System Modeling and Faults Diagnosis of a Five Hydraulic Tank

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Abstract: In modern process industry such as chemical and petrochemical plants, it is important to detect and isolate faults, while the plant is running. This paper investigates a robust unknown input observer (UIO) used for detection and isolation of faults. The impact of disturbances and uncertainty may create difficulties at the decision stage of diagnosis (false alarm); this has resulted to use UIO. Five tank system can be used as a good prototype of many industrial applications in process industry. The main contribution is to construct modeling of this system subject to unknown inputs and results from unknown input observer theory. Two actuator faults are considered, residuals are generated using this kind of observer. The faults will be isolated by using a bank of UIOs in the framework of the Dedicated Observer Scheme (DOS). Simulations results are given to show the effectiveness of the proposed method.

Keywords: unknown inputs observer, residual generation, Dedicated Observer Scheme (DOS), diagnosis, fault detection.

1. INTRODUCTION

The use of the new technologies to increase the products quality and services as well as the productivity, made industrial systems more and more complex and thus more vulnerable to the faults. These latter can reduce the system performances or create serious consequences for safety. Thus, it is necessary to develop methods allowing the detection and isolation of these faults and all undesirable consequences. For this reason, methods based on observers are fairly well developed, especially for linear systems where different types of observers have been proposed depending on the nature of the problem (failure in the presence of noise, disturbances, uncertainties ...), among the unknown input observers **(**UIO**)**.

The study of a real system goes through a modeling phase to obtain a mathematical representation to describe how to operate, where the model-based diagnosis is based on the use of an analytical model of the system to diagnose. The residuals generation based on observers is a technique that has been the object of numerous developments**.** The residual vector is then constructed as the difference between the estimated output and the measured output, that is to say, using the estimation error at the output. These residuals are sensitive to faults, but also to unknown inputs.

The observers were born for purely technological and commercial reasons (minimisation of cost) filling the material sensors by software sensors which allow the reconstruction of the internal information (states, unknown input, unknown parameters) of the system from a model which use the unknown inputs.

The unknown input observer (UIO) can solve the problem of sensitivity to various faults and disturbances, introducing their state matrices in the synthesis equations of the residuals generation observer, where decision-making requires comparing the faults indicator with the threshold obtained empirically or theoretically.

The literature counts several works in this domain.

(Wang et al., 1975) are the first researchers using the UIO in the systems that have certain unknown inputs. These observers were introduced in the detection of faults by (Viswanadham and Srichander, 1987; Hou and Muller, 1994; Chen et al., 1996; Duan and Patton, 2001).

Several authors have presented techniques of state based assessment based on the unknown input observers for unsure linear systems and single systems.

The authors have used mainly methods based on UIO in the research works, (W. Chen et al., 2006; D. Koenig et al., 1996**;** Y. Xiong et al., 1998).

In this context, the generation of residual systems based on linear models has been the subject of several research studies using this state observer; among these researchers (Ding et al., 2002; Jiang et al., 2005; Johansson et al., 2006; Meseguer et al., 2010; Khan and Ding, 2011; Chen and Patton, 1999; Mangoubi, 1998; Rank and Niemann, 1999; Henry and Zolghadri, 2005a, 2005b**)**.

UIO have been widely used in faults diagnosis for industrial processes and installations. For example, (Oscar AZ Sotomayor et al., 2005; Stefen Hui et al., 2005; J. Anzurez Marino et al., 2008**;** Francesco Amatof et al., 2002**)**.

The UIO is an important subject and has been put forward by several authors (Sobhani et al., 2012; Termehchy et al., 2013; Wang and Yang, 2013; Bagherpour et al., 2013; Cristofaro et al., 2014)**.**

To solve the problem of faults isolation of the sensors and actuators, the authors presented a method to design a bank of observers, such as the architectures GOS (Generalized Observer Scheme) or DOS (Dedicated Observer Scheme) see (Mr. Hou et al., 1994; D. Koenig et al., 1996; Chen and Zhang, 1991; Isermann, 2007; Ding, 2008).

The objective of this paper is to design a robust actuator fault detection and isolation for a several tank hydraulic system. An unknown input observer (UIO) is designed for a linear model of hydraulic system subject to unknown inputs. The ability and performance of the UIO is investigated for abrupt fault detection and isolation is performed by a bank of observers (UIOs).

2. DIAGNOSIS WITH UNKNOWN INPUT OBSERVER UIO

Consider the system to be monitored:

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + F_x f(t) + D_x d(t) \\ y(t) = Cx(t) + F_y f(t) + D_y d(t) \end{cases} \quad (1)$$

In case where the vector of the unknown input acts on the output vector, with a bilinear transformation the structure of the UIO is described as follows:

$$\begin{cases} \dot{Z}(t) = Mz(t) + Nu(t) + Py(t) \\ \hat{x}(t) = z(t) - L_y y(t) \end{cases} \quad (2)$$

Where M, N, P, L_y are unknown matrices of appropriate dimensions.

