T C_2^T V^T \\ * & \tilde{\Pi}_{22} & -M_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & \tilde{\Pi}_{33} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \tilde{\Pi}_{44} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -I & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -I & 0 & 0 & 0 & 0 \\ * & * & * & * & * & * & -I & 0 & 0 & 0 \\ * & * & * & * & * & * & * & -I & 0 & -C_h^T V^T \\ * & * & * & * & * & * & * & * & \tilde{\Pi}_{99} & \hat{J}^T C_f^T V^T \\ * & * & * & * & * & * & * & * & * & -I \end{bmatrix},$$

where

$$\tilde{\Pi}_{11} = sym\left\{\begin{bmatrix} \varepsilon(P_2^T(A+A_1)-\bar{K}_1) & P_1-\varepsilon P_2^T \\ P_2^T(A+A_1)-\bar{K}_1 & -P_2^T \end{bmatrix}\right\} + sym\left\{\left(U-\begin{bmatrix} P_1 \\ 0 \end{bmatrix}A_1\right)J+M_1 J\right\} + \tau_1 H_1 + J^T(Q_1+Q_2+C_1^TC_1+U_1^TU_1+U_4^TU_4)J + \hat{J}^T(\tau_1 R_1 + d_1 R_2 + Q_3)\hat{J},$$

$$\tilde{\Pi}_{12} = -U + \begin{bmatrix} P_1 \\ 0 \end{bmatrix}A_1 - M_1 + J^T M_2^T,$$

$$\tilde{\Pi}_{22} = U_2^T U_2 - (1-\tau_2)Q_1,$$

$$\tilde{\Pi}_{33} = -(1-d_2)Q_2 - sym\{M_3\},$$

$$\tilde{\Pi}_{44} = U_3^T U_3 - (1-d_2)Q_3,\quad \tilde{\Pi}_{14} = \begin{bmatrix} P_1 \\ 0 \end{bmatrix}A_2 + J^T M_4^T,$$

$$\tilde{\Pi}_{15} = \begin{bmatrix} P_1 \\ 0 \end{bmatrix}E_{h_1} + J^T M_5^T,\quad \tilde{\Pi}_{16} = \begin{bmatrix} P_1 \\ 0 \end{bmatrix}E_{h_2} + J^T M_6^T,$$

$$\tilde{\Pi}_{17} = \begin{bmatrix} P_1 \\ 0 \end{bmatrix}E_{h_3} + J^T M_7^T,\quad \tilde{\Pi}_{18} = J^T(M_8^T - C_2^T V^T C_h),$$

$$\tilde{\Pi}_{19} = \begin{bmatrix} P_1 \\ 0 \end{bmatrix}\hat{D} + J^T(C_1^T + C_2^T V^T C_f)\hat{J} + J^T M_9^T,$$

$$\tilde{\Pi}_{99} = \hat{J}^T\hat{J} - \gamma^2 I.$$

Then there exists a state feedback controller given in the form $u(t)=K_1e(t)$ which achieve the asymptotic stability and the H_∞ performance condition, simultaneously, in the sense of Definition 2. Moreover, the matrix K_1 can be found by computing

$$K_1 = B^+(P_2^T)^{-1}\bar{K}_1,$$

where $B^+ = (B^TB)^{-1}B^T$.

Proof: Differentiating $V_1(t)$ in t along the trajectory of the error dynamics (6a) we obtain

$$\begin{aligned}\dot{V}_1(t) &= 2e(t)^T P_1\dot{e}(t) = 2\,\bar{\eta}(t)^T P^T\begin{bmatrix}\dot{e}(t)\\0\end{bmatrix} \\ &= 2\bar{\eta}(t)^T\, P^T(\bar{A}\bar{\eta}(t) + \hat{J}^T A_2\,\eta(t-d(t)) \\ &\quad + \hat{J}^T E_{h_1}\psi_1(t,e(t)) + \hat{J}^T E_{h_2}\psi_2(t,e(t)) \\ &\quad + \hat{J}^T E_{h_3}\psi_3(t,\eta(t-d(t))) + \hat{J}^T\hat{D}\hat{w}(t)) + \beta_1(t),\end{aligned} \tag{15}$$

where

$$\bar{A} := \begin{bmatrix} 0 & I \\ A+A_1-BK_1 & -I \end{bmatrix},$$

$$\beta_1(t) = -2\bar{\eta}(t)^T\, P^T\hat{J}^T(A_1+E_{h_2}S)\int_{t-\tau(t)}^t \eta(s)ds.$$

