

Fault Detection in Linear Descriptor Systems Via Unknown Input PI Observer

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Abstract: This paper deals with a fault detection algorithm for linear descriptor systems via unknown input PI observer. An unknown input PI observer is presented and its realization conditions is proposed by using the rank condition of system matrices. From the characteristics of unknown input PI observer, the states of system with unknown inputs are estimated and the occurrences of fault are detected, and its magnitudes are estimated easily by using integrated output estimation error under the step faults. Finally, a numerical example is given to verify the effectiveness of the proposed fault detection algorithm.

Keywords: fault detection, descriptor system, unknown input, PI observer

I. Introduction

The core element of model based fault detection is the generation of residuals which act as the indicators of faults in real application processes [1]-[8]. For the design of the residual generators, there have been various kinds of approaches, among which the class of observer-based approaches have been most widely considered [3]-[5]. The basic idea behind observer-based approaches is to estimate the outputs of the system from measurements by using some type of observer, and then construct the residual by a properly weighted output estimated error. This residual is then examined for the likelihood of faults.

Recently a fault diagnosis method to detect and isolate the actuator and sensor faults was presented by using multiple PI observers [9]. It was based on intensive use of knowledge on the characteristics of PI observer, which estimates and cancels the step actuator faults.

Almost of fault diagnosis method was designed in linear regular system, but only a few results about descriptor system are reported [10]-[11]. The descriptor system can be described in mature form of differential and algebraic equation in practical system and control system design [12]-[13]. The form of descriptor system also appears in many systems, such as engineering systems, social economic systems, network analysis systems, biological systems, and so on. As similar problem in regular system, the problem of detecting the faults of descriptor system is important.

In this paper, we propose an unknown input PI observer for constructing the fault detection algorithm in linear descriptor systems with disturbance and fault. Firstly, the descriptor system and its boundary conditions are described, and the faults of system are defined. Secondly, the unknown input PI observer is introduced and its properties are shown. The fault detection algorithm is proposed by using the integrated output error between actual output and estimated output. Lastly, a numerical

example is given to verify the effectiveness of the proposed fault detection algorithm.

II. Problem formulation

Consider a multivariable linear descriptor system with the disturbance input and state fault as

$$\Sigma_F : \begin{cases} E\dot{x}(t) = Ax(t) + Bu(t) + Dd(t) + Ff(t) \\ y(t) = Cx(t) \end{cases} \quad (1)$$

where $x(t) \in \mathbb{R}^n$ is the state vector, $y(t) \in \mathbb{R}^p$ is the output vector, $u(t) \in \mathbb{R}^m$ is the input vector, $d(t) \in \mathbb{R}^q$ is the unknown disturbance vector, and $f(t) \in \mathbb{R}^r$ is the fault vector; A and E are square real matrices of order n , $E \in \mathbb{R}^{n \times n}$ and rank $E = l (\leq n)$; B, C, D and F are matrices of appropriate dimensions. And we assume that

i) rank $D = q$

ii) System Σ_F is solvable, i.e., there exists a scalar λ such that

$$\det(A - \lambda E) \neq 0$$

iii) System Σ_F is R -observable [14] (observable in the sense of Rosenbrock) if and only if

$$\begin{aligned} \text{rank} \begin{bmatrix} E \\ C \end{bmatrix} &= n \\ \text{rank} \begin{bmatrix} A - sE \\ C \end{bmatrix} &= n, \quad \forall s \in \mathbb{C} \end{aligned}$$

where \mathbb{C} denotes the complex plane.

For the classical regular systems, it is well known that the invariant zeros play an important role in the design of the observer. So, for considering the descriptor systems in the same way as the regular systems, the invariant zeros are defined as the complex scalar satisfying [15]

$$\det \begin{bmatrix} A - sE & B \\ C & 0 \end{bmatrix} < n + \min(p, m) \quad (2)$$

The aim of this paper is to design an algorithm for fault detection in linear descriptor systems via unknown input PI observer. This means that the fault vector $f(t)$ in Σ_F should be detected and isolated effectively.

