Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

ADAPTIVE FAULT DIAGNOSIS OF HYDRAULIC ACTUATION SYSTEM

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ABSTRACT

Hydraulic actuation system is typical displacement control system whose performance is subjected to random inputs from noise, random disturbance from pump vibration or parameter changes. Through importing the integral item of residual error in different rank, this paper establishes the Proportion-Integral Observer (PIO) that can eliminate the influence of random input, parameter excursion and inherent disturbance and realize the fault diagnosis robustly. In order to reach the high fault coverage and low false alarm, this paper provides twin-threshold and corresponding fault decision-making strategy that not only considers the inherent noise existed in the system but also can manifest the fault information effectively. Application and simulation of hydraulic actuator system indicates that the adaptive fault diagnosis can detect the failure in high precision at the stochastic condition.

KEY WORDS

Fault diagnosis, Proportion integral observer, Twin-threshold, Hydraulic actuation system

NOMENCLATURE

u	:	input command
K_q	:	flow gain of servo valve
T_v	:	time constant of servo valve
E_y	:	bulk module of elasticity
V_t	:	volume of cavity
K_c	:	flow-pressure gain of servo valve
K_s	:	rigidity of output pole
A	:	available area of piston
K_b	:	the gain of displacement sensor
M	:	piston mass
D	:	damping coefficient of piston
X_t	:	piston displacement
X_p	:	load output
F	:	load force
$G(s)$	:	load transfer function

INTRODUCTION

Hydraulic actuation system is a key component in flight control system, which performance and fault diagnosis is very important in application. With many nonlinear characteristics existed in hydraulic actuation system such as load flow of servo valve, friction of mechanical structure, fluid compressibility and coupling with hydraulic pump, it makes failure mechanism complex and failure diagnosis difficult [1].

Fault diagnosis method based on mathematic modeling is to design a diagnostic observer that can describe the system performance and detect the failure in certain direction with the residual error between actual system and observer [2]. However, it is difficult to decoupling and determine the failure location actually if some random factors exist, for example the modeling error and disturbance. So it is necessary to study a robust way to separate the failure characteristics from estimated information effectively [3].

Directing to the disturbance existed in hydraulic actuation system, this paper presents the diagnostic observer based on PIO, which imports the integral item of residual error in observer to be suitable to the influence of random input [4]. Considering the inherent disturbance existed in hydraulic actuation system, its output varies with input signal and outside disturbance, so the fixed error threshold is difficult to cover the failure effectively. This paper presents an adaptive twin-threshold, which consists of fixation and variant items and can be adjusted with the input signal and disturbance. The simulation and application indicate that the adaptive observer based on PIO and twin-threshold can diagnose the failures of hydraulic actuation system effectively.

ADAPTIVE FAULT OBSERVER DESIGN

Although the normal fault observer is designed to pick up fault characteristic from residual error usually, it is easy to be get into trouble by some random factors, which always produces false alarm or fail to report. In order to extract the failure information from residual error effectively, PIO is designed to eliminate the influence of random input and unknown disturbance.

PIO Model in One-dimension

Given the linear time-invariant system:

$$\begin{cases} \dot{x} = Ax + Bu + Dd \\ y = Cx \end{cases} \qquad (1)$$

Where $x \in R^n$ is state vector; $u \in R^p$ is system input; $d \in R^m$ is unknown disturbance; $y \in R^q$ is system output; D is allocation matrix of unknown input; A, B, C is coefficient matrix separately.

In order to realize the effective fault diagnosis under random input, not only the difference between actual output and estimation output but also its integral are inducted in observer, and construct the PIO as follows.

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + K_p(y - \hat{y}) + Df \\ \dot{f} = K_I(y - \hat{y}) \end{cases} \qquad (2)$$

Where $\hat{x}$ is the estimation of the state; f is failure vector; $\hat{y}$ is observer output; K_P is proportion gain of observer; K_I is integral gain of observer. Define the state error vector as:

$$e = \hat{x} - x \qquad (3)$$

Then from equation (2) and (3), the dynamic equation of e and f can be formulated to give

$$\begin{pmatrix} \dot{e} \\ \dot{f} \end{pmatrix} = \begin{pmatrix} A - K_p C & D \\ -K_I C & 0 \end{pmatrix} \begin{pmatrix} e \\ f \end{pmatrix} - \begin{pmatrix} D \\ 0 \end{pmatrix} d \qquad (4)$$

With proper selecting of K_I and K_P, all the eigenvalues of matrix $\begin{bmatrix} A - K_p C & D \\ -K_I C & 0 \end{bmatrix}$ are at the left hand side of the complex plane and the PIO converges to the state of plant. So the observer based on PIO can approach the hydraulic actuation system even if the disturbance exists.