By Lemma 1 and (7), it is clear that

$$\begin{aligned}\beta_1(t) &\le \int_{t-\tau(t)}^t \begin{bmatrix}\bar{\eta}(t)\\ \eta(s)\end{bmatrix}^T \begin{bmatrix} H_1 & U-P^T\hat{J}^T(A_1+E_{h_2}S) \\ * & Q_3 \end{bmatrix}\begin{bmatrix}\bar{\eta}(t)\\ \eta(s)\end{bmatrix} ds \\ &\le \int_{t-\tau(t)}^t \eta(s)^T Q_3\,\eta(s)ds + \tau_1\bar{\eta}(t)^T H_1\bar{\eta}(t) \\ &\quad + 2\,\bar{\eta}(t)^T(U - P^T\hat{J}^T A_1)(e(t)-e(t-\tau(t))) \\ &\quad - 2\bar{\eta}(t)^T P^T\hat{J}^T E_{h_2}(\psi_2(t,e(t)) \\ &\quad - \psi_2(t,e(t-\tau(t))))\end{aligned} \tag{16}$$

subject to the LMI (14b). The time derivative of the second and third terms of $V(t)$ are, respectively, as

$$\begin{aligned}\dot{V}_2(t) &= e(t)^T(Q_1+Q_2)e(t) - (1-\dot{\tau}(t))e(t-\tau(t))^T \\ &\quad \times Q_1\,e(t-\tau(t)) - (1-\dot{d}(t))e(t-d(t))^T Q_2\,e(t-d(t)) \\ &\quad + \eta(t)^T Q_3\,\eta(t) - (1-\dot{d}(t))\eta(t-d(t))^T Q_3\,\eta(t-d(t)) \\ &\le e(t)^T(Q_1+Q_2)e(t) - (1-\tau_2)e(t-\tau(t))^T Q_1\,e(t-\tau(t)) \\ &\quad - (1-d_2)e(t-d(t))^T Q_2\,e(t-d(t)) + \eta(t)^T Q_3\,\eta(t) \\ &\quad - (1-d_2)\eta(t-d(t))^T Q_3\,\eta(t-d(t))\end{aligned} \tag{17}$$

and

$$\dot{V}_3(t) = \tau_1\,\eta(t)^T R_1\eta(t) - (1-\tau_2)\int_{t-\tau(t)}^t \eta(s)^T R_1\,\eta(s)ds, \tag{18}$$

$$\dot{V}_4(t) = d_1\,\eta(t)^T R_2\eta(t) - (1-d_2)\int_{t-d(t)}^t \eta(s)^T R_2\,\eta(s)ds. \tag{19}$$

Using Assumption 2, we have

$$0 \le -\psi_1(t,e(t))^T\psi_1(t,e(t)) + e(t)^T U_1^T U_1 e(t), \tag{20a}$$

$$\begin{aligned}0 &\le -\psi_2(t,e(t-\tau(t)))^T\psi_2(t,e(t-\tau(t))) \\ &\quad + e(t-\tau(t))^T U_2^T U_2 e(t-\tau(t)),\end{aligned} \tag{20b}$$

$$\begin{aligned}0 &\le -\psi_3(t,\eta(t-d(t)))^T\psi_3(t,\eta(t-d(t))) \\ &\quad + \eta(t-d(t))^T U_3^T U_3\eta(t-d(t)),\end{aligned} \tag{20c}$$

$$0 \le -\psi_4(t,e(t))^T\psi_4(t,e(t)) + e(t)^T U_4^T U_4 e(t). \tag{20d}$$

Moreover, from the Leibniz-Newton formula and (6a), the following equation holds for any matrix M with appropriate dimension,

$$2\upsilon(t)^T M(e(t) - e(t-d(t)) - \int_{t-d(t)}^t \eta(s)ds) = 0, \tag{21}$$

where

$$\begin{aligned}\vartheta(t) := col\,\{&\bar{\eta}(t), e(t-\tau(t)), e(t-d(t)), \eta(t-d(t)), \\ &\psi_1(t,e(t)), \psi_2(t,e(t-\tau(t))), \psi_3(t,\eta(t-d(t))), \\ &\psi_4(t,e(t)), \hat{w}(t)\}.\end{aligned} \tag{22}$$