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III. Unknown input PI observer for descriptor systems

1. Unknown input PI observer

Consider a linear descriptor system without fault vector ($f(t) = 0$) in Σ_F as

$$\Sigma_D : \begin{cases} E\dot{x}(t) = Ax(t) + Bu(t) + Dd(t) \\ y(t) = Cx(t) \end{cases} \quad (3)$$

and consider a PI observer as represented by

$$\Sigma_{UPI} \begin{cases} \dot{z}(t) = \hat{A}z(t) + \hat{B}y(t) + \hat{J}u(t) + \hat{H}\omega(t) \\ \hat{x}(t) = \hat{C}z(t) + \hat{D}y(t) \\ \dot{\omega}(t) = y(t) - C\hat{x}(t) \end{cases} \quad (4)$$

where $\hat{x}(t) \in \mathbb{R}^n$, $z(t) \in \mathbb{R}^n$ and $\omega(t) \in \mathbb{R}^p$ are the estimated state vector, transformed state vector and estimated output error vector, respectively. \hat{A} , \hat{B} , \hat{C} , \hat{D} , \hat{H} , and \hat{J} are unknown matrices of appropriate dimensions.

Definition 1: The system Σ_{UPI} is said to be an unknown input PI observer for the linear descriptor systems Σ_D if and only if

$$\lim_{t \rightarrow \infty} e(t) = 0, \quad \forall x(0_-), z(0_-), u(\cdot) \\ \lim_{t \rightarrow \infty} \omega(t) = 0, \quad \forall \omega(0_-)$$

where $e(t) = \hat{x}(t) - x(t)$ represents the observer error. ■

Under the Definition 1, we have the following theorem which describes the basic relation between the descriptor system and the unknown input PI observer.

Theorem 1: The system Σ_{UPI} is an unknown input PI observer for the descriptor system Σ_D if

$$\operatorname{Re} \lambda_i \begin{bmatrix} \hat{A} & \hat{H} \\ -C\hat{C} & 0 \end{bmatrix} < 0, \quad i = 1, \dots, n+p \quad (5)$$

and there exists a matrix $U \in \mathbb{R}^{n \times n}$ such that

$$\hat{A}UE + \hat{B}C = UA \quad (6)$$

$$\hat{J} = UB \quad (7)$$

$$UD = 0 \quad (8)$$

$$\hat{C}UE + \hat{D}C = I_n \quad (9)$$

Proof: This proof is omitted. ■

The problem of designing the unknown input PI observer for the descriptor system with disturbance input is reduced to find matrices \hat{A} , \hat{B} , \hat{C} , \hat{D} , \hat{J} , and U such that the conditions of Theorem 1 are satisfied.

In the next section, we will show a condition which need to realize the unknown input PI observer such that Theorem 1 is satisfied.

2. Realization of unknown input PI observer

In the following, we let $\hat{C} = I_n$ for simplicity. Then, from (9) we have

$$UE = I_n - \hat{D}C \quad (10)$$

From the assumption of observability in the sense of Rosenbrock, there exist two matrices $E^\# \in \mathbb{R}^{n \times n}$ and $C^\# \in \mathbb{R}^{n \times p}$ such that [16]

$$E^\#E + C^\#C = I_n, \quad \det E^\# \neq 0 \quad (11)$$

Substitution of (11) into (10) yields

$$UE = U(E^\#)^{-1}E^\#E = U(E^\#)^{-1}(I_n - C^\#C) \\ = I_n - \hat{D}C$$

from which, the matrix U is obtained as

$$U = (I_n - LC)E^\# \quad (12)$$

where

$$L \triangleq \hat{D} - U(E^\#)^{-1}C^\# \quad (13)$$

Substitution of (11) and (12) into (10) yields

$$UE = (I_n - LC)E^\#E = (I_n - LC)(I_n - C^\#C) \\ = I_n - \hat{D}C$$

Since $\operatorname{rank} C = p$, we find

$$\hat{D} = C^\# + L(I_p - CC^\#) \quad (14)$$

By substituting (10) and (12) into (6), we have

$$\hat{A}(I_n - \hat{D}C) + \hat{B}C = (I_n - LC)E^\#A$$

from which,

$$\hat{A} = UA - KC \quad (15)$$

where

$$K = \hat{B} - \hat{A}\hat{D} \quad (16)$$

Also, by using (15) and (16), the matrix \hat{B} is

$$\hat{B} = \hat{A}\hat{D} + K \\ = K(I_p - C\hat{D}) + (I_n - LC)E^\#A\hat{D} \quad (17)$$

Next, from (8) and (12) we have

$$E^\#D = LCE^\#D \quad (18)$$

The solution of this equation exists if

$$\operatorname{rank} CE^\#D = \operatorname{rank} D = q \quad (19)$$

which requires $p \geq q$, i.e., the number of output must be great than or equal to that of input.