If sensor fails, the dynamic model can be expressed as:

$$\begin{cases} \dot{x} = Ax + Bu + Dd \\ y_1 = C_1 x \\ y_2 = C_2 x + F_2 f_s \end{cases} \qquad (5)$$

Where f_s is failure vector of sensor, F_2 is the corresponding fault distribution matrix. Defining $C = \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$, the output of PIO can be described as $y_2 = C_2 \hat{x} + F_2 \hat{f}_s$, then the failure vector can be obtained as

$$\hat{f}_s = (F_2^T F_2)^{-1} F_3^T \left(y_2 - C_2 \hat{x} \right) \qquad (6)$$

If actuator fails, the dynamic system become

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + Dd(t) + Ef_a(t) \\ y = Cx \end{cases} \qquad (7)$$

Where E is the fault distribution matrix and f_a is failure vector of actuator. Then the residual error can be solved from the error differential equation as

$$\varepsilon(t) = e^{(A-K_p c)t}\varepsilon(0) + \int_0^t e^{(A-K_p c)(t-\tau)} D[f(\tau) - d(\tau)]d\tau + \int_0^t e^{(A-K_p c)(t-\tau)} Ef_a(\tau)d\tau \qquad (8)$$

Where $\varepsilon(0)$ is original value of estimated error. Equation (8) provides the failure direction of actuator.

If the system is no fault i.e. $f_a = 0$, then ε =0. As such the estimation f is the estimation of disturbance d under proper selection of K_p, K_I. Otherwise

$f_a \neq 0$ if actuator fails, its residual error can be described as:

$$\varepsilon(t) = \int_0^t e^{(A-K_p c)(t-\tau)} E f_a(\tau) d\tau \qquad (9)$$

PIO Model in Multiple-dimension

When unknown disturbance is not constant, the performance of PIO based on one-dimension is not satisfied with the requirement of error modification. Hence the PIO in multiple-dimension is presented to estimate the disturbance signal in multiple dimension.

For polynomial form of multiple dimension disturbance shown as follows:

$$d(t) = a_0 + a_1 t + a_2 t^2 + \cdots + a_q t^q \qquad (10)$$

Where a_i is coefficient of polynomial $(i = 1,2,\cdots,q)$. Establish the state space equation under polynomial disturbance as follows.

$$\begin{pmatrix} \dot{d}_0 \\ \dot{d}_1 \\ \dot{d}_2 \\ \vdots \\ \dot{d}_q \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix} \cdot \begin{pmatrix} d_0 \\ d_1 \\ d_2 \\ \vdots \\ d_q \end{pmatrix} \qquad (11)$$

Where $d_i(t)$ is the i^{th} unknown disturbance vector whose rank is r_i $(i = 1,2,\cdots,q)$, its state can be described as $d_0 = d(t)$, $d_1 = \dot{d}_0$, $d_2 = \dot{d}_1$, $\cdots$, $d_q = 0$ separately.

On this condition, the all-rank integral items of residual error are acceded to observer, and construct the PIO in multiple dimension as follows.

$$\bar{A} = \begin{pmatrix} A & D_1 & D_2 & \cdots & D_q \\ 0 & \Delta_1 & 0 & \cdots & 0 \\ 0 & 0 & \Delta_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \Delta_q \end{pmatrix} \qquad (12)$$

$$\bar{C} = \begin{pmatrix} C & 0 & 0 & \cdots & 0 \end{pmatrix}$$

Where $D_i = [P_i \quad 0 \quad \cdots \quad 0 \quad 0]_{n\times(r_i+1)}$, $P_i \in R^{n\times 1}$ is the row vector which include uncertainties, noise and unknown input. Δ_i is the unit matrix shown as follow:

$$\Delta_i = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{bmatrix}_{(r_i+1)(r_i+1)} \qquad (13)$$

With considering the influence of polynomial disturbance, all-rank integral items of residual are imported in PIO so as to realize the estimation. The existence condition of multiple PIO is that $(\bar{A},\bar{C})$ can be observed. Its block diagram is expressed in Figure 1.

