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SIMULTANEOUS FAULT DETECTION AND CONTROL OF LINEAR TIME-INVARIANT SYSTEM VIA DISTURBANCE OBSERVER-BASED CONTROL APPROACH†

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Abstract. This paper concerns the problem of simultaneous fault detection and disturbance reject control(SFDDRC) for a class of linear time-invariant system. In the framework of fault detection, residual generators are required to be robust to disturbances existing in the system. Different from most of the existing simultaneous fault and control(SFDC) methods, SFDDRC rejects the influences of disturbances on residual generators by disturbance observer-based control(DOBC). This not only effectively improves the accuracy of fault detection, but also solves the problem that most of the existing SFDC methods require that the disturbance must be bounded. Finally, a numerical example is given to verify the validity of the method.

AMS Mathematics Subject Classification : 65H05, 65F10.
Key words and phrases : Fault detection, disturbance observer-based control, linear time-invariant system, disturbance reject, fault estimation.

1. Introduction

Along with the ever-increasing demands for high performance and high product quality, industrial technology processes [1],[2],[3],[4]are becoming more complex.So, the problems of fault detection [5],[6],[7],[8] and fault tolerant[9],[10],[11] are very important for the modern control systems. Because the separately design on control and detection units increases overall complexity, it is very urgent

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to unify the two units into a single one. Therefore, the problem of SFDC has attracted a lot of attention in the last couple of decades([12]-[18]). In [12], the problem of SFDC was formulated as a mixed H_2/H_∞ optimization problem. In the framework of switched systems, the fault detector/controller gains and the supremum of quantizer range were derived by a convex optimized method in[16]. In multi-agent network system,[18] investigated the problem of distributed simultaneous fault detection and leader-following consensus control. In the framework of SFDC, the residuals are required to be robust to disturbances in the system. This makes the residuals have better sensitivity to faults, which can effectively detect the faults existing in the system. When studying the effects of rejecting disturbances, most are based on H_∞ control method in SFDC. The H_∞ control method is widely used and proved to be effective. But it is the worst case based design where the nominal performance is sacrificed to achieve better robustness. Moreover, the disturbance must be assumed to be bounded.

The DOBC method proposed in the late 1980s [20] has been applied to many control fields due to its improved anti-disturbance ability. [19] used disturbance observer to improve the access time in magnetic hard drive servo systems with rotary actuators. In [21], a novel DOBC method has been proposed by appropriately designing a disturbance compensation gain for nonlinear MAGLEV suspension systems. In [22], the DOBC approach was proposed in PWM-based DC-DC buck power converters. In [23], the DOBC was used to suppress the flexible dynamics and parameter uncertainties in a flexible air-breathing hypersonic vehicle. DOBC is one of the most widely accepted and applied disturbance and uncertainty estimation and attenuation (DUEA). Its fundamental idea is that an observation mechanism is designed to estimate disturbances or uncertainties (or both of them) and corresponding compensation is then generated by making use of the estimate. In this setting, the influence of disturbance on the system is effectively suppressed.

In this paper, the SFDDRC method is constructed based on DOBC and SFDC, where it is very effective in overcoming the effects of disturbances on fault detection. Based on designing observation mechanism to estimate disturbance and generate a compensation, the effect of disturbance on fault detection is effectively suppressed. Therefore, the faults in the system can be effectively detected. Moreover, it also solves the problem that most of the existing SFDC methods require that the disturbance must be bounded.

The rest of the paper is organized as follows: the description of the problem is given in Section 2 . Sections 3-4 contains the main results and thresholds computation, respectively. Section 5 contains the simulation results for the proposed algorithm. Finally, some concluding remarks are included in Section 7.