The error states reconstitution:

$$e_x(t) = \hat{x}(t) - x(t)$$

$$\begin{aligned} e_x(t) &= z(t) - L_y y(t) - x(t) \\ &= z(t) - L_y(Cx(t) + F_y f(t)) - x(t) \\ &= z(t) - (I + L_y C)x(t) - L_y F_y f(t) \\ &= z(t) - Ex(t) - L_y F_y f(t) \end{aligned}$$

$$e_x(t) = Z(t) - Ex(t) - L_y F_y f(t) \quad (3)$$

$$Z(t) = e_x(t) + Ex(t) + L_y F_y f(t)$$

The dynamic error in state estimation is:

$$\begin{aligned} \dot{e}_x(t) &= \dot{Z}(t) - E\dot{x}(t) - L_y F_y f(t) \\ \dot{e}_x(t) &= Me_x(t) + (ME + PC - EA)x(t) + (N - EA)u(t) \\ &-(ML_y F_y + PF_y - EF_x) f(t) - L_y F_y \dot{f}(t) - ED_x d(t) \end{aligned} \quad (4)$$

In which following conditions are fulfilled:
M is a Hurwitz matrix (stable).

$$ME + PC = EA$$
$$N = EB$$
$$ED_x = 0$$
$$ML_y F_y + PF_y + EF_y \neq 0$$
$$L_y F_y \neq 0$$

Note: the estimation error becomes independent of the state on the control input and the unknown input, so is sensitive to faults. The solution of the set of equations is primarily provided to ensure decoupling unknown inputs

$ED_x = 0$ or $E = I + L_y C$

$$(I + L_y C)D_x = 0 \rightarrow (L_y C)D_x = -D_x$$

So to find L_y if $(L_y C)D_x = -D_x$ equality is satisfied if the inverse is generalized of CD_x; $(CD_x)^+$ exists L_y can be calculated by using:

$$(CD_x)^+ = \left[(CD_x)^T (CD_x)\right]^{-1} (CD_x)^T$$

The matrix L_y exists only if the matrix $(CD_x)^T (CD_x)$ is invertible.

The invertibility is verified if the rank $(CD_x) = nd$; with nd is the number of unknown inputs and its dimension; (R. Toscano, 2011).

Note: Decoupling is possible only if the rank of the matrix (CD_x) equals the number of decoupled inputs.

Synthesis algorithm of observer

- $rank(CD_x) = nd$ *then calculate*
- $L_y = -D_x\left[(CD_x)^T (CD_x)\right]^{-1} (CD_x)^T$
- From L_y calculate $E = I + L_y C$
- From E calculate $N = EB$
- Impose M as a Hurwitz diagonal matrix.

Calculate the matrix P such that $PC = EA - ME$, then calculate the transfer matrix linking the fault estimation error output.

$$F = mL_y F_y + PF_y - EF_x$$
$$F' = -L_y F_y$$

The residual vector is:
$$r(s) = Q(s)e_y(s) = Q(s)G_f(s)f(s)$$

The transfer function of fault is:
$$G_f(s) = C(SI - M)^{-1}(F + SF') - F_y$$

$Q(s)$ Allows structure the residuals in order to facilitate faults location.

3. BANK OF OBSERVERS UIOs (DOS)

If only one observer is sufficient to detect a fault, many observers are needed to locate these faults. Indeed, when wishing to determine the source of a fault, a bank of observers must be designed for isolating, based on generation structures of well-defined residuals. The most prevalent structure in the literature is the dedicated observers structure (DOS), shown in figure (1) structure which is appealing in its simplicity. A bank of observers where each one of them will generate a residual which is sensitive excluding actuators faults. The number of observers to be designed is equal to the number of actuators of the system. Thus, for a system having two actuators, a bank of two observers is designed according to this structure can locate actuators faults of the system.

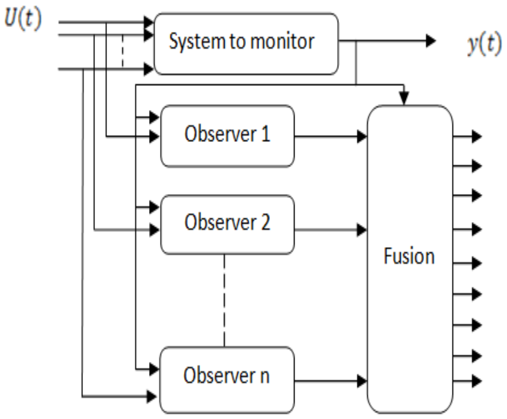


Fig. 1. Bank of observers DOS for actuators faults detection.

4. PROCESS PRESENTATION AND MODELING

The five-tank system model can be viewed as a prototype of many industrial applications in process industry, such as chemical and petrochemical plants, oil and gas systems.

The notion of resistance necessarily implies the existence of obstacles. Among, the valves; orifices, and the states of the inner surface of the paths borrowed by the fluid are mentioned. Note that the valve element is essentially a flow regulating, the obstacle to the flow of a fluid is defined by a resistance R_h which is the pressure change can cause a unit change in debit.

The network of water distribution shown in figure (2) is considered. This network consists of different tanks to the ground section S_i, where i indicates the number of tanks (from 1 to5) connected to pipes section. The network is supplied by two volume flows q_{e1} and q_{e2} coming to tank 1 and 4 respectively. These two flows are controlled by supply pump. Neglecting the losses accrued in the pipes, the system can be modelled by the steps following. Then the hydraulic system of the Figure (2) is studied. As the tank 5 is fed by two sources, one from the two tanks 1 and 2, and the other from the tanks 3 and 4. Where the whole system has two input quantities q_{e1} and q_{e2} and one output variable q_s. To facilitate the modeling of the system which was decomposed into three subsystems $S/S1$ (tank 1 and 2), $S/S2$ (tank 3 and 4), $S/S3$ (tank 5).

This is done using the equation for the resistance and capacity:

$$R_h = \Delta h / q \, (s/m^2)$$

$$q_e(t) - q_s(t) = dV/dt = d/dt(Ah) = A\,dh/dt$$

Since the length of the pipe is small, the hydraulic inductance is neglected.