The general solution of (18) can be written as

$$L = E^\#D(CE^\#D)^+ + G\{I_p - CE^\#D(CE^\#D)^+\}$$

where the superscript $+$ indicates the generalized matrix inverse and G is arbitrary matrix.

By substituting L into (12), we can get

$$U = (I_n - GC)\{I_n - E^\#D(CE^\#D)^+\}E^\#$$

and can see from this equation that there exists the matrix G which makes $(I_n - GC)$ nonsingular, and then the $\operatorname{rank} U = n - q$.

The remaining problem is to find the matrices K and \hat{H} such that (5) is stable. The designing method for matrices K and \hat{H} is presented in references [16][17] under the condition of (C, UA) is observable.

For this, the following lemma should be satisfied.

Lemma 1: [16][17] For the unknown input PI observer Σ_{UPI} in descriptor system Σ_D , there exist the matrices K and \hat{H} if the pair (C, UA) is observable. ■

Thus from the above lemma, the observability of the pair (C, UA) is necessary for designing the matrices K and \hat{H} , i.e.,

$$\text{rank} \begin{bmatrix} sI - UA \\ C \end{bmatrix} = n, \quad \forall s \in \mathbf{C}, \quad \text{Re}(s) \geq 0 \quad (20)$$

Since $\text{rank } D = q$, there exists a matrix $D^+ \in \mathbb{R}^{q \times n}$ such that $D^+D = I_q$. Therefore, under the condition that $\text{rank } U = n - q$, $\text{Ker } U \cap \text{Ker } D^+ = \{0\}$, we have following relations

$$\begin{bmatrix} U & 0 \\ D^+ & 0 \\ 0 & I_p \end{bmatrix} \begin{bmatrix} sE - A & D \\ C & 0 \end{bmatrix} \begin{bmatrix} I_n & 0 \\ -D^+(sE - A) & I_q \end{bmatrix} \\ = \begin{bmatrix} U(sE - A) & 0 \\ 0 & I_q \\ C & 0 \end{bmatrix}$$

Furthermore

$$\begin{bmatrix} I & 0 & s\hat{D} \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} U(sE - A) & 0 \\ 0 & I_q \\ C & 0 \end{bmatrix} = \begin{bmatrix} sI_n - UA & 0 \\ 0 & I_q \\ C & 0 \end{bmatrix}$$

It follows that the following rank conditions are satisfied

$$\text{rank} \begin{bmatrix} sE - A & D \\ C & 0 \end{bmatrix} = q + \text{rank} \begin{bmatrix} sI_n - UA \\ C \end{bmatrix}$$

from which, the detectability condition (20) is equivalent to

$$\text{rank} \begin{bmatrix} sE - A & D \\ C & 0 \end{bmatrix} = n + q, \quad \forall s \in \mathbf{C}, \quad \text{Re}(s) \geq 0 \quad (21)$$

That is, the invariant zeros of the system $\Sigma_D : (E, A, D, C, 0)$ must be stable [15]. From the above statements, we have the following theorem.

Theorem 2: For the descriptor system Σ_D , an unknown-input PI observer Σ_{UPI} exists if

$$\text{i) } \text{rank } CE^\#D = \text{rank } D = q, \quad (p \geq q)$$

$$\text{ii) } \text{rank} \begin{bmatrix} A - sE & D \\ C & 0 \end{bmatrix} = n + q, \quad \forall s \in \mathbf{C}, \quad \text{Re}(s) \geq 0$$

■

Therefore, the unknown input PI observer Σ_{UPI} is rewritten for linear descriptor system as follows

$$\Sigma_{PI} : \begin{cases} \dot{z}(t) = (E^\#A - LCE^\#A - KC)z(t) \\ \quad + (E^\#A\hat{D} - LCE^\#A\hat{D} \\ \quad - KC\hat{D} + K)y(t) + \hat{H}\omega(t) \\ \hat{x}(t) = \hat{C}z(t) + \{C^\# + L(I_p - CC^\#)\}y(t) \\ \dot{\omega}(t) = y(t) - C\hat{x}(t) \end{cases}$$

where $\hat{C} = I_n$, $L = E^\#D(CE^\#D)^+ + G\{I_p - CE^\#D(CE^\#D)^+\}$, and G is an arbitrary matrix.

Remark 1: If $E = I_n$ for linear descriptor systems and if we have $E^\# = I_n$, $C^\# = 0$, and $\hat{D} = L$, then the unknown input PI observer for linear descriptor systems is identified with the unknown input PI observer for regular systems [17].