Notation: The notation $X \geq Y$ (respectively $X > Y$) where X and Y are symmetric matrices, means that the matrix $X - Y$ is positive semi-definite (respectively, positive definite); A^{T} denotes the transposed matrix of A; $sym(X)$ means $X + X^{\mathrm{T}}$;

2. Preliminaries and problem formulation

Consider the following systems with disturbances

$$\begin{aligned} \dot{x}(t) &= A_0x(t) + B_0(u(t) + d(t)) + B_{f0}f(t) \\ y(t) &= C_0x(t) + D_{d0}d(t) + D_{f0}f(t) \end{aligned} \quad (2.1)$$

where $x(t) \in \mathbf{R}^n$ is the state, $f(t) \in \mathbf{R}^q$ is possible fault, $u(t) \in \mathbf{R}^m$ is the control input, and $y(t) \in \mathbf{R}^p$ is the measurement output. A_0, B_0, B_{f0}, C_0, D_{d0} and D_{f0} are assumed to be known constant matrices of appropriate dimensions.

The disturbance $d(t) \in \mathbf{R}^r$ in the control input path can be formulated by the following exogenous system:

$$\begin{aligned} \dot{w}(t) &= Ww(t) \\ d(t) &= Vw(t). \end{aligned} \quad (2.2)$$

where $w(t) \in \mathbf{R}^w$, W and V are matrices with corresponding dimensions.

From (2.2), it can be seen that the disturbance $d(t)$ is unbounded. However, many kinds of disturbances in engineering which are described by (2.2) are not bounded. For example, harmonic disturbance with known frequency ω but unknown phase and magnitude. This leads to the widely used H_∞ control method ($d(t)$ is assumed to be bounded) does not stabilize the system and effectively rejects the influence of disturbance on SFDC. Therefore, it is necessary to design a new detector/controller to solve this problem.

Firstly, the following composite systems are given by (2.1) and (2.2).

$$\begin{aligned} \dot{z}(t) &= Az(t) + Bu(t) + B_f f(t) \\ y(t) &= Cz(t) + D_{f0}f(t) \end{aligned} \quad (2.3)$$

where $z(t) := \begin{bmatrix} x(t) \\ w(t) \end{bmatrix}$, $A := \begin{bmatrix} A_0 & B_0V \\ 0 & W \end{bmatrix}$, $B := \begin{bmatrix} B_0^{\mathrm{T}} & 0 \end{bmatrix}^{\mathrm{T}}$, $B_f := \begin{bmatrix} B_{f0}^{\mathrm{T}} & 0 \end{bmatrix}^{\mathrm{T}}$, $C := \begin{bmatrix} C_0 & D_{d0}V \end{bmatrix}$.

The detector/controller for both $x(t)$ and $\omega(t)$ is designed as

$$\begin{aligned} \dot{\hat{z}}(t) &= A\hat{z}(t) + Bu(t) + Lr(t) \\ \hat{y}(t) &= C_0\hat{z}(t) \\ r(t) &= y(t) - \hat{y}(t) \\ u(t) &= -\hat{d}(t) + K\hat{x}(t) \\ \hat{d}(t) &= V\hat{\omega}(t) \end{aligned} \quad (2.4)$$

where $\hat{z}(t) := \begin{bmatrix} \hat{x}(t) \\ \hat{\omega}(t) \end{bmatrix}$, and L is the detector/controller gain to be determined.

The estimation error $e(t) := z(t) - \hat{z}(t) = \begin{bmatrix} x(t) - \hat{x}(t) \\ \omega(t) - \hat{\omega}(t) \end{bmatrix} = \begin{bmatrix} e_x(t) \\ e_\omega(t) \end{bmatrix}$ is obtained by

$$\dot{e}(t) = Ae(t) + B_f f(t) - Lr(t). \quad (2.5)$$

The residual signal is governed by

$$r(t) = y(t) - \hat{y}(t) = Ce(t) + D_{f0}f(t). \tag{2.6}$$

Combining estimation error (2.1) and (2.5) yields

$$\begin{aligned} \dot{\bar{x}}(t) &= \bar{A}\bar{x}(t) + \bar{B}_f f(t) \\ r(t) &= \bar{C}\bar{x}(t) + D_{f0}f(t) \end{aligned} \tag{2.7}$$

where $\dot{\bar{x}}(t) = \begin{bmatrix} x(t) \\ e_x(t) \\ e_\omega(t) \end{bmatrix}$, $\bar{A} = \begin{bmatrix} A_0 + B_0K & -B_oK & B_0V \\ 0 & A_0 - L_1C_0 & B_0V - L_1C_0 \\ 0 & -L_2C_0 & W - L_2D_{d0}V \end{bmatrix}$, $\bar{B}_f = \begin{bmatrix} B_{f0} \\ B_{f0} - L_1D_{f0} \\ -L_2D_{f0} \end{bmatrix}$, $\bar{C} = \begin{bmatrix} 0 & C_0 & D_{d0}V \end{bmatrix}$ and $L = \begin{bmatrix} L_1 \\ L_2 \end{bmatrix}$.

