A Method on Fault Detection and Isolation of the Actuator Mechanism

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Abstract: The actuator mechanism which is the bridge between the controller and the component, plays an important role in the nonlinear control system. The actuator mechanism fault has much effect on the whole nonlinear system performance. So the Fault Detection and Isolation (FDI) of the actuator mechanism has been researched. But the actuator mechanism fault is always considered as the input type fault in the control system. Some unknown disturbances and uncertainties exist in the system input for the nonlinear system. It makes the designed observer insensitive to the initial state of slow variation fault for actuator mechanism. So, it is difficult to diagnose the incipient fault of the actuator mechanism. A method of the FDI for the actuator mechanism is proposed. The actuator mechanism which is often made up of more than one actuator, is analyzed as the dependent dynamic system and its fault is an output type fault. A batch of sliding mode observers is designed for each actuator of the actuator mechanism. The residuals of the designed observers tend to zero in the actuators fault-free condition. Once the faults exist in the actuators of the actuator mechanism, the residuals of the observers immediately varied. So, the number of the fault actuators can be diagnosed and the fault actuators are isolated. The results show that the proposed method is very effective for the FDI of the actuator mechanism, especially for the incipient state of gradual variation fault.

Key words: Nonlinear system, actuator mechanism, output type fault, sliding mode observer, fault detection and isolation

INTRODUCTION

The automation control and equipment, such as unmanned aerial vehicle, guided missile system and robot system, is very advanced nowadays. The actuator mechanism which is the bridge between a controller and a component, play a vital role. So, the actuator mechanism fault has much effect on the whole nonlinear system performance, even will cause the system paralysis and casualties. It is very necessary to research the actuator mechanism fault, which is in favor of the Fault Detection and Isolation (FDI) of the whole nonlinear system.

Many model-based and specifically observer-based approaches have been put forward to the nonlinear system FDI especially for the control systems (Frank, 1990; Isermann, 2005). Seliger and Frank (1991a, b) came up with Unknown Input Observer (UIO) approaches which extended the UIO method from linear systems to a class of nonlinear systems. The UIO methods are proposed by Chen et al. (1996) and Hou and Muller (1994).

The adaptive nonlinear observer methods on nonlinear FDI were proposed by Yang and Saif (1995) and Ding and Frank (1993). Sliding mode observer (Edwards et al., 2000; Spurgeon, 2008) has good robustness with the disturbances and model uncertainty. So this method has been widely used in the FDI of nonlinear systems. The earliest work with an observer is described in utilizing a discontinuous switched component by Utkin (1992). Sliding mode observer based on Utkin’s method of Equivalent control, Walcott and Zak Sliding mode observer of the FDI for linear and nonlinear uncertain systems and sliding mode output observer based incipient fault diagnosis for nonlinear uncertain systems are in detail designed by Saif and Xiong (2003). The methods on designing the sliding mode observer for the FDI are put forward and the fault signals can be reconstructed (Edwards et al., 2000). A sliding mode observer that have less constraint conditions, which is easier to realize than the existing nonlinear UIO, is presented and designed for the nonlinear uncertain systems by Xiong and Saif (2001).

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The above-mentioned methods based-observers have been used to research the actuator mechanism FDI. A robust detection scheme for detecting and identifying faulty actuator mechanism via unknown input observers is proposed by Chen and Zhang (1991). A Kalman filter-based adaptive observer (Tasi et al., 2007) can solve actuator mechanism faults which use the proposed input compensation method. The actuator mechanism fault method that is based on adaptive observer can be found by Wang and Daley (1996) and Chen and Saif (2007a). The sliding mode observers based FDI scheme have been studied extensively (Yan and Edwards, 2008; Tan and Edwards, 2003; Chen and Saif, 2007b, c, 2008).

The actuator mechanism and component fault is always regarded as a whole for the fault detection and diagnosis in nonlinear control systems. The actuator mechanism fault is served as the input fault and it is often not sensitive to the designed observers-based FDI in the early stage of the fault. The FDI method of the actuator mechanism fault is proposed. The actuator mechanism is considered as the independent dynamic system and its fault is the output fault. Thus a group of observers are designed for each actuator of the actuator mechanism. The FDI of actuator mechanism is diagnosed by the residual change of each actuator observer.

