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Missile Fault Detection Based on Linear Parameter Varying Fault Detection Filter

Cui Yu, Huang Xin Han and Wang Min
Department of Control Science and Engineering,
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract: Focusing on the problem of fault detection and isolation (FDI) for a missile in the cruise phase, a solution based on Linear Parameter Varying (LPV) Fault Detection Filter (FDF) is proposed. The missile LPV model incorporating faults is established and converted to a suitable form for the appliance of LPV FDI via simplifying and other tools. Based on that, a fault detection system of missile is proposed for fault detection and isolation, of which the LPV filter bank can be designed using standard geometrical approach. Simulation results demonstrate that the designed fault detection system will alarm in a short time once faults happen and then locate the fault part correctly. Since the designed fault detection system is suitable for the high maneuverability of the missile and the on-line calculation load is small, the solution is of great practical value.

Key words: Missile LPV model, fault detection and isolation, fault diagnosis

INTRODUCTION

Any control system is dependent upon the quality of the data that it receives (i.e., sensors) and execution of the commands that it issues (i.e., via actuators). However, owing to wear of mechanical and electrical components, both actuators and sensors can fail unexpectedly. To improve the reliability and safety of control systems, it is necessary to detect faults when they occur and locate the fault components as soon as possible so that control systems can adopt corresponding fault tolerant strategies. This so-called fault detection and isolation (FDI) problem is of great importance to the missile control system since once faults occur the missile may cause unpredictable hazard.

Since missile models are usually nonlinear and time varying, it is not easy to apply FDI scheme to the missile system. One common approach is to linearize the missile model around given setpoints, then use gain scheduling method for control. This approach neglects the nonlinear nature of the missile model and the stability of the designed Fault Detection Filter (FDF) during the flight envelope lacks theoretical support. Shamma and Cloutier (1992) demonstrated that fast scheduling parameter variations during flight may corrupt the stability of the FDF.

The more efficient approach is based on Linear Parameter Varying (LPV) technology. LPV methods can capture the nonlinearities of the missile through state transformations to yield a quasi-LPV description of the missile and therefore allow some relatively mature linear-like control method to be applied. Based on that, many theoretical sound control system design methods are successfully applied to the missile LPV systems by Ganguli *et al*. (2002), Tan *et al*. (2000) and Yu *et al*. (2006).

If the control system can be designed for missile LPV systems, it is also reasonable to design FDI for this model class. Among the existing FDI researches on LPV systems, Boker and Balas (2004) extends the fault detection filter for LTI system to a class of LPV systems using standard geometrical algorithms. Abadalla *et al*. (2001) and Casavola *et al*. (2008) proposed frequency domain based FDF design method for a class of polytopic LPV system using H_∞/H_- performance index. However, few literatures have applied these theoretical methods to missile LPV system. Motivated by that, the FDI problem for a missile in cruise phase is fully investigated in this study. A fault detection system incorporating a LPV fault detection filter bank is proposed to detect and isolate the faults of tail actuator and pitch rate sensor. The LPV fault detection bank is designed based on the geometrical algorithms originally proposed by Boker and Balas (2004). The proposed missile fault detection system is well suitable for the high maneuverability of the missile and can be easily implemented using computers.

Corresponding Author: Cui Yu, Department of Control Science and Engineering,
Huazhong University of Science and Technology, Wuhan 430074, China

Notations: Let N be a matrix with appropriate dimensions, Ker N represents the kernel space of N and Im N represents the image space of N.

