NONLINEAR RESIDUAL FEEDBACK OBSERVER FOR PROCESS FAULT DIAGNOSIS

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Abstract: Faults lead to loss of productivity and can eventually lead to loss of human lives. Therefore, fault diagnosis is a critical procedure for increased reliability and safety. Diagnostic observers, especially Unknown Input Observers (UIO) (Frank, 1990), have been well studied in literature. In this paper a novel residual feedback structure is proposed for fault diagnosis of a class of nonlinear systems. Conditions under which such a feedback system converges are discussed. Simulation results of a residual feedback nonlinear observer show that exact fault magnitude estimates are achieved.

Keywords: Fault Diagnosis, Nonlinear systems, Observers

1. INTRODUCTION

Process fault diagnosis is the problem of identifying the causal origins of malfunctions in a process, given current sensor data and *a priori* knowledge about the process behaviour under normal and abnormal conditions. Fault diagnosis is an important procedure relevant to process safety and process economics (Nimmo, 1995). The reliability of fault tolerant schemes is dependent on the diagnostic scheme identifying the correct fault with reliable estimates for the magnitude of failure.

Various techniques have been used to address the problems in fault diagnosis (Isermann and Balle, 1997). Of the various model based techniques, the unknown input observer has been widely studied for residual generation. The structured residual approach integrated with a decision logic is used for fault isolation (Frank, 1990; Garcia and Frank, 1997). Observer theory can also be used to estimate fault magnitudes if each observer residual reflects the occurrence of a single fault. However, the class of nonlinear systems for which such a fault decoupled observer can be constructed is limited. Seliger and Frank (1991) demonstrate the use of such an observer for fault diagnosis in a tank system. The theory of input reconstruction can also be used for diagnosis to get reliable fault magnitude estimates. In this strategy, the faults are posed as unknown inputs to be reconstructed from the measurements and known inputs to the process. This theory is applicable for linear (Hou and Patton, 1998) and linear descriptor (Hou and Patton, 1999*a*; Hou and Patton, 1999*b*) systems.

In this paper, the design for an unknown input observer (Frank, 1990) in addition with fault decoupling is used to develop a nonlinear observer to track parametric and sensor faults. This design is applicable for fault affine processes. The heat exchanger case study used is nonlinear in faults and restricted linearization is used to cast the model in a fault affine form. As shown later, neglecting this critical information leads to biased magnitude estimates, making the construction of a decision logic for fault isolation a difficult task.

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A residual feedback strategy is proposed to compensate the nonlinearity in fault. The convergence criterion for the feedback strategy is also presented. The residual feedback observer gives unbiased fault magnitude estimates. The results for the residual feedback observer are presented for the heat exchanger case study.

2. DESIGN OF NONLINEAR OBSERVER (NLO)

The unknown input observer (Frank, 1990) utilizes a nonlinear model of the system given as,

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{B}(\mathbf{u},\mathbf{y}) + \mathbf{Ed} + \mathbf{K}(\mathbf{x},\mathbf{u})\mathbf{f}\\ \mathbf{y} &= \mathbf{Cx} + \mathbf{Gf}\end{aligned} \tag{1}$$

where, $\mathbf{x}$ is $(n\times 1)$ state vector, $\mathbf{u}$ is $(p\times 1)$ input vector, $\mathbf{y}$ is $(q\times 1)$ vector of measured outputs, $\mathbf{d}$ is the unknown inputs/disturbance vector, $\mathbf{f}$ are the faults and **A, B, C, E, K, G** are known matrices of appropriate dimensions. The term $\mathbf{Ed}$ models the unknown inputs to the actuator and to the dynamic process, $\mathbf{K}(\mathbf{x},\mathbf{u})\mathbf{f}$ models the process and actuator faults, and the term $\mathbf{Gf}$ models the sensor faults. From these equations, it can be seen that the dynamic equations may be nonlinear only in input and output variables and the input distribution matrix of the fault vector may be a function of the inputs and the states.