Construct a HJI function in the form of

$$J[e(t),\hat{w}(t)] = \frac{d}{dt}V(t) + \begin{bmatrix} z_m(t)-z_s(t) \\ r(t)\end{bmatrix}^T\begin{bmatrix} z_m(t)-z_s(t) \\ r(t)\end{bmatrix} - \gamma^2\,\hat{w}(t)^T\,\hat{w}(t), \tag{23}$$

where derivative of $V(t)$ is evaluated along the trajectory of the error dynamics (6a). It is well known that the performance condition (10) is that the inequality $J[e(t),\hat{w}(t)]<0$ for every $\hat{w}(t)\in L_2^s[0,\infty)$ results in a function $V(t)$, which is strictly radially unbounded.

By adding the right- and the left- hand sides of (21)-(22), respectively, to (20), it follows From (15)-(19) that we obtain

$$\begin{aligned} J[e(t),\hat{w}(t)] &\le \vartheta(t)^T (\hat{\Pi}+\bar{d}_{12} M R_2^{-1} M^T)\vartheta(t) \\ &- \int_{t-d(t)}^{t} (\vartheta(t)^T M + (1-d_2)\eta(s)^T R_2)\frac{R_2^{-1}}{1-d_2} \\ &\times (\vartheta(t)^T M + (1-d_2)\eta(s)^T R_2)^T ds \\ &+ \int_{t-\tau(t)}^{t} \eta(s)^T (Q_3-(1-\tau_2)R_1)\,\eta(s)ds, \end{aligned} \tag{24}$$

where the matrix $\hat{\Pi}$ is given by

$$\hat{\Pi}=\begin{bmatrix} \hat{\Pi}_{11} & \hat{\Pi}_{12} & J^T M_3 - M_1 & \hat{\Pi}_{14} & \hat{\Pi}_{15} & \hat{\Pi}_{16} & \hat{\Pi}_{17} & \hat{\Pi}_{18} & \hat{\Pi}_{19} \\ * & \hat{\Pi}_{22} & -M_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & \hat{\Pi}_{33} & 0 & 0 & 0 & 0 & 0 & 0 \\ * & * & * & \hat{\Pi}_{44} & 0 & 0 & 0 & 0 & 0 \\ * & * & * & * & -I & 0 & 0 & 0 & 0 \\ * & * & * & * & * & -I & 0 & 0 & 0 \\ * & * & * & * & * & * & -I & 0 & 0 \\ * & * & * & * & * & * & * & \hat{\Pi}_{88} & -C_h^T V^T V C_f \hat{J} \\ * & * & * & * & * & * & * & * & \hat{\Pi}_{99} \end{bmatrix} \tag{25}$$