Remark 2: For regular systems, without loss of generality, $E = I_n$, we have $E^\# = I_n$, $C^\# = 0$. If the integral gain is neglected ($\hat{H} = 0$), then the conventional unknown input observer matrices are obtained as

$$\begin{aligned} U &= I_n - LC \\ \hat{D} &= L \\ \hat{A} &= (I_n - \hat{B}C)A - KC \\ \hat{B} &= K(I_p - C\hat{B}) + (I_n - \hat{D}C)A\hat{D} \end{aligned}$$

which is equivalent the results of Darouach et. al [18].

< Design Procedure >

Step 1: Obtain two matrices $E^\#$ and $C^\#$ such that

$$E^\#E + C^\#C = I_n, \quad \det E^\# \neq 0$$

Step 2: Check the conditions of Theorem 2.

Step 3: Select matrix G such that $(I_n - GC)$ is non-singular.

Step 4: Calculate the matrices L and U as

$$\begin{aligned} L &= E^\#D(CE^\#D)^+ + G\{I_p - CE^\#D(CE^\#D)^+\} \\ U &= (I_n - GC)\{I_n - E^\#D(CE^\#D)^+C\}E^\# \end{aligned}$$

And check $UD = 0$. If not satisfy, then Step 2 and 3 should be re-checked.

Step 5: Calculate matrix \hat{D} as

$$\hat{D} = C^\# + L(I_p - CC^\#)$$

Step 6: Design the matrices K and \hat{H} such that \hat{A} and eq. (5) are satisfied, where $\hat{A} = UA - KC$.

Step 7: Calculate matrices \hat{B} and \hat{J} as

$$\begin{aligned} \hat{B} &= \hat{A}\hat{D} + K \\ \hat{J} &= UB \end{aligned}$$

Remark 3: In Step 6, the designing matrices K and \hat{H} is depended on the stability of eq. (5). The design method for those matrices can be referred in [16][17].

IV. Fault detection via unknown input PI observer

In this section, we will show that how to detect and isolate the faults by using unknown input PI observer.

Consider the linear descriptor system with the unknown input and fault as Σ_F . First of all, we define an estimation error as

$$\xi(t) = z(t) - UEx(t)$$

From (1) and (4), the dynamics of this error obeys

$$\begin{aligned} \dot{\xi}(t) &= \hat{A}\xi(t) + (\hat{A}UE + \hat{B}C - UA)x(t) + \hat{H}\omega(t) \\ &\quad + (\hat{J} - UB)u(t) - UDD(t) - UFF(t) \end{aligned} \quad (22)$$

And (4) leads to

$$\hat{x}(t) = \hat{C}\xi(t) + (\hat{C}UE + \hat{D}C)x(t) \quad (23)$$

$$\dot{\omega}(t) = C(x(t) - \hat{x}(t)) \quad (24)$$

By substituting (6) – (9) into (22) – (24), we have

$$\begin{aligned} \dot{\xi}(t) &= \hat{A}\xi(t) + \hat{H}\omega(t) - UFF(t) \\ \hat{x}(t) &= \hat{C}\xi(t) + x(t) \\ \dot{\omega}(t) &= -C\hat{C}\xi(t) \end{aligned}$$

Let $\zeta(t)$ be defined as

$$\zeta(t) = \omega(t) - f(t) \quad (25)$$

Under the assumption of step faults, we obtain

$$\begin{aligned} \dot{\zeta}(t) &= \dot{\omega}(t) - \dot{f}(t) \\ &= \dot{\omega}(t) \end{aligned} \quad (26)$$

If the matrix \hat{H} is designed as

$$\hat{H} = UF \quad (27)$$

then, we get

$$\begin{aligned} \dot{\xi}(t) &= \hat{A}\xi(t) + \hat{H}\zeta(t) \\ \dot{\zeta}(t) &= -C\hat{C}\xi(t) \end{aligned}$$

or

$$\begin{bmatrix} \dot{\xi}(t) \\ \dot{\zeta}(t) \end{bmatrix} = \begin{bmatrix} \hat{A} & \hat{H} \\ -C\hat{C} & 0 \end{bmatrix} \begin{bmatrix} \xi(t) \\ \zeta(t) \end{bmatrix}$$

Under the condition (5), $\xi(t) \rightarrow 0$ and $\zeta(t) \rightarrow 0$ ($t \rightarrow \infty$). Thus from eq. (23) and (24), we find that $\hat{x}(t) - x(t) = 0$ and $\omega(t) = 0$. So, the conditions of definition 1 are satisfied.