**MATHEMATICAL MODEL OF ACTUATOR MECHANISM**

**Fault-free model:** To facilitate the analysis and consider the actual structure of the actuator mechanism, it is assumed that actuator mechanism is a single input single output nonlinear system. So, the nonlinear mathematical model of the actuator mechanism can be represented as:

\[
x(t) = Ax(t) + f(x, \theta, t) + B\delta(t) + D\delta(x, t) + \delta - Cx(t)
\]  

(1)

where, \(x(t) \in \mathbb{R}^n\) is the state vector, \(\theta(t) \in \mathbb{R}\) is the input vector, \(\delta(t)\) is the output vector, the nonlinear function \(f(x, u, t)\) which meets the Lipschitz condition, is a known function, \(d(x, u, t)\) are consist of the unknown input disturbance and the structured nonlinear uncertainty. A, B, C and D are the known matrices with appropriate dimension.

**Fault model:** In nonlinear control systems, actuator mechanism fault is often considered as input fault. The actuator mechanism is analyzed as the dependent dynamic system and its fault is an output type fault as shown in Fig. 1. When there has actuator mechanism fault, the mathematical model is given as follows:

\[
x(t) = Ax(t) + f(x, \delta, t) + B\delta(t) + D\delta(x, t) + \delta - Cx(t) + E\delta(t)
\]  

(2)

where, \(f(t)\) is an actuator mechanism fault. \(E\) is a known fault distribution matrix. Other parameters have the same meanings as those of Eq. 1.

**SLIDING MODE OBSERVERS DESIGN**

**Assumption 1:** The system (A, C) is observable in which case a matrix \(L \in \mathbb{R}^{m \times n}\) exist such that \(A-LC\) is Hurwitz. Therefore, for real symmetrical positive definite matrix \(P \in \mathbb{R}^{n \times n}\), \(Q \in \mathbb{R}^{m \times m}\), there is the unique solution to the following Lyapunov equation:

\[
(A-LC)^TP + P(A-LC) = -Q
\]

**Assumption 2:** For nonlinear function \(f(x, u, t)\), there exists a positive constant \(\gamma\) such that \(\|f(x, u, t) - f(x_i, u, t)\| / |\gamma| |x_i - x_i| (|\gamma| > 0)\) hold.

**Assumption 3:** There is a known positive function \(\varphi(t)\) such that \(|d(x, t)| / |\varphi(t)|\).

**Assumption 4:** There exists a matrix \(P \in \mathbb{R}^{n \times m}\) such that \(P^TP = C^TC\).

The observer is constructed as follows:

\[
\dot{x}(t) = A\hat{x}(t) + f(\hat{x}, u, t) + B\hat{\delta}(t) + L(\delta - \hat{\delta}) + Dv
\]

\[
\hat{\delta}(t) = C\hat{x}(t)
\]  

(3)

Where:

\[
v = \begin{bmatrix} Fe_1 \\ \|Fe_1\|_0 \\ e_0 = 0 \\ 0 \\ e_0 = 0 \end{bmatrix}
\]

\(\hat{x}, \hat{\delta}\) are the observed value of \(x, \delta\).

Fig. 1: Sketch of actuators fault
The state error equation and the output error equation (residual of observer) are shown in the following equations:

\[ e = x - \hat{x} = (A - LC) x + f(x, \theta, t) - f(\hat{x}, \hat{\theta}, t) + D(\delta(0, x, t) - \nu) \]
\[ r = e_t = \delta - \hat{\delta} = Ce + Ef_t \tag{4} \]

Based on Assumption 1-4 (Saif and Xiong, 2003; Zhu and Cen, 2010), the error equation of the designed observer exponentially converges to zero in the fault-free condition when the following inequality is satisfied (He, 2009):

\[ \lambda_{\text{min}}(Q) - 2\gamma \lambda_{\text{max}}(P) \geq 0 \]

**DETECTION AND ISOLATION OF ACTUATOR MECHANISM**

Due to the high integration of the mechanical automation and higher and higher nonlinear degree, in the actuator mechanism of the nonlinear system there exists more than one actuator whose structure diagram is shown in Fig. 2. \( \theta_l \) (\( 1 \leq l \leq p \)) and \( \delta_l \) (\( 1 \leq l \leq p \)) denote the input and the output for each actuator of the actuator mechanism, respectively.

