World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:5, No:1, 2011

Implementation of an Innovative Simplified Sliding Mode Observer-Based Robust Fault Detection in a Drum Boiler System

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***Abstract*—**One of the robust fault detection filter (RFDF) designing method is based on sliding-mode theory. The main purpose of our study is to introduce an innovative simplified reference residual model generator to formulate the RFDF as a sliding-mode observer without any manipulation package or transformation matrix, through which the generated residual signals can be evaluated. So the proposed design is more explicit and requires less design parameters in comparison with approaches requiring changing coordinates. To the best author's knowledge, this is the first time that the sliding mode technique is applied to detect actuator and sensor faults in a real boiler. The designing procedure is proposed in a drum boiler in Synvendska Kraft AB Plant in Malmo, Sweden as a multivariable and strongly coupled system. It is demonstrated that both sensor and actuator faults can robustly be detected. Also sensor faults can be diagnosed and isolated through this method.

***Keywords*—**Boiler, fault detection, robustness, simplified sliding-mode observer.

I. INTRODUCTION

A boiler is an essential equipment in a power plant, which produce the required thermal energy for power generation. An important feature that a properly boiler system must have is maintaining a desired steam pressure at the outlet of the drum. This aim will be satisfied by the combustion system. Combustion is a complex process with high nonlinearity, uncertainty and load disturbances. Another important feature is to control the drum water level. Faults in a boiler have effects on the drum pressure and level. So the faults may cause a dangerous occurrence such as explosion in the power plant. Therefore, fault detection in a boiler as soon as possible is very essential [1].

Because of higher performance, safety and stability standards fault detection and isolation (FDI) model-based design has attracted more attention in recent years.

The most common way among the model-based approaches is the observer based approach [2]. Because of the existence of uncertainties and disturbances in real systems the FDI design must be robust. The designed filter should involve two aspects. Firstly, it should be robust to uncertainties and unknown inputs. And secondly, it should be as sensitive as possible to the faults to be detected.

Due to the coupling of the effects of faults and disturbances, a suitable trade-off between robustness and sensitivity should be considered for an FDI design. Sliding-mode technique is a suitable way to solve robust FDI problems [3], [4], [5]. Other methods of unknown input observer design for linear systems could be found in [6], [7], [8].

Some authors such as Zak [4], [9] used a discontinuous term in the observer designing to reject unknown input effects. This method has attracted many authors[10]. The discontinuous term is designed to force the estimation state error to remain on a surface in the error space. But the mentioned method needs a symbolic manipulation package to solve the formulated problem.

Some authors such as Tan and Edwards [11], [12] and Dhahri [13] proposed an approach to find the observer gain matrix for the sliding-mode observer. However, their method utilized state transformation, and it requires both finding transformation matrix and changing coordinates to reach the canonical form. So these methods are more complex.

In this paper, we propose a designing method to find gain matrix of the sliding mode observer, which does not need any manipulation package or transformation matrix. Therefore, the proposed design is less complex and has fewer design parameters. Although process noise, measurement noise and external disturbance are considered in the system, both actuator and sensor faults can robustly be detected. Also sensor faults can preciously be diagnosed and isolated

On the other hand, to our knowledge the sliding-mode technique has not been used to detect actuator and sensor faults in a real boiler. Here we propose an FDI approach in a boiler which is in Synvendska Kraft AB Plant in Malmo, Sweden.

This paper is organized as follows. In section II the problem formulation is presented. In this part a system model including process noise, measurement noise and external disturbance is proposed. Section III represents the observer formulation, the residual generation and their characteristics. This section is the

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core of the present paper, in which the basic design procedure of robust fault detection filter is presented. Section IV represents the residual evaluation. A suitable threshold is considered in section V. To illustrate the derived results a numerical example is given in section VI. The last section, i.e., section VII, represents the conclusion of this paper.

II. System Description and Preliminaries

This section introduces the preliminaries necessary for the work presented in this paper. At first, consider the linear system described by the following model

$$\begin{cases} \dot{x} = Ax + B(u+f_a) + B_{np}n_p + B_w w & n_p \sim (0,Q) \\ y = Cx + Du + f_s + n_s & n_s \sim (0,R) \end{cases} \quad (1)$$

Where $x \in R^n$ is the state vector, $y \in R^p$ is the output vector, $u \in R^m$ is the control input vector, $w \in R^d$ is the unknown external disturbance vector, $n_p \in R^q$ is the process white noise vector, $f_s \in R^p$ is sensor fault vector, $f_a \in R^m$ is the actuator fault vector, $n_s \in R^p$ is the measurement white noise vector. The matrices A, B, C, D are assumed to be time invariant, with suitable dimensions, and p<n.