LPV FDI FILTER

Consider a class of LPV/qLPV system as below:

$$\dot{x}(t) = A(\rho)x(t) + B(\rho)u(t) + \sum_{i=1}^{n} L_i(\rho)f_i(t) \quad (1a)$$

$$y(t) = Cx(t) \quad (1b)$$

where, x is the state vector, y is the measured output, u is the known control input, f_i represents unknown fault signal and the corresponding $L_i(\rho)$ is the known fault signature matrix. The state space matrices depend affinely on the time-varying scheduling parameter ρ:

$$A(\rho) = A_0 + \rho_1 A_1 + \rho_2 A_2 + ... + \rho_N A_N,$$

$$B(\rho) = B_0 + \rho_1 B_1 + \rho_2 B_2 + ... + \rho_N B_N,$$

$$L_i(\rho) = L_{i,0} + \rho_1 L_{i,1} + \rho_2 L_{i,2} + ... + \rho_N L_{i,N},$$

where, $\rho = (\rho_1,...\rho_i...\rho_N) \in P$ is unknown a priori but on-line measurable.

Before giving the general LPV filter for system 1, two geometrical space definitions are given below:

Definition 1: A subspace S is called a parameter varying (C, A)-invariant subspace of system 1, if and only if for any $\rho \in P$ there exists a sate feedback matrix G(ρ) such that:

$$(A(\rho) + G(\rho)C)S \subseteq S$$

The set of all parameter varying (C, A)-invariant subspaces Θ containing a given subspace L admits a minimum denoted by J(C, A, L).

Definition 2: A subspace S is called the unobservability subspace of system 1 if and only if there exists a constant matrix H and state feedback matrix G(ρ) such that S is the largest parameter varying (C, A)-invariant subspace contained in Ker HC.

The following standard algorithms will be employed to compute the unobservability subspace for system 1.

Algorithm 1: The minimal parameter varying (C, A)-invariant subspace J(C, A, L) containing L can be computed by the following steps:

$$W^0 = L$$

$$W^{k+1} = L + \sum_{l=0}^{N} A_l (W^k \cap \ker C), k \geq 0$$

$$J(C, A, L) := \lim_{k} W^{k+1}$$

Algorithm 2: The minimal unobservability subspace J(ker HC, C, A, W) containing a given subspace W can be computed as follows:

$$S^0 = W + \ker C$$

$$S^{k+1} = W + \bigcap_{l=1}^{N} (A_l^{-1} S^k \bigcap \ker C)$$

$$J(\ker HC, C, A, W) := \lim_{k} S^{k+1}$$

Based on the space definitions above, the following Corollary can be derived from the proposition 8 in Boker and Balas (2004), which gives a necessary and sufficient condition for the existence of the FDI filters for system 1.

Corollary 1: For LPV system 1, there exists a LPV FDI filter in the form of:

$$\begin{aligned} \dot{w} &= N(\rho)w - G(\rho)y + F(\rho)u \\ r &= Mw - Hy \end{aligned} \quad (2)$$

that is only sensitive to the fault set $\sum_{j \in \Delta} L_j(\rho) f_j$ if and only if the minimal unobservability subspace S containing:

$$W = \sum_{i=1, i \notin \Delta}^{m} \sum_{k=1}^{N} \text{Im} L_{i,k}$$

and the fault space $L^* = \sum_{k=1, j \in \Delta}^{N} \text{Im} L_{j,k}$ satisfy $S^* \cap L^* = 0$.

The matrix parameters of the LPV FDF are given as follows: H is the solution of ker HC = w+ker C and let projection P: X→→/S*, then M is an unique solution of MP = HC. F(ρ) Let G_0 (ρ) be a solution satisfying $(A+G_0(\rho)C)S^* \subset S^*$ where, $G_0(\rho) = G_{00} \subset \rho_1 G_{01} + ... + \rho_N G_{0N} ... + \rho_N G_{0N}$, then $A_0(\rho = A(\rho) + G_0(\rho)C|\chi/S^*$, $N'(\rho) := A_0(\rho)$.