It is assumed that there exist \( l \) (\( 1 \leq l \leq p \)) actuators in the actuator mechanism. The sliding mode observers are designed for each actuator of the actuator mechanism as follows:

\[
\begin{align*}
\dot{\xi}_l = & A_l \xi_l + f_l(x_l, \theta_l, t) + B_l \theta_l' + L_l(\delta_l - \hat{\delta}_l) + D_l \nu_l \\
\dot{\hat{\delta}}_l = & C_l \xi_l \quad (1 \leq i \leq l)
\end{align*}
\]

Where:

\[
\nu_l = \left[ \begin{array}{c}
\psi(\theta_l) \\
F(\theta_l)
\end{array} \right] \quad F(\theta_l) \neq 0
\]

\[
\psi(\theta_l) = \left[ \begin{array}{c}
\psi(\theta_l) \\
0
\end{array} \right] \quad F(\theta_l) = 0
\]

The deviation \( \varepsilon_l \) and the residual \( r_l \) for each observer are calculated by using the following Eq. 6:

\[
\varepsilon_l = \xi_l - \hat{\xi}_l = (A_l - LC_l) \xi_l + f_l(x_l, \theta_l, t) - f_l(\hat{x}_l, \hat{\theta}_l, t) + D_l \nu_l
\]
\[ r_l = \varepsilon_t - \hat{\varepsilon} - \delta_l = C_l \varepsilon_l + E_l f_{l_t} \tag{6} \]

**Actuator mechanism FDI algorithm:**

**Step 1:** Design a group of \( l \) (\( 1 \leq l \leq p \)) actuators observers by using Eq. 5

**Step 2:** Compute residuals \( r_l (1 \leq l \leq p) \) by using Eq. 6

**Step 3:** Choose a threshold \( \varepsilon^* \). If any residual value goes beyond the corresponding threshold, then faults are detected.

**Step 4:** The number of residual value \( r_l \) that do not tend to zero and exceed corresponding threshold is equal to the number of actuators fault.

**Step 5:** Those actuators corresponding to residuals that do not tend to zero and exceed corresponding threshold are considered to be faulty.

**EXAMPLE AND RESULTS**

The actuator mechanism of certain a miniature unmanned aerial vehicle is analyzed. It is assumed that there have two-order actuators and their mathematical models are shown as follows:

**Actuator 1:**

\[
x_l = A_l x_l + f_l(x_l, \theta_l, t) + D_l \psi(\theta_l, x_l) + B_l \theta_l'
\]
\[ \delta_l = C_l x_l \]

Where:

\[
A_l = \left[ \begin{array}{cc}
0 & 1 \\
1 & 0
\end{array} \right], \quad B_l = \left[ \begin{array}{c}
1 \\
0
\end{array} \right], \quad C_l = \left[ \begin{array}{c}
0.05x_l \cos \theta_l \\
0
\end{array} \right], \quad D_l = \left[ \begin{array}{c}
1 \\
1
\end{array} \right]
\]

The pole of the observer \( l \) is assigned in \((-2, -1)\). Select:

\[
F_l = \left[ \begin{array}{c}
2 & -1 \\
-1 & 1
\end{array} \right], \quad Q_l = \left[ \begin{array}{c}
8 & -3 \\
-3 & 2
\end{array} \right]
\]

The initial values of the system and observer are \( x(0) = \begin{bmatrix} 0 & 0 \end{bmatrix}^T, \quad \dot{x}(0) = \begin{bmatrix} 0.5 & 0.5 \end{bmatrix}, \quad \psi_1 = 5, \quad \theta_1 = 0.3(t) \), respectively.