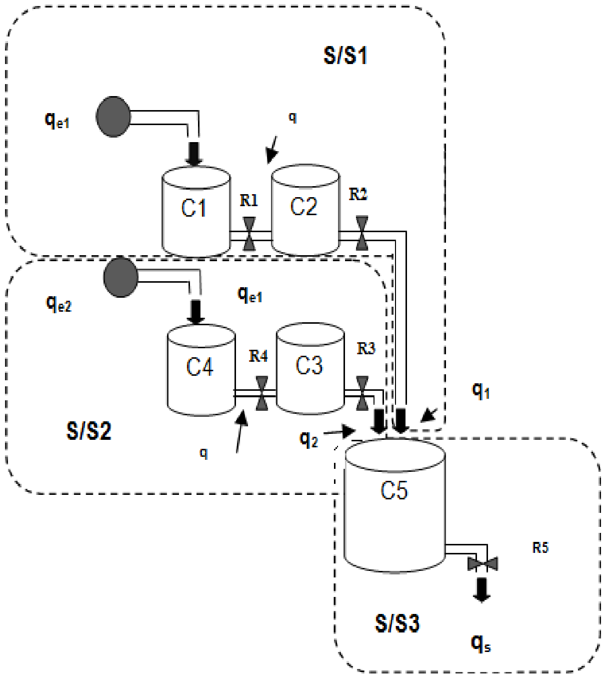


Fig. 2. Hydraulics system monitored.

$C_1 = 1;\ C_2 = 1;\ C_3 = 1;\ C_4 = 1;\ C_5 = 4$

$R_1 = 2;\ R_2 = 2;\ R_3 = 2;\ R_4 = 2;\ R_5 = 4$

4.1 *The subsystem S/ S1*

Remembering that rigid connection through the valve between the two tanks 1 and 2, the equations are written as follows:

$$q_{e1} - q = (C_1)\,dh_1/dt \tag{5}$$

$$R_1 = (h_1 - h_2)/q \tag{6}$$

for tank 3:

$$q - q_1 = (C_1)\,dh_2/dt \tag{7}$$

$$R_2 = h_2/q_1 \tag{8}$$

By combining the two equations (5) and (6) with (7) and (8), then the following differential equations are obtained :

$$q_{e1} - q = (R_1C_1)\,dq/dt + (R_2C_1)\,dq_1/dt \tag{9}$$

$$q - q_2 = (R_1C_1)\,dq_1/dt \tag{10}$$

the differential equation of subsystem S/S1 are obtained by eliminating q from the equations (9) and (10), such that:

$$(R_2R_1C_2C_1)\,d^2/dt^2(q_1) + (R_1C_1 + R_2C_1 + R_2C_2)\,d/dt(q_1) + q_1 = q_{e1} \tag{11}$$

Equation (11) represents the differential equation describing the subsystem S/S1.

4.2 *The subsystem S/ S2*

For the tank 4:

$$q_{e2} - q = (C) - dh_4/dt \tag{12}$$

$$R_4 = (h_4 - h_3)/q \tag{13}$$

For the tank 3, then:

$$q - q_2 = (C_4) dh_3/dt \tag{14}$$

$$R_3 = h_3/q_2 \tag{15}$$

By combining the two equations (12) and (13) with (14) and (15), then the following differential equations are obtained:

$$q_{e2} - q = (R_4C_4)\, dq/dt + (R_3C_4)\, dq_2/dt \tag{16}$$

$$q - q_2 = (R_3C_3)\, dq_2/dt \tag{17}$$

By eliminating q from equations (16) and (17) the differential equation of the subsystem *S/ S2* is obtained, such that:

$$(R_3R_4C_3C_4)\, d^2/dt^2\,(q_2) + (R_4C_4 + R_3C_4 + R_3C_3)\, d/dt\,(q_2) + q_2 = q_{e2} \tag{18}$$

4.3 The subsystem S /S3

For the tank 5:

$$(q_1 + q_2) - q_s = (C_5)\, d/dt\,(h_5) \tag{19}$$

$$R_5 = h_5/q_s \tag{20}$$

By combining the two equations (19) and (20), the differential equation for this subsystem is obtained:

$$(R_5C_5)\, d/dt\,(q_s) + q_s = q_1 + q_2 \tag{21}$$

The mathematical model of the whole system is a combination of the model described by equations (11), (18) and (21), as follow:

$$\begin{cases} (R_2R_1C_2C_1)\, d^2/dt^2\,(q_1) + (R_1C_1 + R_2C_1 + R_2C_2)\, d/dt\,(q_1) + q_1 = q_{e1} \\ (R_3R_4C_3C_4)\, d^2/dt^2\,(q_2) + (R_4C_4 + R_3C_4 + R_3C_3)\, d/dt\,(q_2) + q_2 = q_{e2} \\ (R_5C_5)\, dq_s/dt + q_s = q_1 + q_2 \end{cases} \tag{22}$$

Since the system has two input quantities q_{e1} et q_{e2} and one output variable q_s, the fact of writing two differential equations for the output variable of the system as a function of each input variable is advantageous. By arranging the three previous equations and letting:

Let's put:

$$a_1 = R_1R_2C_1C_2$$

$$a_2 = R_3R_4C_3C_4$$

$$b_1 = R_1C_1 + R_2C_1 + R_2C_2$$

$$b_2 = R_4C_4 + R_3C_4 + R_3C_3$$

$$f = R_5C_5$$

The system can be represented by the equations (22), using the Laplace Transformation:

$$a_1P^2Q_1(p) + b_1Q_1(p) + Q_1(p) = Q_{e1}(p) \tag{23}$$

$$a_2P^2Q_2(p) + b_2Q_2(p) + Q_2(p) = Q_{e2}(p) \tag{24}$$

$$f\;\; pQ_s(p) + Q_s(p) = Q_1(p) + Q_2(p) \tag{25}$$

Choosing as states variables:

$$x_1(t) = q_1(t)$$

$$x_2(t) = d/dt\,(q_1(t))$$

$$x_3(t) = q_2(t)$$

$$x_4(t) = d/dt\,(q_2(t))$$

$$x_5(t) = q_s(t)$$

And noting the fact that:

$$q_{e1}(t) = (a_2)\, d^2/dt^2\,(q_1(t)) + (b_2)\, d/dt\,(q_1(t)) + q_1(t)$$

$$q_{e2}(t) = (a_1)\, d^2/dt^2\,(q_2(t)) + (b_1)\, d/dt\,(q_2(t)) + q_2(t)$$

$$q_s(t) = (-f)\, d/dt\,(q_s(t)) + q_1(t) + q_2(t)$$

The following state representation is obtained:

$$\begin{cases} \begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \\ \dot{x}_4(t) \\ \dot{x}_5(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -1/a_1 & -b_1/a_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1/a_2 & -b_2/a_2 & 0 \\ 1/f & 0 & 1/f & 0 & -1/f \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1/a_1 & 0 \\ 0 & 0 \\ 0 & 1/a_2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} q_{e1}(t) \\ q_{e2}(t) \end{bmatrix} \\ y(t) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix} \end{cases} \tag{26}$$

5. DIAGNOSIS OF FIVE TANKS BY UIO

This section is dedicated to the design of a residual generator using the observer UIO, to illustrate the advantage of the observer UIO in the presence of disturbance, consider the water network of five tanks.

Three non-measurable variables affect the evolution of the network, a leak in the supply line from the tank 1 noted f_{ac11} and the other a wild connection on the network noted f_{ac12}, an infiltration noted $d(t)$ is considered in the tank 5.

The measurements considered in simulation are with and without assignment of the sensors noises, noted $v_i(t)$.

The objective of this observer is to estimate the faults affecting the actuators of the linear system described by the application studied. The advantage of this diagnosis method by the perfect decoupling unknown input observers, allows the detection and the localization. A simultaneous measurement of the faults affecting the actuators is also possible using a bank of observers then an idea is to use a bank of observers for the localization of faults actuators is presented.

The system being monitored correctly is described by the following state representation:

$$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = A \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + Bu + F_x f + D_x d \\ \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} = C \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + D_y d + \begin{bmatrix} v_1(t) \\ v_2(t) \\ v_3(t) \\ v_4(t) \\ v_5(t) \end{bmatrix} \end{cases}$$

With $v_i(t)$ is the measurement noise vector.

The matrices of the state representation are presented:

$$\begin{cases} A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -0,25 & -1,5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -0,25 & -1,5 & 0 \\ 0,0625 & 0 & 0,0625 & 0 & -0,0625 \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 \\ 0,25 & 0 \\ 0 & 0 \\ 0 & 0,25 \\ 0 & 0 \end{bmatrix} \\ C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, D_x = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \; F_x = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, v_i = \begin{bmatrix} v_1(t) \\ v_2(t) \\ v_3(t) \\ v_4(t) \\ v_5(t) \end{bmatrix} \end{cases}$$

The rank of the matrix $CD_x = 1$, which is equals to the number of inputs. A residual generator sensitive to faults and insensitive to disturbance is constructed. In this part the conditions of unknown input observer as in (2) existence for the system as in (26) is verified.

The following matrixes are obtained:

$$L_y = -F\left[(CF)^T (CF)\right]^{-1} (CF)^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

$$E = I + L_y C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \; N = EB = \begin{bmatrix} 0 & 0 \\ 0.25 & 0 \\ 0 & 0 \\ 0 & 0.25 \\ 0 & 0 \end{bmatrix}$$

The eigenvalues of M are given as follow:

$\lambda_1 = -1, \; \lambda_2 = -3, \; \lambda_3 = -2, \; \lambda_4 = -1, \; \lambda_5 = -1.$

$$M = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -3 & 0 & 0 & 0 \\ 0 & 0 & -2 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

Calculating the matrix P such that $PC = EA - ME$, as

C is unitary, and after calculations the following matrix is founded:

$$P = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ -0,25 & 1,5 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 \\ 0 & 0 & -0,25 & -0,5 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

That the matrixes C, D_x are respectively full rank line and full rank column, the product CD_x is full column rank, and the number of measurements is strictly greater than the number of unknown inputs. The existence conditions of an unknown input observer are verified.

An observer with unknown input having the following structure is obtained:

$$\begin{cases} \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \\ \dot{z}_5 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -3 & 0 & 0 & 0 \\ 0 & 0 & -2 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0,25 & 0 & -0,25 & 1,5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 1 & 0 \\ 0 & 0,25 & 0 & 0 & -0,25 & -0,5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} \\ \begin{bmatrix} e_{y1} \\ e_{y2} \\ e_{y3} \\ e_{y4} \\ e_{y5} \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} - C \begin{bmatrix} z_1 \\ z_2 \\ z_3 + y_3 \\ z_4 + y_4 \\ z_5 + y_5 \end{bmatrix} \end{cases}$$