with

$$\begin{aligned} \hat{\Pi}_{11} &= sym\{P^T \bar{A}\} + sym\{(U - P^T \hat{J}^T A_1)J + M_1 J\} \\ &\quad + \tau_1 H_1 + J^T (Q_1 + Q_2 + C_1^T C_1 + U_1^T U_1 + U_4^T U_4 \\ &\quad + C_2^T V^T V C_2)J + \hat{J}^T(\tau_1 R_1 + d_1 R_2 + Q_3)\hat{J}, \\ \hat{\Pi}_{12} &= -U + P^T \hat{J}^T A_1 - M_1 + J^T M_2^T, \\ \hat{\Pi}_{22} &= U_2^T U_2 - (1-\tau_2)Q_1, \\ \hat{\Pi}_{33} &= -(1-d_2)Q_2 - sym\{M_3\}, \\ \hat{\Pi}_{44} &= U_3^T U_3 - (1-d_2)Q_3,\ \hat{\Pi}_{14} = P^T \hat{J}^T A_2 + J^T M_4^T, \\ \hat{\Pi}_{15} &= P^T \hat{J}^T E_{h_1} + J^T M_5^T,\ \hat{\Pi}_{16} = P^T \hat{J}^T E_{h_2} + J^T M_6^T, \\ \hat{\Pi}_{17} &= P^T \hat{J}^T E_{h_3} + J^T M_7^T,\ \hat{\Pi}_{18} = J^T (M_8^T - C_2^T V^T C_h), \\ \hat{\Pi}_{19} &= P^T \hat{J}^T \hat{D} + J^T (C_1^T + C_2^T V^T C_f)\hat{J} + J^T M_9^T, \\ \hat{\Pi}_{88} &= C_h^T V^T V C_h - I, \\ \hat{\Pi}_{99} &= \hat{J}^T (I + C_f^T V^T V C_f)\hat{J} - \gamma^2 I. \end{aligned}$$

Thus, if the inequalities

$$\hat{\Pi} + \bar{d}_{12} M R_2^{-1} M^T < 0, \tag{26a}$$

$$Q_3 - (1-\tau_2)R_1 < 0 \tag{26b}$$

hold, it follows from $J[e(t),\hat{w}(t)]\big|_{\hat{w}(t)\equiv 0} \le 0$ that $\frac{d}{dt}V(t) \le 0$ or $V(t)\le V(0)$.

Then, from (12), it can be deduced

$$\begin{aligned} V(0) &= e(0)^T P_1 e(0) + \int_{-\tau(0)}^{0} e(s)^T Q_1 e(s)ds \\ &+ \int_{-d(0)}^{0} e(s)^T Q_2 e(s)ds + \int_{-d(0)}^{0} \eta(s)^T Q_3 \eta(s)ds \\ &+ \int_{-\tau(0)}^{0}\int_{s}^{0} \eta(\xi)^T R_1 \eta(\xi)d\xi ds \\ &+ \int_{-d(0)}^{0}\int_{s}^{0} \eta(\xi)^T R_2 \eta(\xi)d\xi ds \\ &\le \lambda_{\max}(P_1)\|\varphi\|_2^2 + \lambda_{\max}(Q_1)\int_{-\tau(0)}^{0} \varphi(s)^T \varphi(s)ds \\ &+ \lambda_{\max}(Q_2)\int_{-d(0)}^{0} \varphi(s)^T \varphi(s)ds \\ &+ \lambda_{\max}(Q_3)\int_{-d(0)}^{0} \dot{\varphi}(s)^T \dot{\varphi}(s)ds \\ &+ \lambda_{\max}(R_1)\int_{-\tau(0)}^{0}\int_{s}^{0} \dot{\varphi}(\theta)^T \dot{\varphi}(\theta)d\theta ds \\ &+ \lambda_{\max}(R_2)\int_{-d(0)}^{0}\int_{s}^{0} \dot{\varphi}(\theta)^T \dot{\varphi}(\theta)d\theta ds \\ &\le \sigma_1\|\varphi\|_2^2 + \sigma_2\|\dot{\varphi}\|_2^2, \end{aligned}$$

where

$$\sigma_1 := \lambda_{\max}(P_1) + \tau_1\lambda_{\max}(Q_1) + d_1\lambda_{\max}(Q_1)$$

and

$$\sigma_2 := (d_1\lambda_{\max}(Q_3) + 0.5\,\tau_1^2\,\lambda_{\max}(R_1) + 0.5\,d_1^2\,\lambda_{\max}(R_2)).$$

Then, we have:

$$\lambda_{\min}(P_1)\|\varphi\|_2^2 \le V(t) \le \sigma_1\|\varphi\|_2^2 + \sigma_2\|\dot{\varphi}\|_2^2.$$

Now, by considering $P_3 = \varepsilon P_2$, $\bar{K}_1 = P_2^T B K_1$ (to remove the present nonlinearities in the optimization technique) and applying Schur complement on the matrix inequality (26a), the matrix inequality (26a) is converted into a convex programming problem written in terms of LMI (14c). It is also easy to see that the inequality above implies $sym(P_2^T)<0.$ Hence, the matrices P and P_2 are nonsingular.