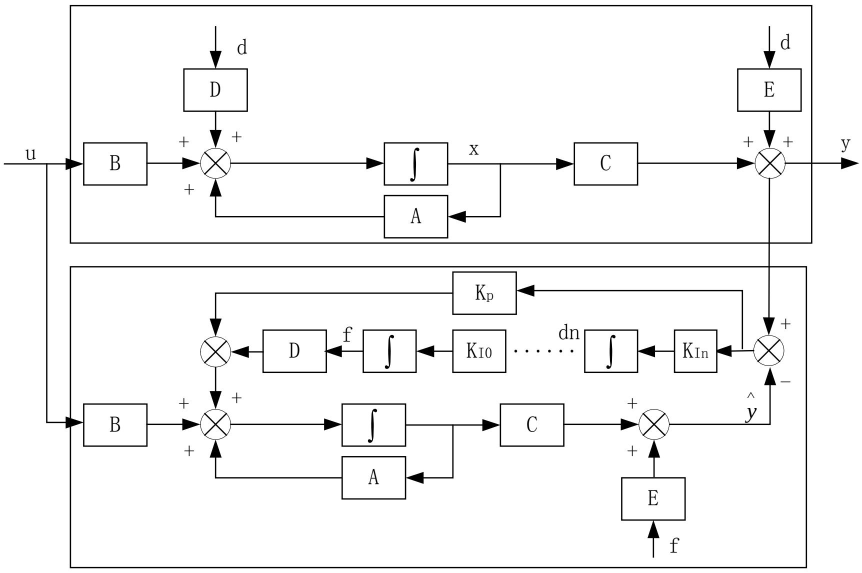

Figure 1 PIO in multiple dimension

It is proved that the dimension of PIO is $n+\sum_{i=1}^{q}(r_i+1)$, which increases with the rank of unknown disturbance. Due to the function of various integral items, PIO is suitable to stochastic system with some noise, unknown input and disturbance.

Twin Threshold

Fault detection and diagnosis are always executed with proper threshold that determine the failure coverage and false alarm. Considering the inherent noise and measurable error existed in control system, it is necessary to provide the preliminary threshold that can describe its inherent disturbance in normal condition. At the same time, the variance due to failures should also be represented in threshold. So the single threshold is not possible to realize the fault diagnosis effectively under random condition. The adaptive twin-threshold include two items as follows.

$$T(t)=T_0(t)+T_1(t) \tag{14}$$

Where $T(t)$ is adaptive twin-threshold, $T_0(t)$ is constant part considering inherent disturbance, $T_1(t)$ is time-variant part that describe the fault variety of system. The failure can be diagnosed according following decision-making strategy:

(1) If residual error is larger than $T_0(t)+T_1(t)$, it determines that the system fails to a certainty.

(2) If residual error is between $T_0(t)$ and $T_0(t)+T_1(t)$, it is doubtful that the failure occurs and begin to monitor. After three times, it determines that the system fails. Otherwise the system is normal.

(3) If residual error is less than $T_0(t)$ at all the time, the system is normal.

The twin-threshold is adaptive to the fault diagnosis of dynamic system, which has higher fault coverage and lower false alarm because the disturbance and fault variance are considered in threshold design. Suppose the allowable error of component in system is $E_i, i=1,2,\cdots,n$, its gain is $R_i, i=1,2,\cdots,n$ separately. The maximum error of system can be described as $T_1=E_{\max}=\sum_{i=1}^{n}|E_i|$, which is the worst condition. $T_0(t)$ is determined by inherent disturbance.

Figure 2 shows the adaptive twin-threshold, in which curve 2 is the adaptive twin-threshold of certain detected signal $T(t)=T_0(t)+T_1(t)$ and curve 1 covers the variance of inherent disturbance $T_0(t)$.