5.1 Theoretical calculation of residuals

Calculate the fault transfer matrix:

$$G_f = C(pI - M)^{-1}\left(F + pF'\right) - F_y$$

$$F = ML_yF_y + PF_y - EF_x = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \; F' = -L_yF_y = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The vector of residuals is then written

$$r(p) = Q(p)Q_d(p)G_f(p)f(p)$$

$$r(p) = \begin{bmatrix} r_{11} \\ r_{12} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} f_{AC1} \\ f_{AC2} \end{bmatrix}$$

$$a = -p^4 - 7p^3 - 17p^2 - 17p - 6 \big/ p^5 + 8p^4 + 24p^3 + 34p^2 + 23p + 6$$

$$b = 0$$

$$c = 0$$

$$d = -p^4 - 5p^3 - 9p^2 - 7p - 2 \big/ p^5 + 8p^4 + 24p^3 + 34p^2 + 23p + 6$$

According to the transfer matrix $G_f(p)$, a directly localizing structure is obtained; a decoupling of the disturbance appeared .Then, a table of theoretical signatures generated by the set of signals r_{ij} defined by:

$$r_{ij} = \begin{cases} 1 \;\; if \;\; the \;\; residual \;\; is \;\; sensitive \;\; to \;\; f_i \\ 0 \;\; if \;\; the \;\; residual \;\; is \;\; not \;\; sensitive \;\; to \;\; f_i \end{cases}$$

The signature table associated to this generator with residuals is drawn up in table 1.
In the signatures table,"1" means that is certain fault f_{ac11} affects the residual r_{ij}. A "0" translated the insensitivity of the residual from the fault.
In our application the signature table is elaborated starting from the following reasoning:
The observer1 UIO, estimates the two faults f_{ac11} and f_{ac12} at the same time. If a fault occurs on the first or the second or both outputs failure is estimated. So with this observer the actuators faults are detected and localized even if they appear simultaneously on both outputs.

Table 1. Table of required signatures of observer 1

	f_{ac11}	f_{ac12}
r_{11}	1	0
r_{12}	0	1

That the residuals are insensitive to disturbances $d(t)$. a structure allowing complete faults localization. Now, the simulation checks the theoretical results obtained for the residuals calculation and their sensitivities to disturbance $d(t)$; figure (3) shows the Simulink file used.

To solve the problem of faults isolation a bank of observers of unknown input is proposed.
The strategy used is to design observers for the monitored system (DOS architecture for faults actuators detection). For this application, there are two inputs and then a bank of observer of two UIO observers is constructed:
The first observer (UIO2) uses the first input and the second (UIO3) uses the second input. For comparison, the first observer (UIO1) previously described using two inputs. The observers used in Figure (4) are in the form (2) illustrates the principle of faults actuators detection by observers dedicated (DOS).

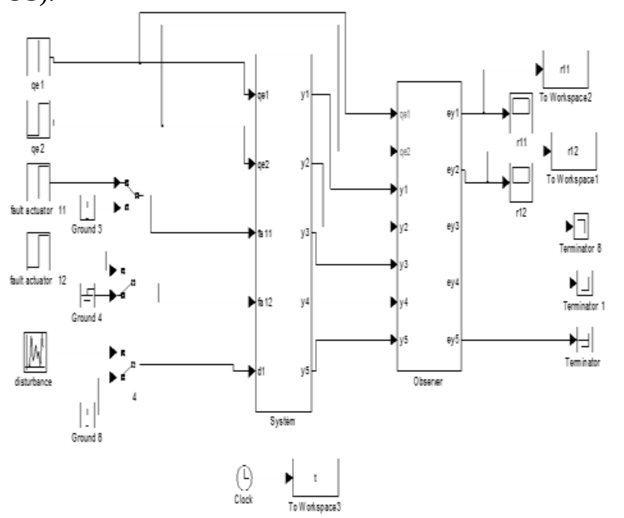


Fig. 3. Simulink scheme.

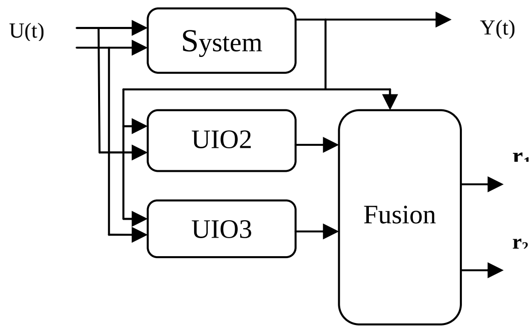


Fig. 4. Bank UIOs (DOS) for the detection of actuators faults

Since all the outputs $y(t)$ are known and there are no sensors faults, the value of $r(t)$ estimates the residual affected by the actuators faults.

Then, a table of generated theoretical signatures is listed in Table2.

Table 2. Table of theoretical signatures for actuator faults

	Obs1		Obs2	Obs3
Residuals	r_{11}	r_{12}	r_1	r_2
f_{ac11}	1	0	1	0
f_{ac12}	0	1	0	1

The signature table is made from the following reasoning:
The Observer1, estimates the two faults f_{ac11} and f_{ac12} at the same time. If a fault occurs on the first output or the second output or both outputs failure is estimated.

The observer bank generates residuals $r(t)$ defined by: The observer 2 reconstructs the output of the hydraulic system using only input q_{e1} .This output is affected by a fault that will be estimated and will represent the residual. So if residual r_1 deviates from zero, the existence of a fault actuator f_{ac11} is certain. Oppositely, the third observer uses the second output which is not affected by the fault actuator f_{ac11}, the residual r_2, then remains around zero if there is no fault on the second output, these observer estimate the second fault f_{ac12}.

With observer 1, the fault actuator is detected and localized.
In the application, that faults on the actuator are defined as follows:

$$f_{ac11} = \begin{cases} 2 & t \geq 4 \\ 0 \;\; elsee \;\; where \end{cases}$$

$$f_{ac12} = \begin{cases} 6 & t \geq 30 \\ 0 \;\; elsee \;\; where \end{cases}$$

6. RESULTS AND INTERPRETATION

Results shown in figure (5) present that the residuals are perfectly decoupled from the disturbance $d(t)$, they are associated to the observer 1 in the absence of faults and in the presence of the disturbance.