Remark 5: It is worth noting that one of advantages of the descriptor model (9) is that Lemma 1 and slack variables in (16) can be exploited to reduce conservatism in robust synthesis and the proposed LMI conditions have the numerical advantage of being strict.

Remark 6: It is noted that our approach is different from that in the reference [31] in several perspectives: a) the system structure in [31] considers norm-bounded unknown nonlinear perturbations and in compare to our case do not center on the Lipschitz condition in A2), i.e., the results in [31] can not be directly applied to the systems with Lipschitz nonlinear functions; b) the main problem in [31] is to study the problem of robust stability analysis for time-delay systems in compare to our case that the problem of synchronization with the fault detection and a disturbance attenuation level are considered; c) employing the descriptor technique in the present paper can reduce conservatism in the derived conditions in comparison with the reference [31].

4. NUMERICAL EXAMPLE

Consider the master-slave systems (1) and (4), where the system matrices are given by

$$A=\begin{bmatrix}0&0&1&0\\0&0&0&1\\-0.4&-0.1&-1&-0.5\\-3.6&-5.9&-5&-1.5\end{bmatrix},$$

$$A_1=\begin{bmatrix}0&0&0&0\\0&0&0&0\\-0.2&-0.05&-0.5&-0.25\\-1.8&-2.95&-2.5&-0.75\end{bmatrix},$$

$$A_2=\begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&-0.5&0\\0&0&0&-0.5\end{bmatrix},\quad E_{h_1}=\begin{bmatrix}0&0\\0&0\\-1&-0.5\\5&20.5\end{bmatrix},$$

$$E_{h_2}=\begin{bmatrix}0&0\\0&0\\-0.5&-0.25\\2.5&10.25\end{bmatrix},\quad C_1=\begin{bmatrix}1&1&0&0\end{bmatrix},$$

$$C_2=\begin{bmatrix}1&0.5&0&0\\1&1&0&0\end{bmatrix},\quad E_f=\begin{bmatrix}0\\0\\1\\1\end{bmatrix},$$

$$B=\begin{bmatrix}0\\0\\-1\\1\end{bmatrix},\quad D=\begin{bmatrix}0\\0\\0.1\\0.1\end{bmatrix}.$$

The delays $\tau(t)=d(t)=(1-e^{-t})/(1+e^{-t})$ are time-varying and satisfy $0\le\tau(t)=d(t)\le 1$ and $\dot{\tau}(t)=\dot{d}(t)\le 0.5$. For simulation purpose, a uniformly distributed random signal, shown in Fig. 1, with minimum and maximum -1 and 1, respectively, as the disturbance is imposed on the response system. The fault signal $f(t)$ is

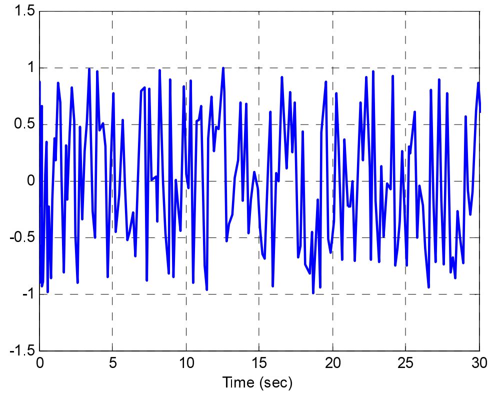


Fig. 1. The disturbance signal.