Also, the faults can be detected and isolated perfectly from eq. (25) as

$$\hat{f}(t) = \omega(t), \quad t \rightarrow \infty \quad (28)$$

From eq. (28), we know that the residuals are generated by integration of output estimated errors, and the occurrences of faults are detected by its magnitudes. Thus, it is verified that the unknown input PI observer can estimate the state of system with unknown input disturbance and detect the fault effectively.

To estimate the state of system and to detect the faults by using the unknown input PI observer, Theorem 1 should be modified under the conditions of Theorem 2 as follows:

Theorem 3: The system Σ_{UPI} is an unknown input PI observer for estimating the state of descriptor system Σ_F and detecting the fault vector $f(t)$, if

$$\text{Re } \lambda_i \begin{bmatrix} \hat{A} & \hat{H} \\ -C\hat{C} & 0 \end{bmatrix} < 0, \quad i = 1, \dots, n+p \quad (29)$$

and there exists a matrix $U \in \mathbb{R}^{n \times n}$ such that

$$\hat{A}UE + \hat{B}C = UA \quad (30)$$

$$\hat{J} = UB \quad (31)$$

$$UD = 0 \quad (32)$$

$$\hat{C}UE + \hat{D}C = I_n \quad (33)$$

$$\hat{H} = UF \quad (34)$$

Remark 4: If $D = F$ or $D \ni F$, the matrix \hat{H} become zeros in eq. (34). Thus, the conditions of theorem 3 could not satisfied for detecting the faults in the system Σ_F . By using the PI observer [16] in this case, we can estimate the occurrences of faults, but there needs an isolation technique for isolating the disturbance signals.

Remark 5: In other faults case, It is desirable that the general structured observer [19] is applied to the descriptor system with the disturbance input and state fault.

V. Numerical example

Consider a descriptor system with

$$\begin{aligned} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \dot{x}(t) &= \begin{bmatrix} -5 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & -3 & -1 \end{bmatrix} x(t) \\ + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} d(t) + \begin{bmatrix} 0.01 & -0.02 \\ 10 & -200 \\ 0.1 & -100 \end{bmatrix} f(t) \\ y(t) &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(t) \end{aligned}$$

Step 1: Calculate the matrices $E^\#$ and $C^\#$ as

$$E^\# = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}, \quad C^\# = \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

Step 2: The rank conditions in Theorem 2 are checked as

$$\text{rank } CE^\#D = \text{rank } D = 1$$

and

$$\text{rank} \begin{bmatrix} A-sE & D \\ C & 0 \end{bmatrix} = 4, \quad \forall s \in \mathbb{C}, \text{Re}(s) \geq 0$$

So, an unknown-input PI observer can be realized.

Step 3: Select matrix G such that $(I_n - GC)$ is non-singular as

$$G = \begin{bmatrix} 0 & 1 \\ 1 & -1 \\ 0 & 0 \end{bmatrix}$$

Step 4: Calculate matrices L and U as

$$L = \begin{bmatrix} 1 & 0 \\ -0.5 & 0.5 \\ 0 & 0 \end{bmatrix}, \quad U = \begin{bmatrix} 0 & 0 & 0 \\ 0.5 & 0 & 0.5 \\ 0 & 1 & 0 \end{bmatrix}$$

From the obtained matrix U , we can easily see that $UD = 0$.

Step 5: Calculate matrix \hat{D} as

$$\hat{D} = \begin{bmatrix} 1 & 0 \\ -0.5 & 1 \\ 0 & 0 \end{bmatrix}$$

Step 6: The matrix \hat{H} is pre-selected by Theorem 3, and the matrix \hat{A} is obtained such that and eq. (5) are satisfied as follows:

$$\hat{A} = \begin{bmatrix} -20.023 & 0.354 & 0.000 \\ 0.939 & -39.977 & -0.500 \\ -24.452 & 599.736 & 0.000 \end{bmatrix},$$

$$\hat{H} = \begin{bmatrix} 0.000 & 0.000 \\ 0.055 & -50.010 \\ 10.000 & -200.000 \end{bmatrix}$$

Step 7: The matrices \hat{B} and \hat{J} are calculated as

$$\hat{B} = \begin{bmatrix} -0.177 & 0.000 \\ 17.488 & -1.500 \\ -299.868 & -2.000 \end{bmatrix}, \quad \hat{J} = \begin{bmatrix} 0.000 \\ 0.000 \\ 1.000 \end{bmatrix}$$