The basic idea of SFDDRC can be illustrated by Fig. 1, where G, u, d, f, y, r, $\hat{d}$ represent the real physical plant, the control input, the external disturbance, the fault signal to be detected, the system output, the residual signal, and the estimate of external disturbance, respectively.

From Fig. 1, it is shown that the detector/controller with disturbance estimation and compensation mechanism is not activated under without the disturbance d in system. For this resaon, the stability of the system will not be affected. In addition, when the system is affected by disturbances, the observation mechanism is activated to estimate interference. The corresponding compensation is then generated by using the estimate value. Hence, the influence of disturbance on fault detection is overcome.

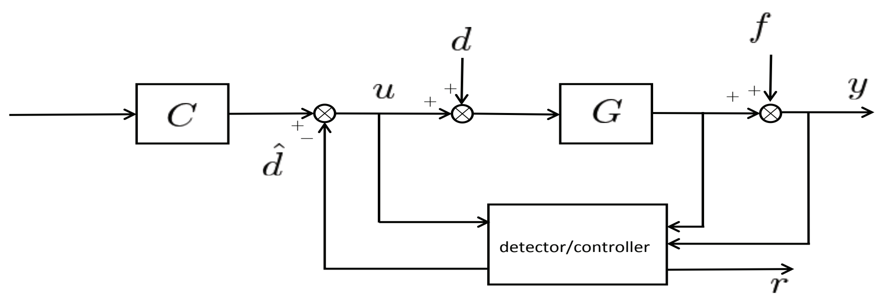

Fig. 1: Conceptual diagram of SFDDRC

The SFDDRC problem is that of designing a detector/controller (2.4) such that the systems (2.7) are stable, and the effects of disturbance on residual signal $r(t)$ is minimized, whereas the effects of fault on residual signal $r(t)$ are maximized. More specifically, the effects of fault on residual signal is replaced by a standard H_∞ model matching problem as follows

$$\|W_f - G_{rf}(s)\| < \gamma \tag{2.8}$$

where $G_{rf}(s) = \bar{C}(sI - \bar{A})^{-1}\bar{B}_f + D_{f0}$. The W_f is assumed as the following form:

$$W_f = \left[\begin{array}{c|c} A_F & B_F \\ \hline C_F & D_F \end{array}\right] \tag{2.9}$$

where A_F is a Hurwitz matrix. Then

$$W_f - G_{rf}(s) = \tilde{C}(sI - \tilde{A})^{-1}\tilde{B} + \tilde{D} \tag{2.10}$$

where

$$\begin{bmatrix} \tilde{A} & \tilde{B} \\ \tilde{C} & \tilde{D} \end{bmatrix}$$

$$= \left[\begin{array}{cccc|c} A_F & & 0 & & B_F \\ & A_0 + B_0K & -B_oK & B_0V & B_{f0} \\ 0 & 0 & A_0 - L_1C_0 & B_0V - L_1C_0 & B_{f0} - L_1D_{f0} \\ & 0 & -L_2C_0 & W - L_2D_{d0}V & -L_2D_{f0} \\ \hline C_F & 0 & C_0 & D_{d0}V & D_F - D_{f0} \end{array}\right] \tag{2.11}$$

It can be seen from the above conditions that the residual signal $r(t)$ robustly tracks the filtered version of the fault signal $W_f f$.