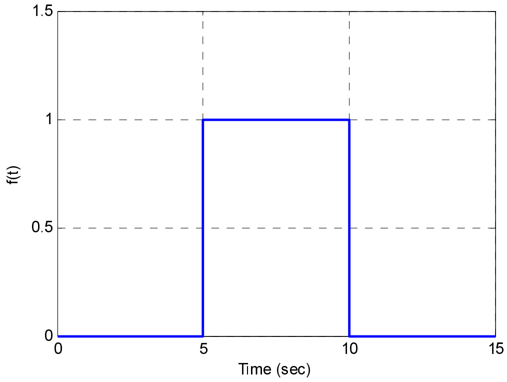
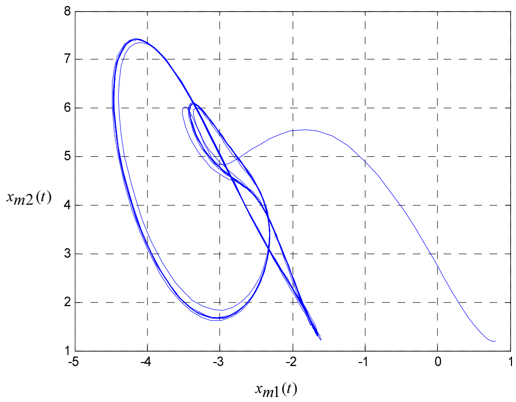
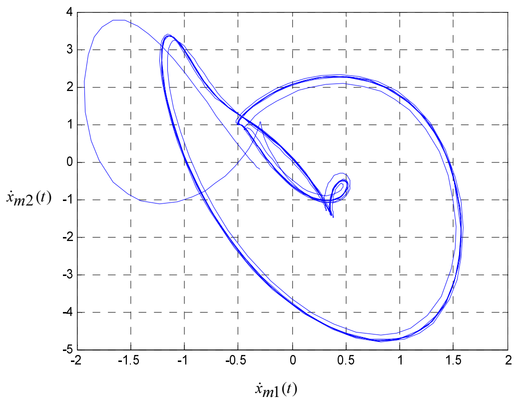


Fig. 2. Fault signal $f(t)$ (abrupt fault).



(a) $x_{m1}-x_{m2}$ plot.



(b) $\dot{x}_{m1}-\dot{x}_{m2}$ plot.

Fig. 3. The phase trajectories.

simulated as a square ware of unite amplitude occurred from 5 to 10 sec, shown in Fig. 2. With the above parameters, the master-slave systems (1) and (2) exhibit chaotic behaviours such the $x_{m1} - x_{m2}$ and $\dot{x}_{m1} - \dot{x}_{m2}$ planes with initial conditions

$$\phi(0) = col\{0.4, 0.6, -0.3, -0.2\}$$

and

$$\varphi(0) = col\{0.8, -0.7, 0.1, 0.1\},$$

respectively, are shown in Fig. 3.

It is required to design the control law $u(t) = K_1 e(t)$ such that the synchronization error system (9) is asymptotically stable and satisfies the H_∞ performance measure. To this end, in light of Theorem 1, we solved LMIs (14) with the disturbance attenuation $\gamma = 0.8$ and obtained the following control gain by using Matlab LMI Control Toolbox:

$$K = [0.9543 \quad -1.4119 \quad 2.0951 \quad -1.5799].$$

Now, by applying the synchronization control signal with the parameters above, the synchronization error between the drive system and response system is shown in Fig. 4. It shows that the synchronization error converges to zero. The curve of control signal is shown in Fig. 5. Also, Fig. 6 shows the residual signals obtained with the synchronization. It can be seen that clearly by monitoring the fault estimates, it would be possible to detect fault behaviours.

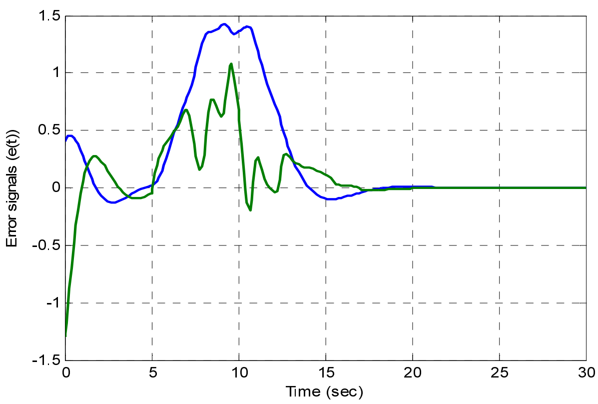


Fig. 4. The synchronization errors.