The nonlinear observer is given by the equations (Frank, 1990)

$$\begin{aligned}\dot{\mathbf{z}} &= \mathbf{Rz} + \mathbf{J}(\mathbf{u},\mathbf{y}) + \mathbf{Sy}\\ \mathbf{r} &= \mathbf{L_1 z} + \mathbf{L_2 y}\\ \mathbf{z}(\mathbf{t}=\mathbf{0}) &= \mathbf{z_0}\end{aligned} \tag{2}$$

where $\mathbf{z} = \mathbf{Tx}$ **iff** $\mathbf{f} = \mathbf{0}$. This observer is valid for fault detection if the residual $\mathbf{r}$ has the following properties

$$\lim_{\mathbf{t}\to\infty} \mathbf{r}(\mathbf{t}) = \mathbf{0} \quad \textbf{if } \mathbf{f} = \mathbf{0} \quad \forall\, \mathbf{u},\mathbf{d},\mathbf{x_0},\mathbf{z_0} \tag{3}$$

and

$$\mathbf{r} \neq \mathbf{0} \quad \textbf{if } \mathbf{f} \neq \mathbf{0} \tag{4}$$

The derivation of the conditions on the observer matrices follows from the linear equivalent (Frank, 1990), and the necessary/sufficient conditions for their existence (Frank and Wunnenberg, 1989) are available in literature . For sake of brevity, the matrix conditions are presented here.

$$\begin{aligned}\mathbf{TA} - \mathbf{RT} &= \mathbf{SC}\\ \mathbf{J}(\mathbf{u},\mathbf{y}) &= \mathbf{TB}(\mathbf{u},\mathbf{y})\\ \mathbf{TE} &= \mathbf{0}\\ \mathbf{TK} &\neq \mathbf{0}\\ \mathbf{L_1 T} + \mathbf{L_2 C} &= \mathbf{0}\end{aligned} \tag{5}$$

For the residuals to go to zero, $\mathbf{R}$ is required to be stable i.e., have eigenvalues in the left half of the s-plane.

3. DESIGN OF NONLINEAR OBSERVER WITH RESIDUAL FEEDBACK (NLOFB)

In the previous section, a nonlinear observer design for fault affine processes was presented. To account for nonlinearity in fault, a modified observer structure based on the previous design is proposed. A nonlinear residual feedback is used for direct compensation of the nonlinearity in fault. The nonlinear model of the process is of the form,

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{B}(\mathbf{u},\mathbf{y}) + \mathbf{K}(\mathbf{y},\mathbf{u})\mathbf{f} + \phi(\mathbf{y},\mathbf{f})\\ \mathbf{y} &= \mathbf{Cx} + \mathbf{Gf}\end{aligned} \tag{6}$$

where $\phi(\mathbf{y},\mathbf{f})$ is Lipschitz in $\mathbf{f}$, i.e

$$\|\phi(\mathbf{y},\mathbf{f_1}) - \phi(\mathbf{y},\mathbf{f_2})\| \le \gamma(\mathbf{y})\|\mathbf{f_1} - \mathbf{f_2}\|$$

and the input distribution matrix may be a function of the measurements and inputs.

The observer constructed is of the form,

$$\begin{aligned}\dot{\mathbf{z}} &= \mathbf{Rz} + \mathbf{J}(\mathbf{u},\mathbf{y}) + \mathbf{Sy} + \mathbf{T}\phi(\mathbf{y},\mathbf{r})\\ \mathbf{r} &= \mathbf{L_1 z} + \mathbf{L_2 y}\\ \mathbf{z}(\mathbf{t}=\mathbf{0}) &= \mathbf{z_0}\end{aligned} \tag{7}$$

Claim 1. For step faults in the dynamic system as defined in Equation 7, the residuals converge to the faults if matrices $\mathbf{R},\mathbf{J},\mathbf{S},\mathbf{T},\mathbf{L_1},\mathbf{L_2}$ exist and the following conditions are satisfied.