The LPV FDF given above can not necessarily guarantee the quadratically stability on ρ = P. Therefore, an extra term is added to N(ρ) by setting $N(\rho) = N'(\rho) + G_1(\rho)M$, where, $G_1(\rho) = G_{10} + \rho_1 G_{11} +,,, + \rho_N G_{1N}$. $G_1(\rho)$ is determined such that:

$$X^T N(\rho) + N(\rho)^T X < 0$$

holds for all $\rho \in P$ with a suitable symmetrical matrix X>0.

With $G_0(\rho)$, $G_1(\rho)$ computed above, we get $G(\rho) = PG_0(\rho)+G_1(\rho)H$.

MISSILE MODEL AND FAULT MODELS

Here, a missile model will be given that will be used as the design object and the fault models of the missile components is analyzed and established. For the convenience of applying LPV FDF to the missile model, necessary transformation is used to rewrite the missile model with fault models included into the form of system 1.

Missile model: The so-called Reichert's missile model is often used as a benchmark (Nichols *et al*., 1993; Adounkpe *et al*., 2004; Shamma and Cloutier, 1993). This is a pitch-axis model of a highly maneuverable missile. Its state-space equations are given as:

$$\begin{bmatrix}\dot{\alpha}\\ \dot{q}\end{bmatrix} = \begin{bmatrix}A_{11} & 1\\ A_{21} & 0\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix} + \begin{bmatrix}B_{11}\\ B_{12}\end{bmatrix}\delta_c \quad (3)$$

$$y = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix} \quad (4)$$

with

$$A_{11} = MK_\alpha[a_n^2\alpha^2 + b_n|\alpha| + c_n]\cos(\alpha)$$

$$A_{21} = M^2K_q[a_m^2\alpha^2 + b_m|\alpha| + c_m]$$

$$B_{11} = MK_\alpha d_n \cos(\alpha)$$

$$B_{21} = M^2K_q d_m$$

where, α represents attack angle(deg) with $|\alpha|\leq 20$, q represents pitch rate (deg/sec), δ_c represents tail defection angle (deg), M represents the Mach number the missile is traveling at and the outputs of the missile system include attack angle and pitch rate. It should be pointed that unlike airplanes the angle of attack angle can not be directly measured in the case of realistic missile systems. Adounkpe *et al.* (2004) solve this problem by constructing an observer to obtain it (Adounkpe *et al*., 2004). Numerica data are given in the Table 1.

Here the Reichert missile model in cruise phase is considered, i.e., Mach number M is constant. To apply LPV FDF, important simplifications are made to the missile model without the loss of the accuracy.

Note that $\cos(\alpha)$ is close to 1, if $|\alpha|\leq 20$ deg. So just let $\cos(\alpha)$ for simplicity. Moreover, note that $\cos(\alpha)$ is an

Table 1: Missile coefficients

Coefficients	Values	Cofficients	Values
K_α	1.1855	K_q	70.586
a_n	0.000103	a_m	0.000215
b_n	-0.00945	b_m	-0.0195
c_n	-0.1696	c_m	0.051
d_n	-0.034	d_m	-0.206

almost affine function of A_{21} when $|\alpha|\leq 20$ deg and M is constant. The relation between A_{11} and A_{21} can be derived via linear interpolation, i.e.,

$$A_{11} = \beta A_{21} + b$$

With the above simplifications, the missile model is now able to be transformed into the form of system 1. Here the parameter A_{21} is written as a function of the normalized parameter ρ:

$$A_{21} = A_{21}^0 + \rho A_{21}^1 = \frac{1}{2}(\bar{A}_{21} + \underline{A}_{21}) + \rho\frac{1}{2}(\bar{A}_{21} - \underline{A}_{21})$$

where, $\bar{A}_{21}$ is the maximum possible value of A_{21} during flight and $\underline{A}_{21}$ is the minimum possible value of A_{21} during flight. Then the Reichert's missile model can be rewritten as follows:

$$\dot{x}(t) = (A_0 + \rho A_1)x(t) + Bu(t) \quad (5)$$

$$y(t) = Cx(t) \quad (6)$$

Where:

$$A_0 = \begin{bmatrix}\beta A_{21}^0 + b & 1\\ A_{21}^0 & 0\end{bmatrix},\ A_1 = \begin{bmatrix}\beta A_{21}^1 & 0\\ A_{21}^1 & 0\end{bmatrix}$$

$$B = \begin{bmatrix}MK_\alpha d_n\\ M^2K_q d_m\end{bmatrix},\ C = 1$$

FAULT MODELS

The missile considered above includes two main components, i.e., tail actuator and pitch rate sensor. The fault model of each component is established below to capture the behavior of the fault.

The behavior of the tail actuator fault can be represented by $f_{act} = L_1(\rho)f_1(t)$, where, the fault signature $L_1(\rho) = B$. f_1 (t) can be different functions so as to model different fault types. If the tail actuator has a bias b, then f_1 (t) = b. If the tail actuator is dead and doesn't response to controller input, then f_1 (t) = $1u_c$. If the actuator saturates like in a zone [b ∞], then $f_1(t) = b-u_c$.

The behavior of pitch rate sensor can be modeled in a similar way. The fault can be represented by f_{sensor} =

$L_2(\rho)\, f_2(t)$. Without loss of generality, here we just let $L_2(\rho) = [0 \quad 1]$. $f_2(t)$ can also be set to different functions to model different fault types. For example, to model the sensor bias fault, just set $f_2(t) = b$. The other types are just treated the same way as to the tail actuator fault, so, here it is omitted. Note that the pitch rate sensor fault occurs in the output channel of the system, the fault model term should appear in the right hand of Eq. 6. However, it isn't consistent with the form of the system 1. To solve this problem, the sensor fault needs to be modeled as a pseudo actuator fault through appropriate state augmentation. Without loss of generality, the sensor fault $f_2(t)$ can be assumed as an output of an imaginary LTI system:

$$\dot{f}_2(t) = af_2(t) + s(t) \tag{7}$$

where, s(t) is an unknown time varying function and $\underline{A}_{21}$ is a scalar. For simplicity, here we just let a = -1.

MISSILE MODEL FOR LPV FDF DESIGN

Based on the discussion above, the combined state and component fault model of missile has the following form:

$$\begin{aligned} \begin{pmatrix} \dot{x} \\ \dot{f}_2 \end{pmatrix} &= A'(\rho)\begin{bmatrix} x \\ f_2 \end{bmatrix} + B'(\rho)u(t) + L'(\rho)\begin{bmatrix} f_1 \\ s \end{bmatrix} \\ y(t) &= C'\begin{bmatrix} x \\ f_2 \end{bmatrix} \end{aligned} \tag{8}$$

with

$$A'(\rho) = A'_0 + \rho A'_1 = \begin{bmatrix} A_0 & 0 \\ 0 & -I \end{bmatrix} + \rho\begin{bmatrix} A_1 & 0 \\ 0 & 0 \end{bmatrix}$$

$$B'(\rho) = \begin{bmatrix} B \\ 0 \end{bmatrix},\ L'(\rho) = \begin{bmatrix} L_1(\rho) & 0 \\ 0 & I \end{bmatrix},\ C' = [C \quad L_2(\rho)]$$

Note that the pitch rate sensor fault is removed from the output channel of the model. Since $L_1(\rho)$, $L_2(\rho)$ is constant, system 8 has the same form of system 1. Now the suitable FDFs can be designed using geometric approach for the missile system to achieve fault detection and isolation.