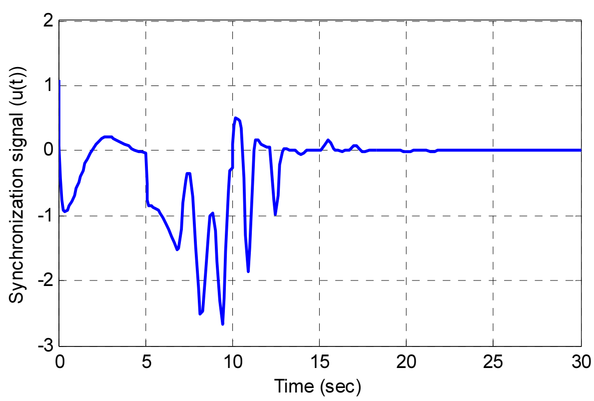


Fig. 5. Control law for system.

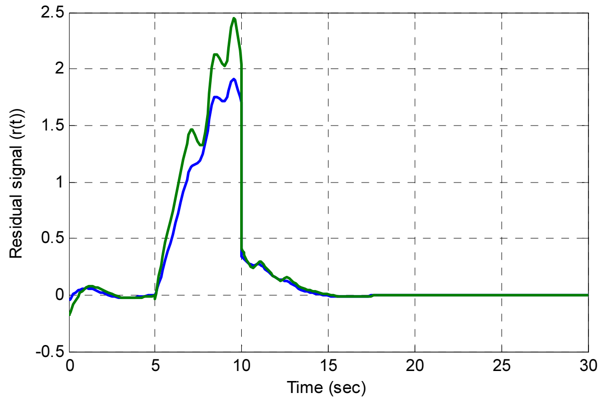


Fig. 6. Residual signals.

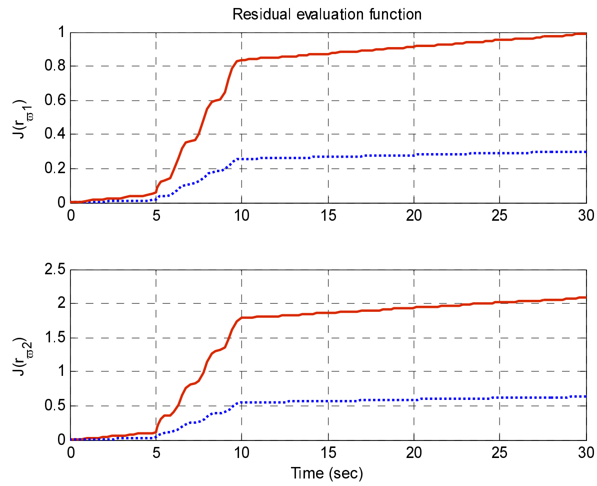


Fig. 7. Evolution of $J(r_\varpi(t)) := \left(\int_{t_1}^{t_2} r(t)^T r(t) dt\right)^{0.5}$.

In Fig. 7, the evolution of $J(r_\varpi(t)) := \left(\int_{t_1}^{t_2} r(t)^T r(t) dt\right)^{0.5}$ is presented for both faulty case and fault-free case, respectively. We can see that the fault f(t) can be detected 1.6 sec after its occurrence based on $J_{th} = 0.26$ for the first residual signal $r_{\varpi_1}(t)$, shown in Fig. 7.

5. CONCLUSIONS

The problem of robust synchronization and fault detection for a class of master-slave systems subjected to some nonlinear perturbations and mixed neutral and discrete time-varying delays was investigated based on an H∞ performance condition. By introducing a descriptor technique, using Lyapunov-Krasovskii functional and a suitable change of variables, new required sufficient conditions were established in terms of delay-dependent linear matrix inequalities to synthesize the residual generation scheme. The explicit expression of the synchronization law was derived for the fault such that both asymptotic stability and a prescribed level of disturbance attenuation were satisfied for all admissible nonlinear perturbations. A numerical example was given to show the effectiveness of the method.

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