The following lemmas are used in the next section:

Lemma 2.1. *(Bounded Real Lemma) For the following systems:*

$$\begin{aligned} \dot{x}(t) &= Ax(t) + B\omega(t) \\ z(t) &= Cx(t) + D\omega(t), \end{aligned} \tag{2.12}$$

H_∞ performance, with $\gamma > 0$ is equivalent to the existence of $P = P^{\mathrm{T}} > 0$ satisfying:

$$\begin{bmatrix} A^{\mathrm{T}}P + PA & PB & C^{\mathrm{T}} \\ * & -\gamma^2 I & D^{\mathrm{T}} \\ * & * & -I \end{bmatrix} < 0. \tag{2.13}$$

3. Simultaneous Fault Detection and Disturbance Rejection Control

In this section, the LMI formulation for solving SFDDRC problem would be given. Firstly, the disturbance rejection control is transformed into LMI feasibility constraints in the following:

Lemma 3.1. *Consider the systems (2.1) with disturbance (2.2) and $f(t) = 0$. If there exist P_1 and R_1 satisfying*

$$sym(A_0P_1 + B_0R_1) < 0 \tag{3.1}$$

and $P_2 = \begin{bmatrix} P_{21} & 0 \\ 0 & P_{22} \end{bmatrix} > 0$, $R_2 = \begin{bmatrix} R_{21} \\ R_{22} \end{bmatrix}$ *satisfying*

$$\begin{bmatrix} sym(P_{21}A_0 - R_{21}C_0) & P_{21}B_0V - R_{21}D_{d0}V - C_0^TR_{22}^T \\ * & sym(P_{22}W - R_{22}D_{d0}V) \end{bmatrix} < 0, \tag{3.2}$$

then the closed-loop systems (2.7) under detector/controller (2.4) with $K = R_1Q_1^{-1}$ and $L = P_2^{-1}R_2$ are asymptotically stable.

Proof. Let $V_1(x(t),t) = x^{\mathrm{T}}(t)Q_1x(t)$ where $Q_1 = P_1^{-1}$. Along with the trajectories of (2.1) with disturbance (2.2) and $f(t) = 0$, we have

$$\dot{V}_1(x(t),t) = x^{\mathrm{T}}(t)(A_0 + B_0K)^{\mathrm{T}}Qx(t) + x^{\mathrm{T}}(t)Q(A_0 + B_0K)x(t). \tag{3.3}$$

It can be verified that $\dot{V}_1(x(t),t) < 0$ is equivalent to

$$(A_0 + B_0K)^{\mathrm{T}}Q + Q(A_0 + B_0K) < 0. \tag{3.4}$$

Now, pre- and post multiplication of (3.4) by P, inequality (3.1) is obtained.

Denote $V_2(e(t),t) = e^{\mathrm{T}}(t)P_2e(t)$. Similarly, $\dot{V}_2(e(t),t) < 0$ is equivalent to (3.2) holds.

Let $\eta_1,\ \eta_2 > 0$. Following (3.1) and (3.2), it can be verified that $\dot{V}_1(x(t),t) \leq -\eta_1\|x\|^2$ and $\dot{V}_2(e(t),t) \leq -\eta_2\|e\|^2$. Define $V(x(t),e(t),t) = V_1(x(t),t)+\eta_0V_2(e(t),t)$ where η_0 is a proper constant. The next proof of this theorem is similar to that of Theorem 1 of [26], so the closed-loop systems (2.7) are asymptotically stable.

After getting the controller that stabilizes the systems, the constraints for maximizing the effect of fault on residual signal will be given below. □

Theorem 3.2. *If there exist symmetric positive-definite matrices P_F, Q, P_{21}, P_{22} and matrices R_{21}, R_{22} and a prescribed positive constant γ satisfying*

$$\begin{bmatrix} sym(P_FA_F) & 0 & 0 & 0 & P_FB_F & C_F^{\mathrm{T}} \\ * & \Lambda_{22} & -Q_1B_0K & Q_1B_0V & Q_1B_{f0} & 0 \\ * & * & \Lambda_{33} & \Lambda_{34} & \Lambda_{35} & -C_0^{\mathrm{T}} \\ * & * & * & \Lambda_{44} & -R_{22}D_{f0} & -V^{\mathrm{T}}D_{d0}^{\mathrm{T}} \\ * & * & * & * & -\gamma^2I & D_F^{\mathrm{T}} - D_{d0}^{\mathrm{T}} \\ * & * & * & * & * & -I \end{bmatrix} < 0. \tag{3.5}$$