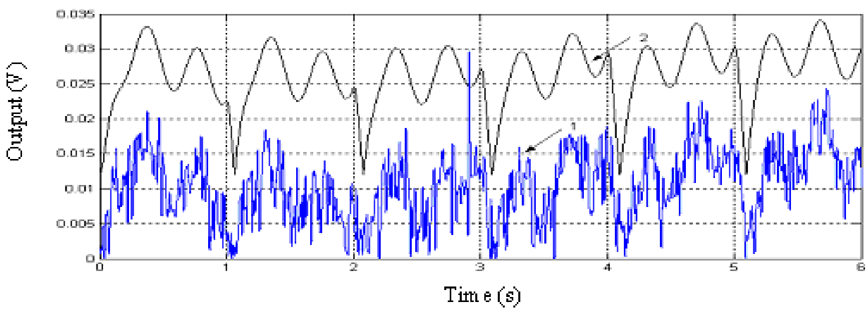

Figure 2 Adaptive twin threshold of a certain signal

It is obvious that the twin-threshold can solve the conflict between false alarm and fail to report of fault diagnosis in great degree so as to improve the robust. In practice, the adaptive twin-threshold is difficult to cover all the failure absolutely especially to the abnormal point shown in Figure 2. For example, the value at 2.8 second is greater than twin-threshold whereas the system is normal in general.

APPLICATION OF HYDRAULIC ACTUATION SYSTEM

PIO Design

Hydraulic actuation system is a key component that can be driven by command to realize the displacement control, which consists of displacement sensor, amplifier, servo valve and cylinder. Its block diagram is shown in Figure 3.

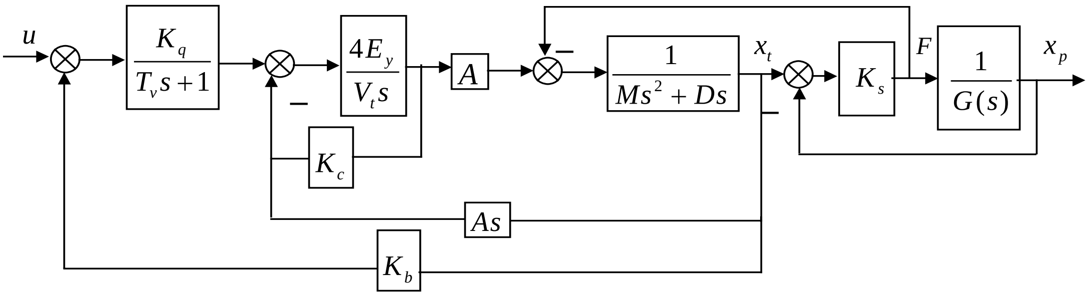

Figure 3 The block diagram of hydraulic actuation system

Establish the state space model of hydraulic actuation system as:

$$
\left.\begin{aligned}
\dot{x} &= \begin{pmatrix} -6.2834\times10^{2} & 0 & -1.4138\times10^{3} & 0 & 0 \\ 2.4459\times10^{3} & -2.237\times10^{3} & 1.5061\times10^{8} & 0 & -1.5061\times10^{8} \\ 0 & 0.5 & -3.5\times10^{4} & 0 & 3.5\times10^{4} \\ 0 & 0 & 3.5\times10^{4} & -5 & -3.5\times10^{4} \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix} x + \begin{pmatrix} 1.4138\times10^{4} \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} u + \begin{pmatrix} 0 \\ 2.1515\times10^{3} \\ -0.5 \\ 0 \\ 0 \end{pmatrix} F \\
y &= \begin{pmatrix} 0 & 0.56841 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} x + \begin{pmatrix} 0 \\ 1 \end{pmatrix} f_s
\end{aligned}\right\} \quad (15)
$$

Adopting the eigenvalue configuration, design the Luenberger observer and PIO whose integral gain is $K_I = 64.542$. If the system is normal with inherent noise of square signal with amplitude 10 and period 2s, the PIO output can be described as the real line and the output of Luenberger observer is shown as broken line in Figure 4.

It is obvious that the output residual error is less than the one of Luenberger observer, so PIO has the better performance comparing with the Luenberger observer.

Figure 5 shows the estimation effect of PIO in multiple dimension, in which curve 1 shows the disturbance existed in system and curve 2 is the corresponding estimation of PIO. It indicates that PIO can approach the model of stochastic system effectively.