$$\begin{aligned}\mathbf{TA} - \mathbf{RT} &= \mathbf{SC}\\ \mathbf{J}(\mathbf{u},\mathbf{y}) &= \mathbf{TB}(\mathbf{u},\mathbf{y})\\ \mathbf{TK} &\neq \mathbf{0}\\ \mathbf{R} &= -c_0\mathbf{I},\ c_0 > 0\\ \mathbf{L_1 T} + \mathbf{L_2 C} &= \mathbf{0}\\ \mathbf{L_1}(\mathbf{SG} - \mathbf{TK}) &= (\mathbf{RL_2 G} - \mathbf{R})\\ \|\mathbf{L_1 T}(\phi(\mathbf{y},\mathbf{f_1}) - \phi(\mathbf{y},\mathbf{f_2}))\|_2 &< c_0\|\mathbf{f_1} - \mathbf{f_2}\|\end{aligned} \tag{8}$$

PROOF. Construct the following Lyapunov function,

$$v = \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{r} - \mathbf{f})^{\mathbf{T}}(\mathbf{r} - \mathbf{f})$$

The derivative of the Lyapunov function is ($\dot{\mathbf{f}}$ is zero for step faults, and $\mathbf{e} = \mathbf{z} - \mathbf{Tx}$),

$$\begin{aligned}\dot{v} &= (\mathbf{r} - \mathbf{f})^{\mathbf{T}}\dot{\mathbf{r}}\\ &= (\mathbf{r} - \mathbf{f})^{\mathbf{T}}[\mathbf{L_1}(\dot{\mathbf{e}} + \mathbf{T}\dot{\mathbf{x}}) + \mathbf{L_2}\dot{\mathbf{y}}]\end{aligned} \tag{9}$$

Using $\mathbf{L_1 T} + \mathbf{L_2 C} = \mathbf{0}$, $\dot{\mathbf{f}} = \mathbf{0}$,

$$\dot{v} = (\mathbf{r}-\mathbf{f})^{\mathbf{T}}\mathbf{L_1}\dot{\mathbf{e}}$$

Given that the matrix conditions in the claim hold, the error dynamics of the feedback nonlinear observer in presence of fault nonlinearity can be written as,

$$\begin{aligned}\dot{\mathbf{e}} &= \dot{\mathbf{z}} - \mathbf{T}\dot{\mathbf{x}} \\ &= \mathbf{Re} + (\mathbf{SG} - \mathbf{TK}(\mathbf{y},\mathbf{u}))\mathbf{f} + \mathbf{T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f}))\end{aligned}$$

This leads to,

$$\begin{aligned}\dot{v} &= (\mathbf{r}-\mathbf{f})^{\mathbf{T}}[\mathbf{L_1R}(\mathbf{z}-\mathbf{Tx}) + \mathbf{L_1}(\mathbf{SG}-\mathbf{TK})\mathbf{f}] \\ &\quad + (\mathbf{r}-\mathbf{f})^{\mathbf{T}}\mathbf{L_1T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f})) \end{aligned} \quad (10)$$

Since $\mathbf{R} = -c_0\mathbf{I}$, $\mathbf{L_1Rz} = \mathbf{RL_1z} = \mathbf{R}(\mathbf{r}-\mathbf{L_2y})$, $\mathbf{RL_2C} - \mathbf{L_1RT} = \mathbf{R}(\mathbf{L_2C}-\mathbf{L_1T}) = \mathbf{0}$, the first term in the above expression can be simplified to

$$(\mathbf{r}-\mathbf{f})^{\mathbf{T}}[\mathbf{Rr} - (\mathbf{RL_2G} - \mathbf{L_1}(\mathbf{SG}-\mathbf{TK}))\mathbf{f}]$$

If $\mathbf{L_1}$ is chosen as in Equation 8, the above term further simplifies to $-c_0\|(\mathbf{r}-\mathbf{f})\|^{\mathbf{2}}$. Therefore,

$$\begin{aligned}\dot{v} &= -c_0\|(\mathbf{r}-\mathbf{f})\|^{\mathbf{2}} \\ &\quad + (\mathbf{r}-\mathbf{f})^{\mathbf{T}}\mathbf{L_1T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f})) \\ \dot{v} &\le -c_0\|\mathbf{r}-\mathbf{f}\|^{\mathbf{2}} \\ &\quad + \|(\mathbf{r}-\mathbf{f})^{\mathbf{T}}\mathbf{L_1T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f}))\| \end{aligned} \quad (11)$$