For simplicity, the case is considered in which only one single sensor or actuator is faulty at one time. The objective is to design an observer to generate output estimation $\hat{y}(t)$ with the input u and the output y available. The following assumptions are used throughout:

1) The unknown disturbance is norm bounded such that

$$\|B_w w\| < \gamma \quad (2)$$

where the positive scalar γ is known.

2) Only one actuator or sensor is faulty at one time.

III. Designing the Sliding mode Observer

In this section, we are interested in designing a fault detection filter as follows

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + Lv(S) \\ \hat{y} = C\hat{x} + Du \end{cases} \quad (3)$$

where $\hat{x}(t) \in R^n$ and $\hat{y}(t) \in R^q$ are the estimated state and output vectors, respectively. $v(S)$ is a nonlinear function which will be defined later.

We consider the sliding surface as follows:

$$S = e_y = \hat{y} - y \quad (4)$$

Thus by considering (1) and (3) we have (in fault and noise free case)

$$S = C(\hat{x} - x) \quad (5)$$

If the following sliding condition is satisfied, then the scalar S will be kept at zero [14].

$$\dot{S} \le -\eta \,\mathrm{sgn}(S) \quad (6)$$

Therefore, in the fault free case the estimated states converge to the true states.

So we have

$$\begin{aligned} \dot{S} &= C\left[A(\hat{x}-x) + Lv(S)\right] \\ &= C\left[AC^{-1}S + Lv(S)\right] \end{aligned} \quad (7)$$

We assume $v(s)$ as follows

$$v(S) = -M\,\mathrm{sgn}(S) \quad (8)$$

where

$$M > \max\left|A(\hat{x}-x)\right| \quad (9)$$

So we have

$$\dot{S} = C\left[AC^{-1}S - LM\,\mathrm{sgn}(S)\right] \le -\eta\,\mathrm{sgn}(S) \quad (10)$$

We know the following relationship

$$\dot{S} = C\left[AC^{-1}S - LM\,\mathrm{sgn}(S)\right] \le \left\|CAC^{-1}S\right\|_\infty - CLM\,\mathrm{sgn}(S) \quad (11)$$

Then it follows from (10) and (11) that

$$CLM = \left\|CAC^{-1}S\right\|_\infty + \eta \quad (12)$$

Therefore

$$L = \frac{1}{M}C^{-1}\left[\left\|CAC^{-1}S\right\|_\infty + \eta\right] \quad (13)$$

where L is the designed observer gain matrix.

But in practice we find out that there is chattering in the simulation results. A method for solving the chattering problem is to use saturation function instead of sign function [14]. So we utilize the following $v(S)$ instead of (8) as below:

$$v(S) = -Msat(S) \quad (14)$$

where M satisfies (9).

We consider the residual signal as below:

$$r = y - \hat{y} \quad (15)$$

Therefore from (1) and (3) we have

$$r = C(x-\hat{x}) + f_s + n_s \quad (16)$$

As a conclusion the residual signal depends not only on f_s and u, but also on the state x and therefore on the actuator faults.

It has been demonstrated that the designing method proposed in this section is very simple and does not require changing coordinates or designing manipulation package.

IV. Residual Evaluation

After designing of the sliding mode observer, the remaining task for fault detection and isolation is the evaluation of the generated residual signals. In this step a threshold $J_{th} > 0$ is imperative to be selected. The method for designing threshold will be discussed in the next section. Therefore, the fault occurrence can be alarmed if the absolute value of the residual signal exceeds the threshold.

In other words, we use the following logical relationship to detect the fault.

$$\begin{array}{l} |r(t)| > J_{th} \;\Rightarrow\; a \;\; fault \;\; has \;\; occured \;\Rightarrow alarm \\ |r(t)| \le J_{th} \;\Rightarrow\; no \;\; fault \;\; has \;\; occured. \end{array} \quad (17)$$

V. Design of Threshold

We consider the designed residual generation system (15). We have

$$\max|r(t)| = \max|r_u(t) + r_f(t)| \quad (18)$$

Now we establish an estimate of the effect of control inputs u(t) on the residual r(t). Here $r_u(t)$ and $r_f(t)$ are defined as follow

$$\begin{array}{l} r_u(t) = r(t)\big|_{f=0} \\ r_f(t) = r(t)\big|_{u=0} \end{array} \quad (19)$$

In the fault-free case the residual evaluation function is

$$|r(t)| \le J_{th,u} \quad (20)$$

where

$$J_{th,u} = \max|r_u(t)| \quad (21)$$

VI. Simulation on a Drum Boiler Model

This section involves following tasks. A real drum boiler model is presented firstly. A new simplified sliding-mode observer is designed secondly. And finally, simulation results will be demonstrated to prove the effectiveness of the method.