In reality, the residuals values are not equal to zero, due to measurement noise.

The fault 1 is considered as a leak at the time $t \geq 4s$ and the fault 2 is also considered as a wild connection on the network at time $t \geq 30s$.

By successively simulating the appearance of a fault f_{ac11} of amplitude 2 at the time $t \geq 4s$ and the second fault f_{ac12} of amplitude 6 at the time $t \geq 30s$, the residual table shown in figure (6) and (7) in the absence and the presence of the fault is obtained, the residuals evolve in accordance with the theoretical signatures table1 of the previously calculates.

Where figure (6) without measurement noise, but in figure (7) random signals are superimposed on the measures in order to take into account the noise measurement influence $v_i(t)$.

The simulation of the system presented with the bank of observers allows to find the residual, whose analysis of this last provided by the first observer (UIO2) leads to the conclusion that there is indeed a fault on the first actuator. Similarly, if a fault occurs on the second actuator will be estimated by the second observer (UIO3), these results of bank of observers are illustrated in the figure (8).

Results of our simulation correspond to the signatures theoretical table 2 and the fact of using observers UIO 2 UIO3 dedicated bank of observers (DOS) to estimate each actuator fault, makes it possible to detect and locate. Note also that alarms false are avoided comparing with the first observer (UIO1) using both inputs at once. Whereas, at the accident time with the first observer the rapid change of the defects causing false alarms.

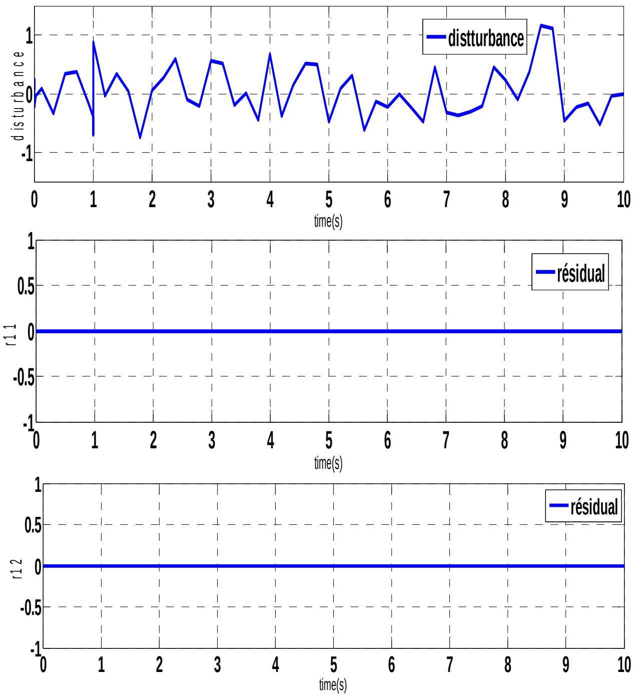


Fig. 5.Insensitivity of residuals to disturbance

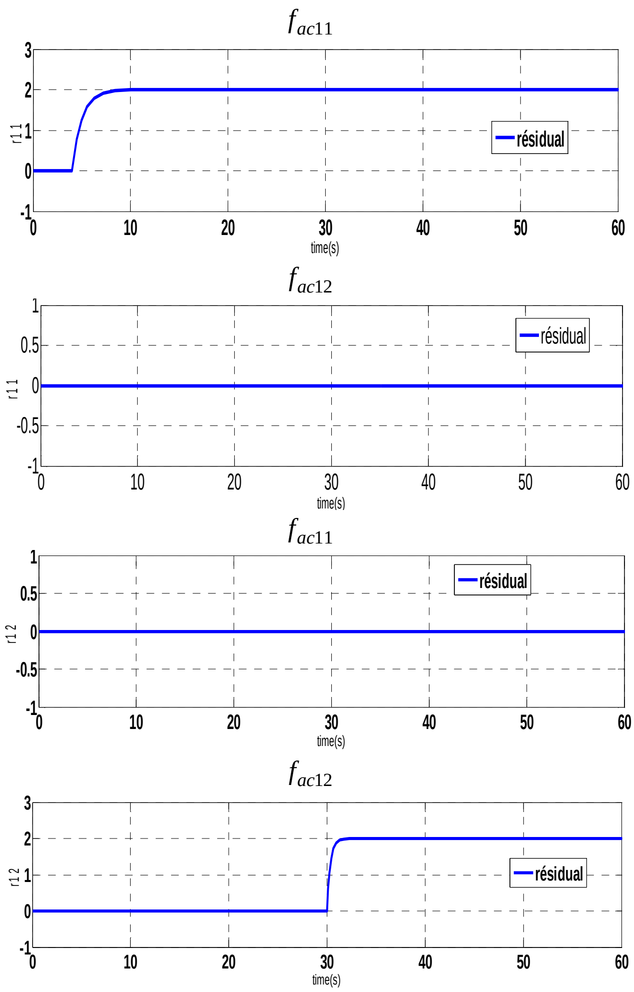
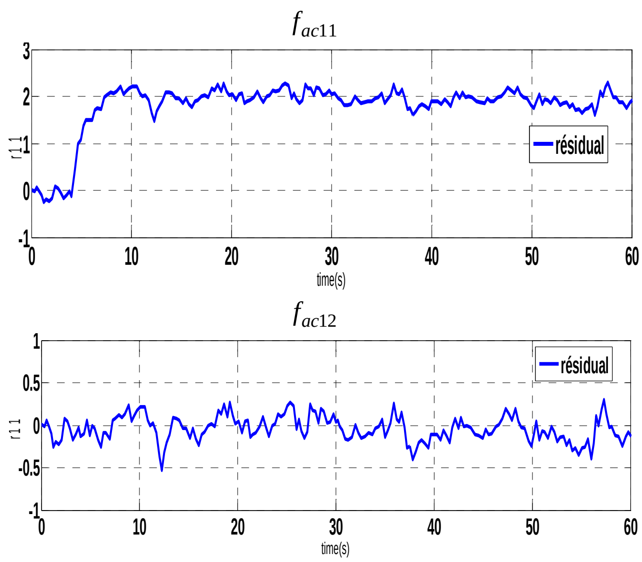


Fig. 6. Table of residuals without measurement noise (UIO1).