In simulation, we will verify the properties which estimating the state system with unknown disturbance and detecting the fault vector by using the unknown input PI observer effectively. The sampling time is assumed as 5[ms] and the initial states are given as

$$x(0) = \begin{bmatrix} -0.1 \\ 0.3 \\ 0.1 \end{bmatrix}, z(0) = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \omega(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

For estimating the states of system, we assume two type of unknown input disturbance, step and sinusoidal, as $d(t) = -0.5$ and $d(t) = 0.1\sin(0.2\pi t)$. In this case, the simulation results are shown in Fig. 1 and 2, respectively.

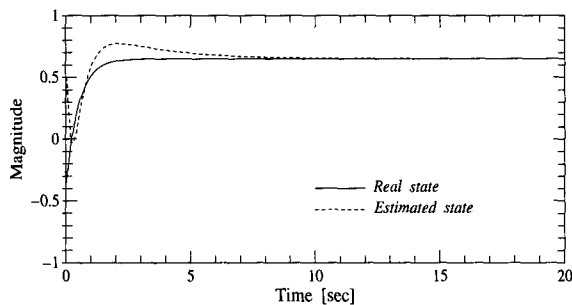


Fig. 1. Response of estimated state $\hat{x}_3(t)$ with step unknown input disturbance.

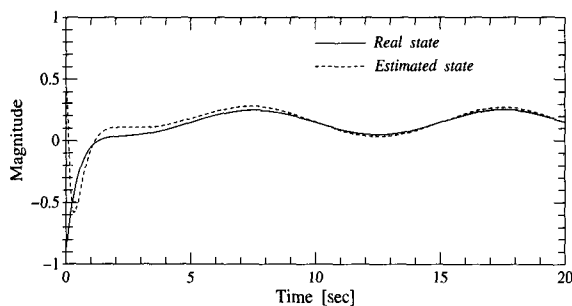


Fig. 2. Response of estimated state $\hat{x}_3(t)$ with sinusoidal unknown input disturbance.

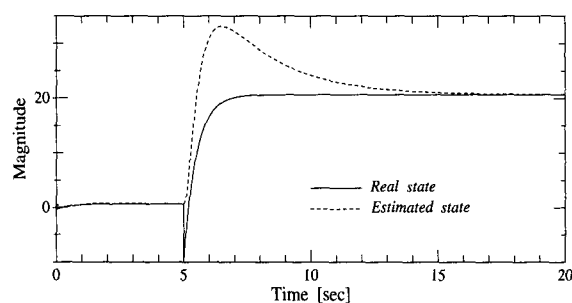


Fig. 3. Response of estimated state $\hat{x}_3(t)$ with step disturbance and fault.

Also for detecting the fault vector, we assume the fault is raised at 5[sec] as

$$f(t) = \begin{bmatrix} 0 \\ 0.1 \end{bmatrix}$$

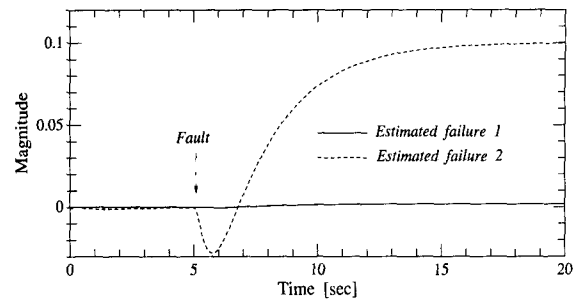


Fig. 4. Response of estimated fault vector.

In case, the simulation results are shown in Fig. 3 and 4, respectively.

Fig. 1 and 2 are shown that the estimated state of system $\hat{x}_3(t)$ is perfectly converged to the real state in case of step and sinusoidal disturbance, respectively.

Also, in Fig. 3 is shown that the estimated state $\hat{x}_3(t)$ is converged to the real state $x_3(t)$ with step disturbance and fault. In Fig. 4, the fault vector $f(t)$ is estimated effectively.

Thus, we can verified that the proposed fault detection algorithm is effective to estimate the states and the faults in the linear descriptor system with unknown input and fault.

VI. Conclusions

In this paper, we have proposed a fault detection method via unknown input PI observer for linear descriptor systems. The unknown input PI observer is can be realized by easily checking the system's rank condition. Also, the proposed fault detection algorithm by using unknown input observer can estimate the states of descriptor system and detect the state faults.

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