**Actuator 2:**

\[
x_l = A_l x_l + f_l(x_l, \theta_l, t) + D_l \psi(\theta_l, x_l) + B_l \theta_l'
\]
\[ \delta_l = C_l x_l \]
Where:

\[ t^2 = 0.02 \left[ e^{-t} \sin(x_1 + x_2^2) \cos(x_1 + x_2^2) \right]^T, \]
\[ A^2 = \begin{bmatrix} -1 & 2 \\ 0 & -1 \end{bmatrix}, B^2 = \begin{bmatrix} 2 \\ -1 \end{bmatrix}, C^2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \]
\[ D^2 = \begin{bmatrix} 3 \\ -1 \end{bmatrix}, d^2 = 0.05 \cos(2.5t). \]

The pole of the observer 1 is assigned as (-1, -2). Select:

\[ F^1 = I, P^1 = \begin{bmatrix} 0.5 & 0.667 \\ 0.667 & 1.583 \end{bmatrix}, Q^1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \]

The initial values of the system and observer are \( x^1(0) = [0 \ 0]^T, \hat{x}(0) = [0.5 \ 0.5], \varphi = 5, \theta^1 = 0.3(t), \) respectively.

- There are no faults in both actuator 1 and actuator 2, and the residual values are shown in Fig. 3.

Figure 3 shows that the residuals \( r^1 \) and \( r^2 \) tend to zero in finite time with fault-free in the actuator 1 and actuator 2. At the same time, it also explains that the designed observers have robustness with the disturbances and the system uncertainties.

- There is no fault in actuator 1. The fault in actuator 2 is:

\[ f^2(t) = \begin{cases} 0 & t < 5 \\ 3 + \cos(2t) & t \geq 5 \end{cases} \]

and the residual is shown in Fig. 4.

Figure 4 shows in the actuator mechanism there exists only one fault actuator because the residual of the only actuator 2 does not tend to zero in finite time. When one actuator of the actuator mechanism breaks down, the residual of the corresponding observer will immediately vary. As is seen in above Fig. 4 the residual \( r^2 \) of the observer 2 is equal to zero in faulty time \( t = 5 \) when the slow deviation type fault in the actuator 2 arises. There exists one fault actuator, which is actuator 2, in the actuator mechanism and then the isolation of fault actuator 2 can be realized.

- There are faults in both actuator 1 and actuator 2 with:

\[ f^1(t) = \begin{cases} 0 & t < 3 \\ 6 \sin(5t) & t \geq 3 \end{cases}, f^2(t) = \begin{cases} 0 & t < 5 \\ 4 & t \geq 5 \end{cases} \]

and their residuals are shown in Fig. 5.

Fig. 3(a-b): (a) Residual of actuator 1 with no fault and (b) Residual of actuator 2 with no fault.

Fig. 4: Residual of actuator 2 with fault
Fig. 5(a-b): (a) Residual of actuator 1 with fault and (b) Residual of actuator 2 with fault

Figure 5 demonstrates that in the actuator mechanism there are two fault actuators because the residuals of the two observers do not tend to zero in finite time. It is also known that their residuals \( r^1 \) and \( r^2 \) of the actuator 1 and actuator 2 alter in the faulty time \( t = 3 \) and \( t = 5 \), respectively. So, the slow deviations fault and abrupt fault exist in the actuator 1 and the actuator 2 of the actuator mechanism, respectively.

In a word, in the event of each actuator fault for the actuator mechanism, whether the abrupt fault, the gradual fault or the slow deviations fault, the residual will vary in the faulty time at once. Even in the initial state of the fault, the residual of the observer is very sensitive to the fault.

CONCLUSION

In the nonlinear systems, the actuator mechanism fault is always analyzed as the input type fault. It is difficult to distinguish the initial information of the actuator mechanism fault from the disturbances and the system uncertainties that accompany with the system input. In order to solve the problem, this method is put forward.

The actuator mechanism of the nonlinear system is regarded as the independent dynamic system and so its fault is the output type fault. So, the fault-free and fault mathematical models are established. Then a batch of sliding mode observers is designed for each actuator of the actuator mechanism. The fault detection of each actuator is diagnosed and the fault isolation can be realized according to the residual change of the observer. Through simulation, this method can achieve the fault detection and isolation of actuator mechanism of the nonlinear system.

ACKNOWLEDGMENT

This study is funded by the National Natural Science Foundation of China (61175092).

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