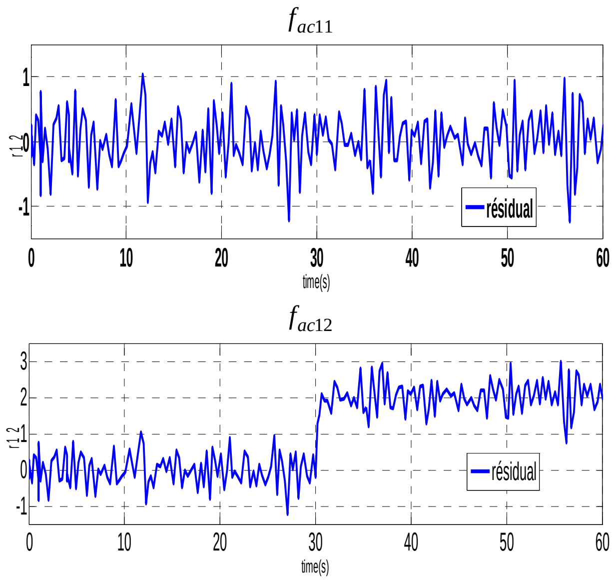


Fig. 7. Table of residuals with measurement noise (UIO1).

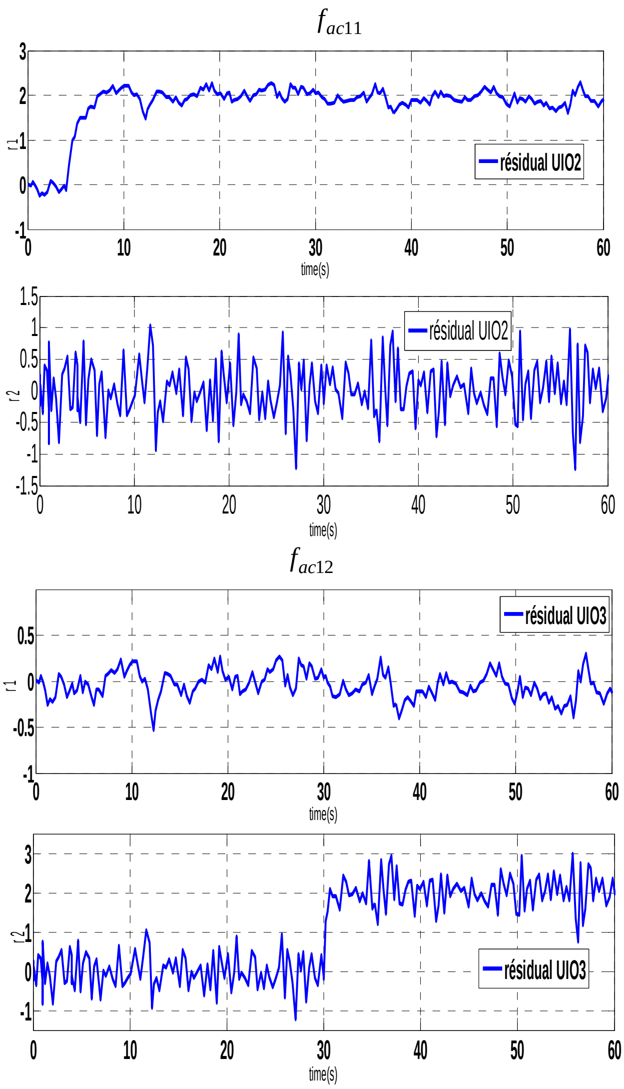


Fig. 8.Table of residuals UIO (2, 3).

7. CONCLUSIONS

The problem of disturbance decoupling has been studied by many previous methods in the literature. Disturbance decoupling was firstly intended for state estimation because proportional observers are not capable to yield to good estimation of states when disturbances perturb the system. However UIOs observers are more robust and usually require less restrictive existence conditions therefore it is more logical to use a UIO observer to have an independent state estimation in the presence of disturbances. However, in some applications an unknown input observer is the better choice.

In this paper a design of unknown input observer is applied for actuators fault detection and isolation in simplified five tanks hydraulic system. This system can be viewed as a prototype of many industrial applications in process industry, such as chemical and petrochemical plants, oil and gas systems.

We extend the system by unknown inputs observer to generate robust residuals where the isolation is performed by a bank of observers (UIOs) in which the alarms false are avoided compared to only one observer (UIO). The effectiveness and capabilities of the suggested method have been demonstrated by simulation results.

The presentation of a general methodology to solve the residuals robustness problem in UIO design and other possible extensions are left as future research topics.

The future work can be extended to the linear system where decoupling conditions (UIO with perfect decoupling) is not verified, the use of observer with approximate decoupling unknown input is proposed and to the nonlinear case, particularly, systems with Takagi-Sugeno representation (multimodèl).