MISSILE FAULT DETECTION SYSTEM

Here, a missile fault detection system is proposed to detect and isolate tail actuator and pitch rate sensor faults. The configuration of the system is shown in Fig. 1,

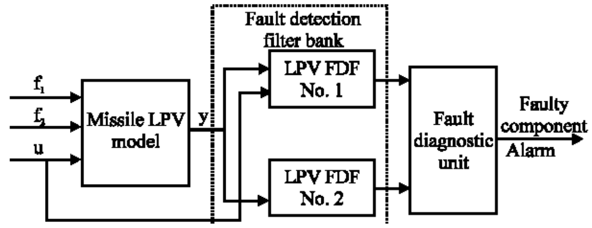

Fig. 1: Missile fault detection system

(a)

	r_1	r_2
f_1	√	√
f_2	√	×

(b)

	r_1	r_2
f_1	√	×
f_2	√	√

(c)

	r_1	r_2
f_1	×	√
f_2	√	×

Fig. 2: Feasible mapping relationships between residual set and fault set (√ represents that the residual is sensitive to the fault, × represents that the residual is insensitive to the fault)

where, f_1 and f_2 represent tail actuator fault and pitch rate sensor fault respectively, u is the missile controller input.

The fault detection system consists two main parts, i.e., LPV fault detection filter bank and fault diagnostic unit, both of which can be implemented using computer microprocessors. The LPV fault detection filter bank is to generate a set of residuals (r_1, r_2) from the measured signal and controller input. For fault detection filter bank, two FDFs are needed at least for the purpose of FDI. To lower system cost, the filter bank is designed only to contain the necessary ones, i.e. two FDFs. To achieve fault detection and isolation, the residual (r_1, r_2) generated by LPV filter bank must satisfy specific mapping relationship with the fault set (f_1, f_2).The feasible mapping relationships between the residual set and the fault set are shown in Fig. 2.

All the mapping relationships in Fig. 2 can be employed in the design of LPV FDI bank to achieve the fault detection and isolation. From the design point of view, mapping a and b are easier to be realized by FDF design approach, since it is usually more difficult to design a FDF that is only sensitive to a certain fault by geometric approach than to design a FDF sensitive to all faults. The mapping employed will be stored in the computer. When performing on-line fault diagnosis, the fault diagnostic unit will read the output of LPV fault detection filter bank in interval time and then look up the mapping table to decide whether a fault has occurred and where it comes from.

DESIGN EXAMPLE

A design example of the missile traveling at 3 Mach is presented in detail to describe the design of the fault detection system based on LPV FDF. It should be pointed that the design process is similar when the missile is traveling at a different speed.

When M = 3, by linear interpolation one can get $A_{11} = \beta A_{21}+b$, where, $\beta = 2.366\times10^{-3}$, b = -0.693. The linear interpolation is achieved with less than 3% of relative errors respectively in A_{11}.

On computing $\bar{A}_{21}$ and $\underline{A}_{21}$, system 8 is attained with following numerical parameters:

$$A_0' = \begin{bmatrix} -0.8477 & 1 & 0 \\ -64.15 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$A_1' = \begin{bmatrix} -0.2298 & 0 & 0 \\ 96.55 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, L'(\rho) = \begin{bmatrix} -0.1209 & 0 \\ -130.87 & 0 \\ 0 & 1 \end{bmatrix}$$

$$B' = \begin{bmatrix} -0.1209 \\ -130.87 \\ 0 \end{bmatrix}, C' = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix}$$

According to the discussion in the last section, three available mapping relationships can be employed to detect and isolate the tail actuator fault and pitch rate sensor fault. Here, the more complicated one, i.e., mapping relationship (c) is employed. Two LPV Filters are to be designed: filter No. 1 is only sensitive to the pitch rate sensor fault f_2 and filter No. 2 is only sensitive to the tail actuator fault f_1.

The design of the LPV FDF bank is given as below. Since kerC = $[0\ \ -1\ \ 1]^T$ and L_1:= imL_1, L_2:= imL_2 are not in kerC, using Algorithm 1 one can immediately get J(C, A, L_1) = L_1, i = 1, 2∘ Using Algorithm 2, the unobservability space is derived that $S_1^* = W_1^*, S_2^* = W_2^*$. Since $S_1^* \cap L_2 = \varnothing$ and $S_2^* \cap L_1 = \varnothing$, according to Corollary 1, there exist FDI filter No. 1 and FDI filter No. 2 in the form of Eq. 2 satisfying the mapping relationship (c) for detecting and isolating the tail actuator fault and pitch rate sensor fault.