Using the Cauchy-Schwarz-Buniakowsky inequality,

$$\begin{aligned}\dot{v} &\le -c_0\|\mathbf{r}-\mathbf{f}\|^{\mathbf{2}} \\ &\quad + \|(\mathbf{r}-\mathbf{f})\|\|\mathbf{L_1T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f}))\| \end{aligned} \quad (12)$$

If the nonlinearity in fault (ϕ) is Lipschitz in $\mathbf{f}$, so is $\mathbf{L_1T}\phi(\mathbf{y},\mathbf{f})$ and by the condition in Equation 8

$$\|(\mathbf{L_1T}(\phi(\mathbf{y},\mathbf{r}) - \phi(\mathbf{y},\mathbf{f}))\| < c_0\|\mathbf{r}-\mathbf{f}\| \quad (13)$$

Therefore,

$$\dot{v} < 0 \quad (14)$$

The derivative of the Lyapunov function is negative definite and the residuals (**r**) asymptotically converge to the actual fault magnitude (**f**).

4. HEAT EXCHANGER CASE STUDY

The heat exchanger is an important process unit in any chemical engineering operation and the transients of the process are extremely nonlinear. The first principles model of a counter-current heat exchanger is as follows

$$\begin{aligned}V_c\dot{T}_c &= q_c(T_{ci} - T_c) + \frac{UA}{\rho_c C_{pc}}\Delta T \\ V_h\dot{T}_h &= q_h(T_{hi} - T_h) - \frac{UA}{\rho_h C_{ph}}\Delta T \end{aligned} \quad (15)$$

where, V is the volume and subscript ‘c’ and ‘h’ refer to cold and hot side respectively, q is the known flow rate, ρ and C_p are the density and specific heat of the two streams and ΔT is the log mean temperature difference,

$$\Delta T = \frac{(T_{hi} - T_c) - (T_h - T_{ci})}{\log(T_{hi} - T_c) - \log(T_h - T_{ci})} \quad (16)$$

Table 1. Parameters for the heat exchanger

Notation	Variable	Steady state value
V_c	Holdup on cold side	0.05 m^3
V_h	Holdup on hot side	0.05 m^3
UA	Heat transfer coeff. × area	10 $KJ/^oC\ min$
T_c	Cold stream temp.	53.03 ^oC
T_h	Hot stream temp.	62.63 ^oC
T_{ci}	Cold stream inlet temp.	25 ^oC
T_{hi}	Hot stream inlet temp.	100 ^oC
ρ_c, ρ_h	Fluid densities	500 kg/m^3
C_{ph}, C_{pc}	Specific heats	3 $KJ/^oCkg$
q_c	Cold stream flow rate	0.01 m^3/min
q_h	Hot stream flow rate	0.0075 m^3/min

The steady state and parameters for the heat exchanger operation are presented in Table 1. The inputs to the heat exchanger, i.e. flow rates of hot and cold stream are known. The outlet temperatures (T_c and T_h) are measured, while the inlet temperatures (T_{ci} and T_{hi}) are the simulated parametric faults.

5. PARAMETRIC FAULTS CASE STUDY

In the following case study, the previously discussed observers are designed to monitor the changes in the inlet temperatures. The heat exchanger problem is nonlinear in fault and restricted linearization is carried out to cast the process model in a fault affine form for design of the nonlinear observer. For the residual feedback observer, the actual nonlinearity in fault is compensated. Therefore, it is expected that the nonlinear observer would give biased fault magnitude estimates, while the residual feedback observer should give exact estimates of the fault severity.