REFERENCES

Amatof, F., Matteif, M., lervolino, R., Paviglianiti, G. (2002). A Nonlinear UIO Scheme for the FDI on a Small Commercial Aircraf. *Proceedings of the 2 IEEE International Conferences on Control Applications*, September 18-20, Glasgow, Scotland U.K.

Anzurez-Marin, J., Pitalua-Diaz, N., Cuevas-Silva, O., Villar-Garca, J. (2008). Unknown input observers design for fault detection in a two-tank hydraulic system. *Robotics and Automotive Mechanics Conference*. CERMA '08.Electronics, 373–378.

Bagherpour, E., Hairi-Yazdi, M. (2013). Disturbance Decoupled Residual Generation with Unknown Input Observer for Linear Systems. *Conference on Control and Fault-Tolerant Systems (SysTol)*, October 9-11, Nice, France.

Chen, J., Patton, R. J. (1999). Robust model based fault diagnosis for dynamic systems. Kluwer Academic Publishers, Amesterdam.

Chen, J., Patton, R., Zhang, H. (1996). Design of unknown input observers and robust fault.

Chen, J., Zhang, H. (1991). Robust detection of faulty actuators via unknown input observers. *International Journal of Systems Science*, 22(10), 1829–1839.

Chen, W., Saif, M. (2006). Fault Detection and Isolation Based on Novel Unknown Input Observer Design. *Proceedings of the ACC*, 5129- 5134. Minneapolis Minnesota, USA.

Cristofaroa, A, Johansenb,T.(2014). A Fault tolerant control allocation using unknown input observers, *Automatica*, vol. 50, 1891–1897

Ding, S. X. (2008). Model-Based Fault Diagnosis Techniques Design Schemes, *Algorithms and Tools*. Springer-Verlag.

Ding, S.X., Frank, P.P. (2002).An Approach to the Detection of Multiplicative Faults in Uncertain Dynamic Systems. *Proceeding of the 41st IEEE Conference on Decision and Control*,6,4371-4376.Las Vegas, Nevada USA.

Duan, G., Patton, R. (2001). Detection using Luenberger-type unknown observers- A parametric approach, *International Journal of Systems Science*, 32,533–540.

Henry,D., Zolghadri,A. (2005b). Design of fault diagnosis filters:A multi-objectiveapproch, *Automatica*,vol.342,Issue4,421-446.

Henry,D., Zolghadri,A. (2005a). Design and analysis of robust residual generators for systems under feedback control, *Automatica*,vol.41,Issue2,251-264.

Hou, M. , Muller, P.C. (1994). Fault detection and isolation observers. *International Journal of Control*, vol. 60, 827-846.

Isermann, R. (2007). Fault-diagnosis systems: An introduction from fault detection to fault to lerance, *Springer*.

Jiang , B., Chowdhury, F.N.(2005). Parameter fault detection and estimation of a class of nonlinear systems using observers. *Journal of the Franklin Institute*, vol. 342,725-736.72.

Johansson, A., Bask, M., Norlander, T. (2006). Dynamic Threshold Generators for Robust Fault Detection in Linear Systems with Parameter Uncertainty. *Automatica*.vol.42, 1095-1106.

Khan , A. Q., Ding , S. X. (2011). Threshold computation for fault detection in a class of discrete-time nonlinear systems. *International journal of adaptive control and signal processing*. vol. 25, 407-429.

Koenig , D., Nowakowski , S., Bourjij, A. (1996) . New design of robust observers for fault detection and isolation. *Proceedings of the CDC*, 1464-1467.Kobe Japan.

Mangoubi, R.S. (1998). Robust estimation and failure detection :a conciste treatment,*springer Verlag*.

Meseguer, J., Puig, V., Escobet, T., Saludes, J. (2010). Observer gain effect in linear interval observer-based fault detection, Journal *of Process Control*, vol. 20, 944-956.

Oscar, A. Z., Sotomayor, Darci Odlomak. (2005). Observer-based fault diagnosis in chemical plants. *Chemical Engineering Journal*, 112:93-108.

Rank, M. L., Niemann, H. (1999). Norm based design of fault detectors. *International Journal of control*, vol.72, Issue9, 773-795.

Sobhani, M. H., Poshtan, J. (2012). Fault Detection and Isolation using Unknown input observers with structured Residual generation. *International Journal of Instrumentation and Control Systems*, vol.2, Issue2.

Stefen Hui, Stanislaw H. Zak ,(2005). Low-Order Unknown Input Observers. *American Control Conference* June 8-10, 4192-4197. Portland, OR, USA.

Termehchy, A., Afshar,A., Javidsharifi, M.(2013). A Novel Design of Unknown Input Observer for Fault Diagnosis in the Tennessee-Eastman Process , System to Solve Non-minimum Phase Problem. *Proc. of the IEEE International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)*, 26-27 November, Kuala Lumpur, Malaysia

Toscano, R., (2011).Commande et diagnostic des systèmes dynamiques (Modélisation, Analyse, Commande par PID et par retour d'état, Diagnostic). *Livre Ellipses Edition*.

Viswanadham, N., Srichander, R. (1987). Fault detection using unknown input observers. *Control Theory and Advanced Technology*, vol. 3, Issue2, 91 – 101.

Wang, G. S., Xia, F., Yang, W. L. (2013). Design of robust finite time functional observers in uncertain linear systems. *International Journal of Advanced Mechatronic Systems*,vol.5,Issue4,223-231.

Wang, S.H., Davisonet, E.J., Dorato, P. (1975). Observing the states of systems with unmeasurable disturbances. *IEEE Transactions on Automatic Control*, vol. 20, 716–717.

Xiong ,Y. , Saif, M. (1998). A novel design for robust fault diagnostic observers. Proceedings of the CDC, 592-597 , Florida.