A. The drum boiler model

A third order non-linear state space model was obtained from the mass and energy balance equations [15]. Three state variables which are selected here are the drum pressure, electric output, and fluid density [16]. The linearized model at a nominal operating point is obtained from this non-linear model.

The linear boiler model with process and measurement white noise and external disturbance has three control inputs, and three states. This boiler is in Synvendska Kraft AB Plant in Malmo, Sweden. The capacity of the mentioned boiler is 160MW.

The linearized state space model is as follows [16]

$$\begin{cases} \dot{x} = Ax + B(u + f_a) + B_{np} n_p + B_w w & n_p \sim (0, Q) \\ y = Cx + Du + f_s + n_s & n_s \sim (0, R) \end{cases} \quad (22)$$

where

$$A = \begin{bmatrix} -2.509e-3 & 0 & 0 \\ 6.940e-2 & -0.1 & 0 \\ -6.690e-3 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.9 & -0.349 & -0.15 \\ 0 & 14.155 & 0 \\ 0 & -1.398 & 1.659 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 6.34e-3 & 0 & 4.71e-9 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0.253 & 0.512 & -0.014 \end{bmatrix} \quad (23)$$

The details about the definition and units of system inputs, states, and outputs are listed below [16]

The inputs are defined as:

u_1 - valve position for fuel flow, cm

u_2 - valve position for steam control, cm

u_3 - valve position for feed water flow, cm.

The states are defined as:

x_1 : drum pressure, Kg/cm^2

x_2 : electric output, MW

x_3 : fluid density, Kg/cm^2

The measured outputs are defined as:

y_1 : drum pressure, Kg/cm^2

y_2 : electric output, MW

y_3 : drum water level, cm

Here, we assume that there are totally three actuators and three sensors in the system. And only one single actuator or sensor is faulty in one time.

Here, by considering the fault free case $J_{i\,th,u}$, $i = 1,2,3$

are as below:

$$\begin{aligned} J_{1th,u} &= 0.7 \\ J_{2th,u} &= 1 \\ J_{3th,u} &= 0.015 \end{aligned} \qquad (24)$$

The residual signals are as follow:

$$\begin{aligned} r_1(t) &= y_1(t) - \hat{y}_1(t) \\ r_2(t) &= y_2(t) - \hat{y}_2(t) \\ r_3(t) &= y_3(t) - \hat{y}_3(t) \end{aligned} \qquad (25)$$

So by evaluating the residual signal we can detect the fault occurrence. In the next part we consider real actuator and sensor faults in the boiler.

B. Simulation Results of Actuator Faults

The actuator faults are considered 10% of the nominal inputs [17]. We consider that one actuator is faulty in one time.

If the first actuator is faulty, then the residual signal is shown in Fig. 1. If the second or the third actuator is faulty separately, the residual signals will be shown in
Fig. 2 and Fig. 3 respectively.

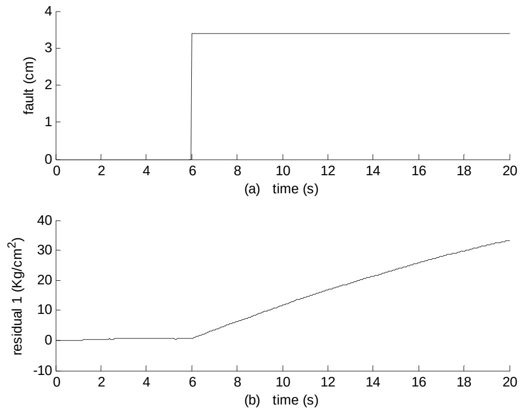

Fig. 1 (a): fault signal in the first actuator (b): the first residual signal.

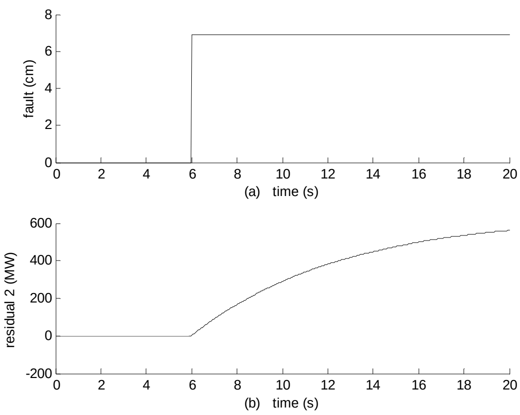

Fig. 2 (a): fault signal in the second actuator (b): the second residual signal.