5.1 Observer Design- NonLinear Observer (NLO)

For design of nonlinear observer, the heat exchanger model equations given in Equation 15 are cast in the fault affine (Ref Equation 1), by restricted linearization where,

$$\mathbf{y} = \mathbf{x} = \begin{bmatrix} T_c \\ T_h \end{bmatrix} \quad \text{and} \quad \mathbf{f} = \begin{bmatrix} \Delta T_{ci} \\ \Delta T_{hi} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} -\frac{q_c}{V_c} & 0 \\ 0 & -\frac{q_h}{V_h} \end{bmatrix}$$

$$\mathbf{B}(\mathbf{u},\mathbf{y}) = \begin{bmatrix} K_c\frac{\theta_1 - \theta_2}{\log\frac{\theta_1}{\theta_2}} + \frac{q_c}{V_c}25 \\ -K_h\frac{\theta_1 - \theta_2}{\log\frac{\theta_1}{\theta_2}} + \frac{q_h}{V_h}100 \end{bmatrix}$$

$$\mathbf{K}(\mathbf{y},\mathbf{u}) = \begin{bmatrix} \frac{q_c}{V_c} + \frac{\alpha K_c}{d} & \frac{\beta K_c}{d} \\ -\frac{\alpha K_h}{d} & \frac{q_h}{V_h} - \frac{\beta K_h}{d} \end{bmatrix}$$

where

$$K_c = \frac{UA}{\rho_c C_{pc} V_C} \quad \text{and} \quad K_h = \frac{UA}{\rho_h C_{ph} V_h}$$

$$\theta_1 = 100 - T_c, \quad \theta_2 = T_h - 25 \quad \text{and} \quad d = \left(\log \frac{\theta_1}{\theta_2}\right)^2$$

$$\alpha = \left(\log \frac{\theta_1}{\theta_2} + 1 - \frac{\theta_1}{\theta_2}\right)$$

$$\beta = \left(\log \frac{\theta_1}{\theta_2} - 1 + \frac{\theta_2}{\theta_1}\right)$$

The nonlinear observer as described in Equation 2 is implemented with the following choice of the observer matrices that satisfies the conditions in Equation 5: $\mathbf{T} = \mathbf{I_2}$, $\mathbf{R} = -\mathbf{I_2}$, $\mathbf{S} = \mathbf{A} - \mathbf{R}$, $\mathbf{J} = \mathbf{TB}(\mathbf{u},\mathbf{y})$, $\mathbf{L_1} = -\mathbf{K}(\mathbf{y},\mathbf{u})^{-1}$ and $\mathbf{L_2} = -\mathbf{L_1}$.

5.2 Observer Design- NonLinear FeebBack Observer (NLOFB)

The system equations (Ref Equation 15) are conveniently written in the following form

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}(\mathbf{u},\mathbf{y}) + \mathbf{K}(\mathbf{y},\mathbf{u})\mathbf{f} + \phi(\mathbf{y},\mathbf{f})$$

where

$$\mathbf{y} = \mathbf{x} = \begin{bmatrix} T_c \\ T_h \end{bmatrix} \quad \text{and} \quad \mathbf{f} = \begin{bmatrix} \Delta T_{ci} \\ \Delta T_{hi} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} -\frac{q_c}{V_c} & 0 \\ 0 & -\frac{q_h}{V_h} \end{bmatrix} \quad \text{and } \mathbf{B}(\mathbf{u},\mathbf{y}) = \begin{bmatrix} \frac{q_c}{V_c}25 \\ \frac{q_h}{V_h}100 \end{bmatrix}$$

$$\mathbf{K}(\mathbf{y},\mathbf{u}) = \begin{bmatrix} \frac{q_c}{V_c} & 0 \\ 0 & \frac{q_h}{V_h} \end{bmatrix} \quad \text{and } \phi = \begin{bmatrix} K_c \\ -K_h \end{bmatrix} \Delta T$$

where ΔT is as defined in Equation 16. The nonlinear observer as described in Equation 7 is implemented with the following choice of the observer matrices that satisfies the conditions in Equation 8: $\mathbf{T} = \mathbf{I_2}$, $\mathbf{R} = -\mathbf{I_2}$, $\mathbf{S} = \mathbf{A} - \mathbf{R}$, $\mathbf{J} = \mathbf{TB}(\mathbf{u},\mathbf{y})$, $\mathbf{L_1} = \mathbf{RK}(\mathbf{y},\mathbf{u})^{-1}$ and $\mathbf{L_2} = -\mathbf{L_1}$.