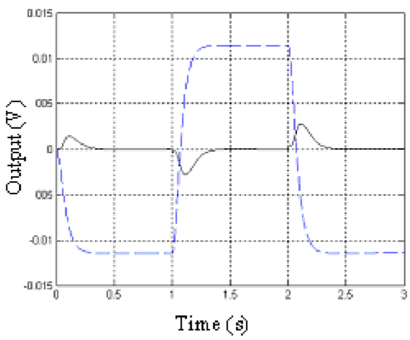

Figure 4 Comparison between PIO and Luenberger observer

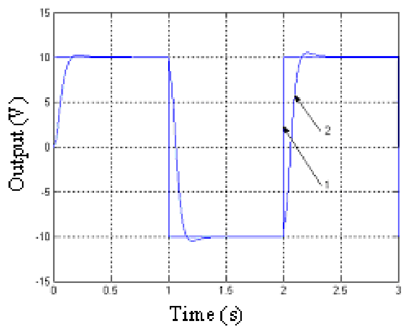

Figure 5 Comparison of disturbance and its estimation

If the sensor fails gradually according to the following rule:

$$
f_s = \begin{cases} b_2 * \sin(2\pi/10) & 1.2s \le t \le 3s \\ 0 & others \end{cases} \quad (16)
$$

Then obtain the output residual of system shown in Figure 6, in which the real line is the residual of normal system and the broken line is the residual under sensor failures. It indicates that PIO can detect the fault sensor effectively.

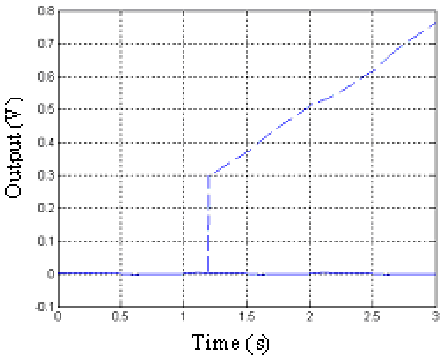

Figure 6 The residual under failures

Twin Threshold of Hydraulic Actuation System

Usually, parameter variable, flow pulse and Gauss noise can affect the threshold, so consider the inherent disturbance to determine T_0 and accumulate the tolerance of all components to determine T_1 shown in Figure 2. Select the control period is 10*ms* and let $T_1 = 10T_0$, then obtain the twin threshold in Figure 7, in which curve 1 expresses the threshold T_0, curve 2 denotes the threshold $T_0 + T_1$, curve 3 is the residual under gradual failure and curve 4 means the median of $T_0 + T_1$.

The corresponding decision-making strategy is shown as follows:

(1) If $\varepsilon > T_0 + T_1$, system fails.

(2) If $T_0 < \varepsilon < 1/2(T_0 + T_1)$ and last for 30 times in 60 clock period, then the system fails, otherwise the system is normal.

(3) If $1/2(T_0 + T_1) < \varepsilon < T_0 + T_1$ and last for 20 times in 40 clock period, then the system fails, otherwise the system is normal.

(4) If $\varepsilon < T_0$, the system is normal.

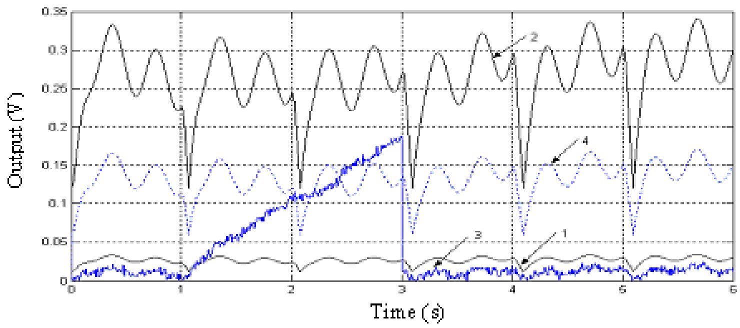

Figure 7 Fault diagnosis based on twin-threshold

In Figure 7, the failure occurs at 1.0 second. The residual error exceeds T_0 at 1.1 second, and went on until the residual error is greater than $1/2(T_0 + T_1)$ at 2.7s. After detecting for 30 clock period, PIO determines the gradual failure according to the fault diagnosis strategy, and remove the fault sensor in 3.0 second, so the system recovers to normal condition.

CONCLUSIONS

This paper provides the PIO and twin-threshold to hydraulic actuation system so as to improve the adaptability in fault diagnosis. Application indicates that the performance of PIO is better than the Luenburger observer, and twin-threshold not only can detect various failures rapidly but also can improve its robusticity.

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ACKNOWLEDGEMENT

This work was supported by National Natural Science Foundation of China under grant number 60371043, Beijing Natural Science Foundation under grant number 4012009, and Chinese Excellent Talent Plan of New Century.