where

$$\begin{aligned} \Lambda_{22} &= sym(Q_1A_0 + Q_1B_0K), \\ \Lambda_{33} &= sym(P_{21}A_0 - R_{21}C_0), \\ \Lambda_{34} &= P_{21}B_0V - R_{21}D_{d0}V - C_0^{\mathrm{T}}R_{22}^{\mathrm{T}}, \\ \Lambda_{35} &= P_{21}B_{f0} - R_{21}D_{f0}, \\ \Lambda_{44} &= sym(P_{22}W - R_{22}D_{d0}V), \end{aligned} \tag{3.6}$$

then the closed-loop systems (2.7) with gain $L = \begin{bmatrix} R_{21}P_{21}^{-1} \\ R_{22}P_{22}^{-1} \end{bmatrix}$ *are stable and the condition (2.10) holds.*

Proof. Define

$$\tilde{P} = \begin{bmatrix} P_F & 0 & 0 & 0 \\ 0 & Q & 0 & 0 \\ 0 & 0 & P_{21} & 0 \\ 0 & 0 & 0 & P_{22} \end{bmatrix} > 0. \tag{3.7}$$

Applying Lemma 1 to (2.7), the closed-loop systems (2.7) is stable and the condition (2.10) holds are equivalent to

$$\begin{bmatrix} sym(\tilde{P}\tilde{A}) & \tilde{P}\tilde{B} & \tilde{C}^{\mathrm{T}} \\ * & -\gamma^2 I & \tilde{D}^{\mathrm{T}} \\ * & * & -I \end{bmatrix} < 0. \tag{3.8}$$

Using (2.11) and (3.7) to calculate (3.8), we have

$$sym(\tilde{P}\tilde{A}) = \begin{bmatrix} sym(P_F A_F) & 0 & 0 & 0 \\ * & \Lambda_{22} & -QB_0K & QB_0V \\ * & * & \Lambda_{33} & \Lambda_{34} \\ * & * & 0 & \Lambda_{44} \end{bmatrix} \tag{3.9}$$

and

$$sym(\tilde{P}\tilde{B}) = \begin{bmatrix} P_F B_F \\ B_{f0} P \\ P_{21} B_{f0} - R_{21} D_{f0} \\ * \end{bmatrix}. \tag{3.10}$$

Bring (3.9) and (3.10) into (3.8), (3.5) can be obtained. Then by selecting $L = \begin{bmatrix} R_{21}P_{21}^{-1} \\ R_{22}P_{22}^{-1} \end{bmatrix}$, the closed-loop systems (2.7) are stable and the condition (2.10) holds. □

Remark 3.1. The detector/controller design can be obtained separately as follows:

- Solve (3.2) to obtain K;
- Compute the observer gain L via (3.5)
- Construct the detector based on (2.4).

4. Thresholds Computation

Once the observer gain L is obtained, the next step is to evaluate the residual signal and compare it with threshold value to detect the presence of fault in the system. The residual evaluation function $J_{r(t)}(t)$ is chosen as

$$J_{r(t)} = \sqrt{\frac{1}{t}\sum_{s=s_0}^{s_t} r^{\mathrm{T}}(s)r(s)}$$

where s_0 implies the initial evaluation time instant and s_t denotes the whole evaluation time steps.