Now consider the design of filter No. 1.With the minimal parameter varying unobservability subspace containing imL_1, one is able to calculate the projection:

$$P_1 \mid \mathcal{X} \to \mathcal{X}/S_1^* = \begin{bmatrix} 1 & -0.0009 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

and a sate feedback matrix that makes S_1* (C, A)-invariant:

$$G_{01}(\rho) = \begin{bmatrix} 1.8477 & -1 \\ 64.15 & 1 \\ 0 & 0 \end{bmatrix} + \rho \begin{bmatrix} 1.2298 & 0 \\ -96.55 & 1 \\ 0 & 0 \end{bmatrix}$$

Having G_{01} (ρ) calculated, we get:

$$A_0(\rho) = \begin{bmatrix} 1 & -1.0009 \\ 0 & 1 \end{bmatrix} + \rho \begin{bmatrix} 1 & -0.0009 \\ 0 & 0 \end{bmatrix}$$

The rest of matrices are given as below:

$$N(\rho) = A_0(\rho),\ H_1 = [-1 \quad 0.0009],\ M_1 = [-1 \quad 0.0009],\ F_1 \approx [0 \quad 0]^T$$

To guarantee the quadratically stability of the filter No. 1, extra item G_{11} (ρ)M is added to N (ρ). With the aid of matlab LMI toolbox, it is easy to compute G_{11} (ρ):

$$G_{11}(\rho) = \begin{bmatrix} 2.8737 \\ -4.8099 \end{bmatrix} + \rho \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Then,

$$N_1(\rho) = \begin{bmatrix} -1.8737 & -0.9983 \\ 4.8099 & 0.9957 \end{bmatrix}$$

$$G_1(\rho) = \begin{bmatrix} -1.0853 & -0.9983 \\ 4.8099 & -0.0043 \end{bmatrix} + \rho \begin{bmatrix} 0.3190 & 0 \\ 0 & 0 \end{bmatrix}$$

It can be observed that tail actuator fault space Im $L_1(\rho)f_1(t)$ is contained in the unobservable space of the LPV FDF No. 1, so residual r_1 will stay near zero when tail actuator fault occurs. Meanwhile, according to Corollary 1, pitch rate sensor fault space Im$L_2(\rho)f_2$ doesn't intersect the unobservable space of the LPV FDF No. 1, so the residual r_1 will rise once the sensor fault occurs.

The design of the filter No. 2 is in a similar way. The system matrices of filter No. 2 are given as follows:

$$F_2 = [-0.1209 \quad -130.87]^T,\ N_2(\rho) = \begin{bmatrix} -1.0714 & 1 \\ -1.4286 & 0 \end{bmatrix}$$

$$G_2 = \begin{bmatrix} -0.2237 & 0 \\ 62.72 & 0 \end{bmatrix} + \rho \begin{bmatrix} 0.2298 & 0 \\ -96.55 & 0 \end{bmatrix}$$

$$M_2 = H_2 = [-0.03 \quad 0]$$

With the FDFs designed above, the missile fault detection system is built according to Fig. 1.

SIMULATION RESULTS

To demonstrate the effectiveness of the designed missile fault detection system, a simulation result is given with sampling time 100 msec and missile scheduling parameter ρ changing in Fig. 3. In Fig. 4, the dashed lines represent tail actuator bias fault f_1 (occurred from 20 to 70 sec, otherwise is zero) and pitch rate sensor bias fault f_2 (occurred from 50 to 95 sec, otherwise is zero) and the solid lines represent the residual output (r_1, r_2) of the designed LPV fault detection filter bank during the simulation. It is easily observed that the residual r_1 is only sensitive to fault f_2 and that the residual r_2 is only sensitive to fault f_1. The diagnostic information generated by fault diagnostic unit is shown in Fig. 5, where the value 1 denotes alarm. From Fig. 5 we can conclude that the designed fault detection system can detect faults shortly after they occur and locate the faulty component correctly.