In addition to the matrix conditions, the following condition is a sufficient condition for the convergence of the observer.

$$\|\mathbf{L_1}\mathbf{T}(\phi(\mathbf{y},\mathbf{f_1}) - \phi(\mathbf{y},\mathbf{f_2}))\|_2 < c_0\|\mathbf{f_1} - \mathbf{f_2}\| \qquad (17)$$

For the particular choice of the design matrices, this implies

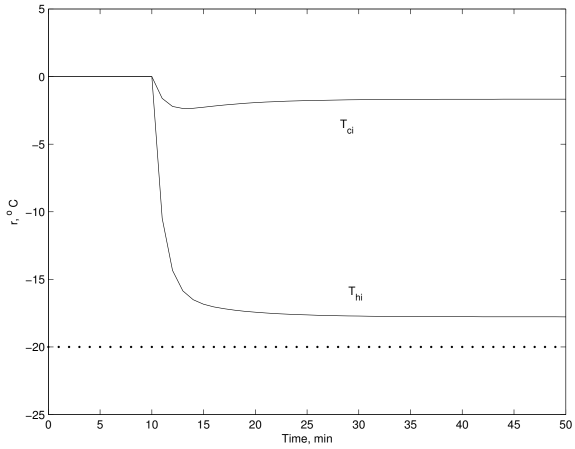

Fig. 1. NLO result: $\Delta T_{hi} = -20^o C$

$$\frac{|\Delta T(\mathbf{f}) - \Delta T(\mathbf{r})|}{\|\mathbf{r} - \mathbf{f}\|_2} \left(\left(\frac{K_h V_h}{q_h}\right)^2 + \left(\frac{K_c V_c}{q_c}\right)^2 \right)^{0.5} < 1 (18)$$

where

$$\Delta T(\mathbf{f}) = \frac{(T_{hi} + f_2 - T_c) - (T_h - T_{ci} - f_1)}{\log(T_{hi} + f_2 - T_c) - \log(T_h - T_{ci} - f_1)}$$
$$\mathbf{f} = [f_1, f_2]^t \qquad (19)$$

It should be noted that the above is only a sufficiency condition and so, it is possible that the $\mathbf{r} \rightarrow \mathbf{f}$ as $t \rightarrow \infty$ even if the above condition is violated. This may occur, for example, when the fault magnitudes are large. The observer design is validated through simulation results involving different fault magnitudes and directions, which are presented in the subsequent section.

5.3 Case Study Results

Results of the NonLinear Observer (NLO) for two fault cases ($\Delta T_{hi} = -20^o C$ and $\Delta T_{ci} = 10^o C$) are presented in Figures 1 and 2 respectively. It is seen that, the estimates of the fault magnitudes are biased; this occurs because the nonlinearity in fault is not compensated for during restricted linearization. For example, when ($\Delta T_{hi} = -20^o C$), the residual for T_{ci} is non-zero and the magnitude of the residual for T_{hi} depends on the magnitude of the actual T_{hi} fault. Therefore, the use of absolute thresholding of residuals is not possible to achieve fault isolation.

Results of the NonLinear Observer with FeedBack (NLOFB) are presented in Figures 3, 4 and 5 for three different fault levels: $\Delta T_{hi} = -20^o C$, $\Delta T_{ci} = 10^o C$ and a simultaneous occurrence of both faults: $\Delta T_{hi} = 30^0 C$ and $\Delta T_{ci} = 20^o C$. The terminal values of the residuals approach the corresponding fault magnitudes for all cases. Thus, this ensures complete decoupling of faults and correct estimation of the fault magnitudes. This validates the design of the NLOFB.