The threshold value is chosen as

$$J_{th}(t) = \sup_{f(t)=0} J_{r(t)}(t). \tag{4.1}$$

Based on this, the occurrence of faults can be detected by the following logic rule.

$$\| J_{r(t)} \| \leq J_{th} \qquad \textit{the system no alarm}$$

$$\| J_{r(t)} \| > J_{th} \qquad \textit{the system with alarm}$$

5. Numerical Example

The following numerical example given in [26] is used to verify the validity of the SDDFRC theoretical framework. The parameters of the system (2.1) are as follows.

$$A_0 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 6.51 & 24.69 & 33.7 & 35.54 \\ 0 & 0 & 0 & 1 \\ -12.52 & -50.1 & -56 & -68.5 \end{bmatrix}, B_0 = \begin{bmatrix} 0 \\ 0.2469 \\ 0 \\ -12.52 \end{bmatrix},$$

$$B_{f0} = \begin{bmatrix} 0 \\ 0.5 \\ 0 \\ -0.5 \end{bmatrix}, C_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{bmatrix}, D_{d0} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, D_{f0} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \tag{5.1}$$

Reference model parameters for residual are selected as:

$$A_F = \begin{bmatrix} -2 & -1 \\ 0 & 0 \end{bmatrix}, B_F = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, C_F = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, D_F = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{5.2}$$

The model parameters for disturbance (2.2) are selected as:

$$W = \begin{bmatrix} 0 & 5 \\ -5 & 1 \end{bmatrix}, V = \begin{bmatrix} 25 \\ -5 \end{bmatrix}. \tag{5.3}$$

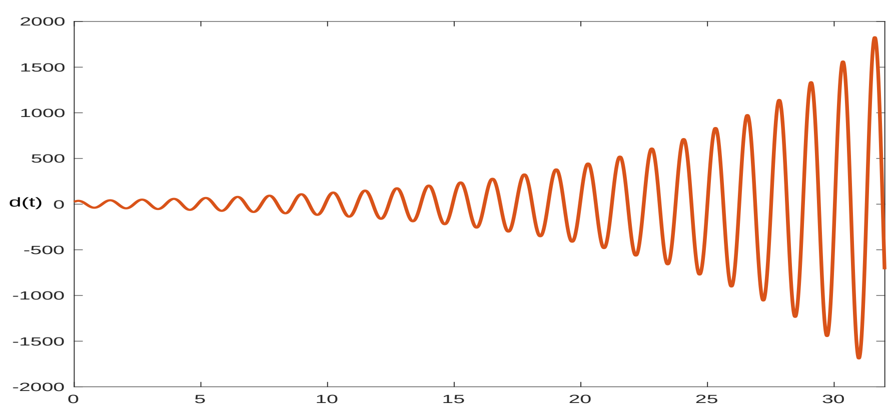

Fig. 2: Disturbance in system

From Fig. 2, we know that the disturbance is unbounded in the system. Therefore, the assumptions of the existing SFDC method are not satisfied, which means that some existing SFDC methods are unable to complete the tasks of control and fault detection. In the framework of SFDDRC, applying the approach in Lemma 2, we can obtain

$$K = \begin{bmatrix} -23.5072 & -103.4239 & -98.1917 & 0 \end{bmatrix} \tag{5.4}$$

and the controller is $u(t) = -\hat{d}(t) + K\hat{x}(t)$.

Based on Theorem 1, from obtained controller and defined parameter $\gamma = 1.5$, it can be obtained that

$$L = \begin{bmatrix} 27.6971 & -27.7981 \\ -30.6801 & 30.3770 \\ -15.9044 & 15.9573 \\ 31.0743 & -30.7255 \\ 0.0252 & 0.0219 \\ 0.0023 & 0.0020 \end{bmatrix}. \tag{5.5}$$

To demonstrate the effectiveness of the design, the fault is assumed as $f(t) = 30$ from $t = 20$ to $t = 30$. When there is no fault in the system, the estimation errors for system are denoted in Fig. 3 and the state responses x(t) of the systems are shown in Fig. 4. Fig. 3 shows the convergence to track the external disturbance and Fig. 4 shows the stability of the closed-loop system .