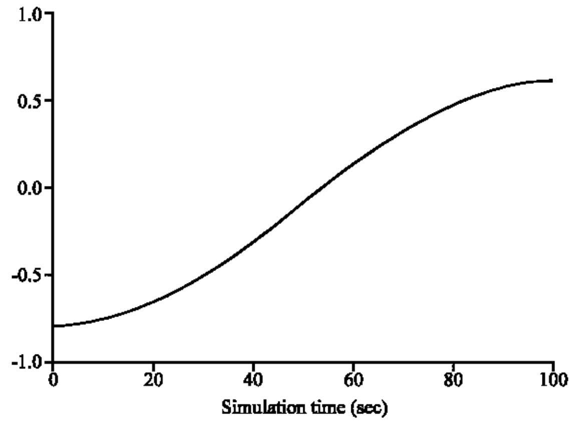

Fig. 3: Scheduling parameter β

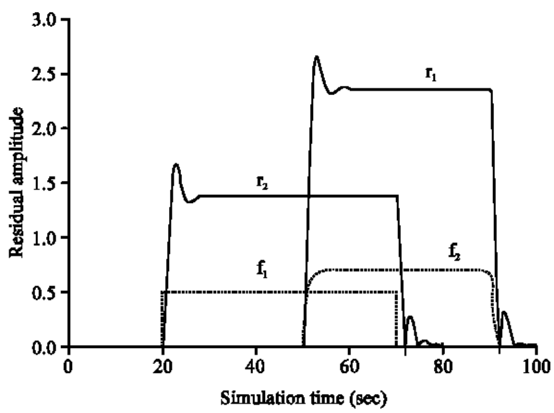

Fig. 4: The residual generated by FDF bank

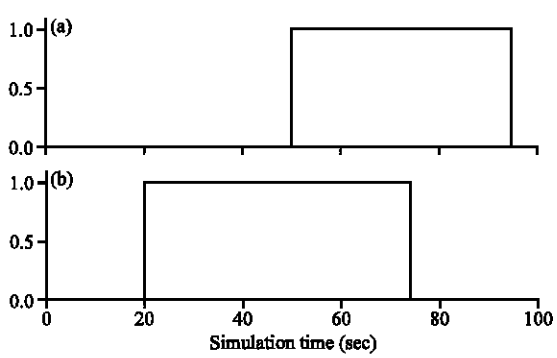

Fig. 5: The alarm signal generated by fault diagnostic unit (a) Pitch rate sensor fault alarm and (b) Tail actuator fault alarm

CONCLUSION

In this study, the FDI problem for a missile in cruise phase is studied. A fault detection system including LPV fault detection filter bank and fault diagnostic unit is propose to detect and isolate the tail actuator fault and pitch rate sensor fault. The specific mapping relationship between residual set generated by LPV fault detection filter bank and fault set is satisfied using standard geometrical algorithms. The simulation result shows that the fault detection system performs well during the cruise phase. Due to LPV technology the missile fault detection can maintain stability even when the scheduling parameter is changing very fast, which is well suitable for the high maneuverability of the missile. Moreover, since the on-line computation load of FDI is quite small, the fault detection system can be easily implemented using computer program, thus enjoying great practice value.

It should be noted that the case of system disturbance is not considered in this study. But if the disturbance signature matrix is pre-known, the disturbance can be treated as a pseudo-fault signal. Then the disturbance rejection problem is converted to the design of LPV fault detection filters insensitive to the pseudo-fault, which can be solved by Corollary 1 using standard geometrical algorithms.

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