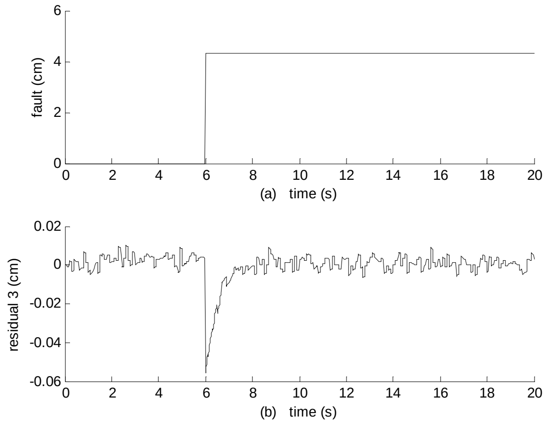

Fig. 3 (a): fault signal in the third actuator, (b): the third residual signal.

Obviously it can be seen that the actuator faults can be detected quickly.

C. Simulation Results of Sensor Faults

For the boiler application, all sensor faults can be diagnosed. Now, we consider abrupt sensor faults. In these cases, sensor measurement suddenly becomes zero from a higher value [17]. Consider that one sensor is faulty in one time.

Figures 4, 5 and 6 show the residual signals and the faults in the first, the second and the third sensor respectively.

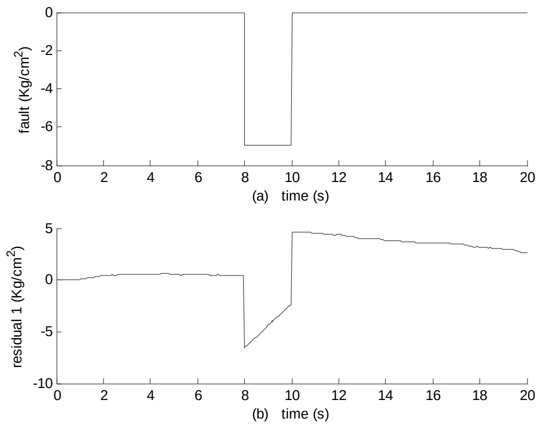

Fig. 4 (a): fault signal in the first sensor (b): the first residual signal.

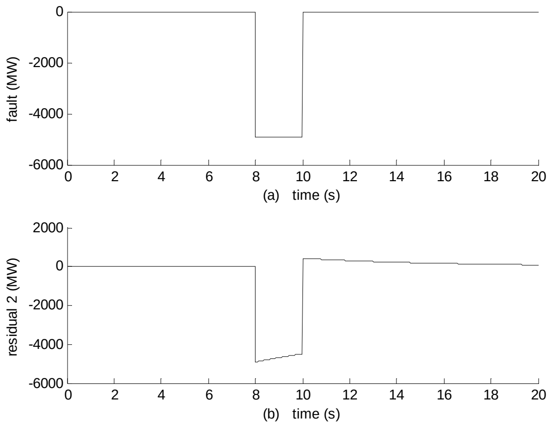

Fig. 5 (a): fault signal in the second sensor (b): the second residual signal.

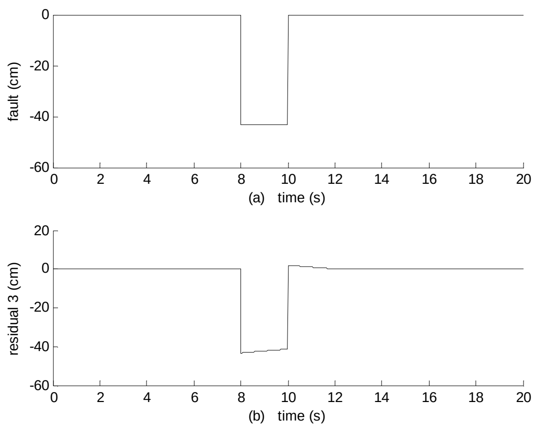

Fig. 6 (a): fault signal in the third sensor. (b): the third residual signal.

By considering these figures it can be demonstrated that sensor faults not only can be detected but also can be diagnosed and isolated effectively.

VII. Conclusion

In this paper, the observer-based robust fault detection filter (RFDF) design problem is studied for a linear time invariant system with process and measurement white noise and disturbance. The main contribution of our study is to propose an innovative simplified sliding mode performance index which takes into account the robustness of the fault detection filter against disturbance and noise, and sensitivity to faults simultaneously. Through this procedure by which the optimal reference residual model can be evaluated to detect faults. This simplified method does not require any manipulation package or transformation matrix. Finally the designed method is applied to a real drum boiler system in Synvendska Kraft AB Plant in Malmo, Sweden to illustrate the efficiency of the proposed fault detection method.

Simulation results have demonstrated that although there are process noise, measurement noise and external disturbance in the system, but the procedure can detect the actuator and sensor fault occurrence successfully and effectively. Also sensor faults can be diagnosed and isolated preciously.

Acknowledgment

The authors would like to thank Iran Power Plant Projects Management Company (MAPNA) for its grants.

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