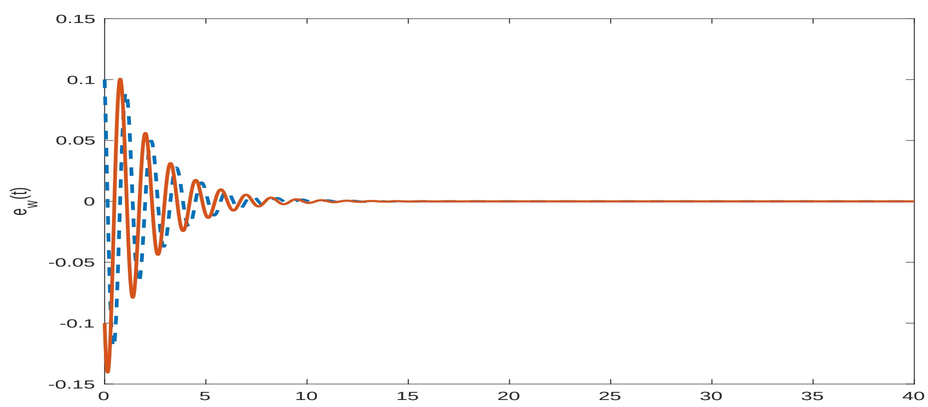

Fig. 3: Estimation errors for system disturbances

By calculation, the threshold is set to 0.4465 and is indicated by the dashed line in Fig. 5. When k = 20, system exists fault. At this point, $\| J_{r(t)} \| > J_{th}$, and the system generates an alarm to effectively detect the fault in the system.

6. Concluding remarks

In this paper, the method of SFDDRC has been given for a class of linear time-invariant system. The feature of this kind of method is that it deals with the disturbance suppression problem in SFDC problem based on DOBC method. This effectively suppresses the influence of disturbances in the system on fault

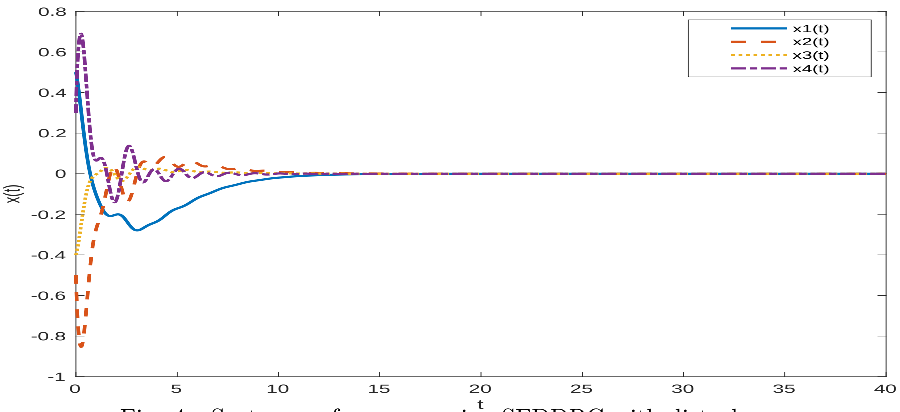

Fig. 4: System performance using SFDDRC with disturbances

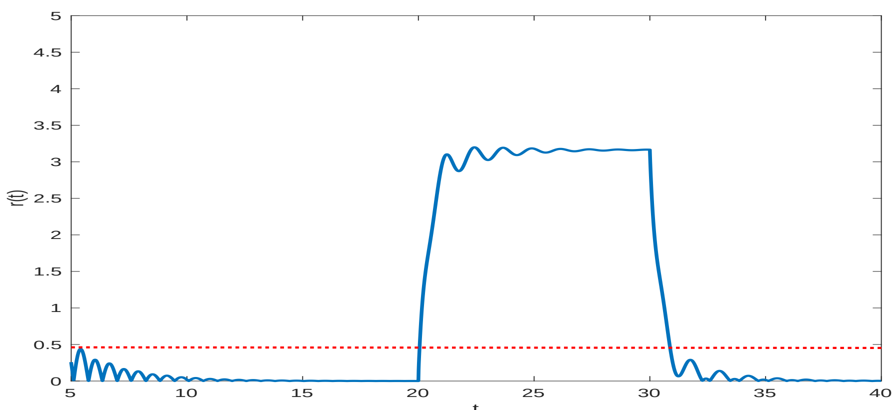

Fig. 5: Solid line: residual evaluation output; dashed line: threshold

detection, thereby greatly improving the accuracy of fault detection. Moreover, the problem that the response on the disturbances in the system must be bounded has been solved. At last, a numerical example is given to verify the validity of the method.

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