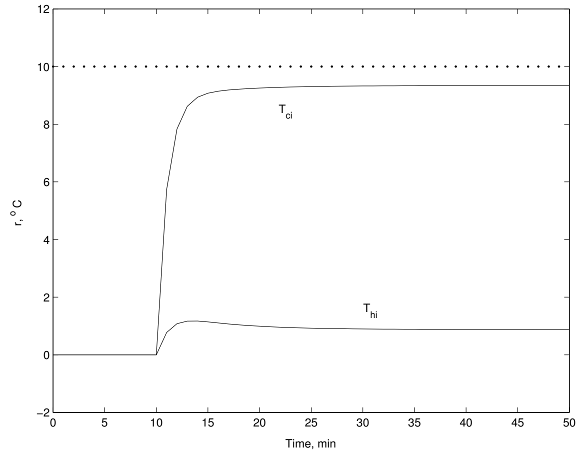

Fig. 2. NLO result: $\Delta T_{ci} = 10^o C$

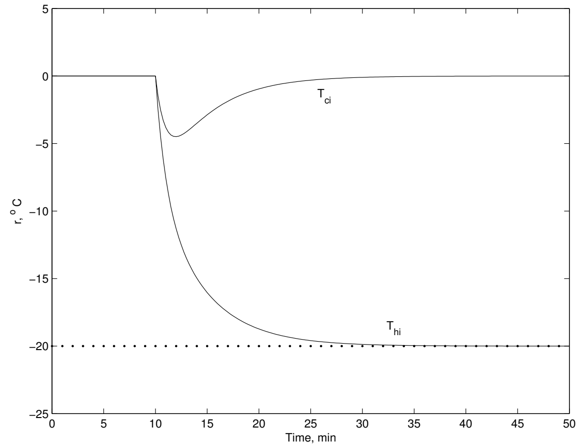

Fig. 3. NLOFB result: $\Delta T_{hi} = -20^o C$

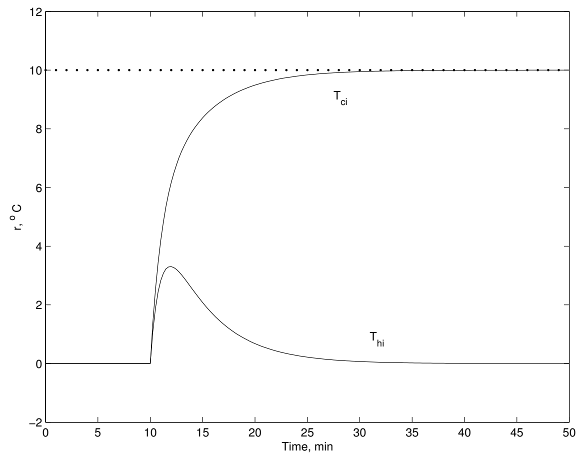

Fig. 4. NLOFB result: $\Delta T_{ci} = 10^o C$

6. CONCLUSIONS

A feedback structure for the unknown input observer for a system with a specified structure of nonlinearity has been presented. This feedback structure extends the capacity of the diagnostic observer towards fault identification by mimicking the nonlinearity in fault by aid of residuals. This has been demonstrated by achieving unbiased fault magnitude estimates in the

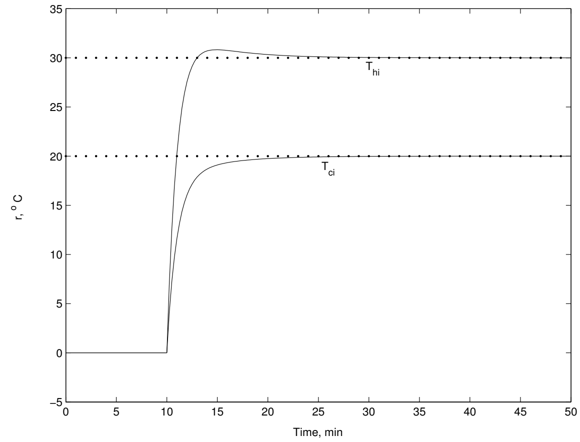

Fig. 5. NLOFB result: $\Delta T_{hi} = 30^o C, \Delta T_{ci} = 20^o C$

case of parametric faults in the heat exchanger case study.

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