Fault Diagnosis and Fault Estimation for actuator fault based on Bond Graph approach

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***Abstract*— Engineering systems becomes more and more complex, this is why Fault detection and isolation (FDI) for large complex systems are very important in order to ensure safe operation of industrial processes. Therefore, the design of complex dynamic systems has become complicated. This is why we chose to use Bond Graph (*BG*) tool in this paper. Thanks to its graphic nature which is suitable for the analysis of the multidisciplinary system's behavior. Furthermore, the BG tool is developed here to synthesize a fault diagnosis based on analytical redundancy relations (ARRs). Once a fault is detected, an effective algorithm for fault estimation has been suggested. Finally, an hydraulic system with two tanks has been studied herein, in order to validate theoretical results and to improve the rapidity of the fast fault estimation for actuator fault.**

***Keywords—component;* Fault Diagnosis, Fault Estimation, Bond Graph, Analytical redundancy relation, Actuator Fault.**

I. INTRODUCTION

Nowadays, engineering systems are of ever-growing complexity and shall be considered as multidisciplinary systems from different engineering disciplines. According to the multidisciplinary nature of most industrial systems (electrical, mechanical, hydraulic, thermal, …), a graphical unified description formalism is needed for analysis and model synthesis. The bond graph created by Paynter [1] and has become a widespread in use since then all over the world. It is a graphical representation language of physical systems, based on the modelling of the energy phenomena occurring inside these systems. Furthermore, the bond graph modeling methodology enables to the generation of not only a behavioral model [2], but also it can be used for structural and causal analysis which are important to design control and monitoring systems [3]. Furthermore, the structural and causal properties provides by this graphical representation can be used for design of supervision systems [2]. Also, bond graph modeling may be considered as an integrated computer aided design tool in the field of system engineering.

Besides, Fault Detection and Isolation (FDI) procedures are necessary in the supervision platform and even obligatory in some situations in order to ensure safe operation of industrial processes and to protect the environment [4]. Because faults in a process will often cause an undesired sequence of events and the consequence could be damaging to the plant, the personnel and the environment. So fault diagnosis means to detect and to isolate faults and to analyses their type and their magnitude.

Two types of approaches are used: qualitative and quantitative methods. Quantitative methods are based on knowledge of a mathematical model of the process and qualitative methods are founded on the competence of the engineer with a very good command of the equipment being monitored.

In this work, we are interested to the quantitative method which called model-based methods, the first step generates a set of residuals called analytical redundancy relations (ARRs) and through elimination of unknown variables from the corresponding BG model using causal path, ARRs equations can be obtained and Fault Signature Matrix (FSM) can be established [5]. Indeed, the method for making the diagnosis is to generate residual analytical redundancy relations calling from linear mono power bond graph model are studied in Tagina [6] by following the causal paths. Also, ARRs are static or dynamics constraints which link the time evolution of the known variables when a system operates according to its normal operation model.

The objective of this paper is to study model-based fault estimation schemes and develop a general framework for fast fault estimation based on ARRs. Successful results can be established in several excellent books [2][7][8][9], survey papers [10-11].

In [12] Touati and al propose an algorithm of fault isolation for the faults which have the same signature. The developed procedure of this idea is based on the residuals sensitivity and in the generation of the fault estimation equations.

This paper is organized as follows. The diagnosis using bond graph model is presented in Section II. Section III contains the actuator fault estimation. In this part, actuator failure is detected and estimated. An hydraulic two tank system are provided in Section IV, and some concluding remarks are given in Section V.

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II. Diagnosis based Bond graph Approach

A. *Bond graph modeling*

The Bond graph has been defined by Henry Paynter in 1961 [1], subsequently developed by Karnopp in 1975 [13], Rosenberg in 1983 [14]. It is an excellent tool to model complex systems. The energetic approach of BG works to emphasize analogies between different fields of physics (mechanics, electricity, hydraulics, thermodynamics, etc. ...) and represent in uniform multidisciplinary physical systems. The bond graph modeling is based on the exchange of power in a system, which in normally the product of an effort variable and a flow variable. This exchange takes place in bonds represented by a simple line. The concept of power *p(t)* can be depicted as indicated in (1):

$$p(t) = e(t).f(t)$$

Where *e(t)* and *f(t)* are the effort and the flow respectively. This equation illustrates the energy transfer in the system using power links. A link power is symbolized by a half-arrow, whose orientation indicates the direction of power transfer. Thus, Fig. 1 shows the power transfer from subsystem A to subsystem B.

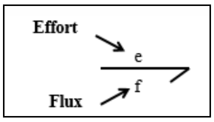

Fig. 1. BG power transfer

In this manuscript, the bond graph is used not only for modeling, but also for fault estimation diagnosis and simulation of dynamical systems.

B. *Diagnosis using the analytical redundancy relations*

Fault diagnosis is to detect and to isolate faults and to analyses their type and their magnitude. Fault indicators can be obtained by evaluation of analytical redundancy relations between known input signals into a system and measured output signals. We have synthesized fault detection and isolation (FDI) for hybrid system in our previous work [15]. Analytical Redundancy Relations (ARRs) can be derived straightforwardly off-line from a BG of a physical model in a systematic manner and ARR residual [16].

$$f(k) = 0 \tag{2}$$

The number of redundancy relations derivable from any system model is equal to the number of sensors in the system. An ARR is then written as

$$ARR: f(D_e, D_f, S_e, S_f, MS_e, MS_f, \theta) = 0 \tag{3}$$

Where

- k is the set known variables(sources and measured values specified by detectors),
- D_e, D_f are effort and flow sensors,
- S_e, S_f are effort and flow sources,
- MS_e and MS_f are modulated effort and flow sources,
- θ is represented a vector of all parameters.

Residual symbolized by r is the numerical value of ARR (evaluation of ARR) that can be written as follow:

$$r - f(k) \approx 0 \tag{4}$$

The block diagram of such a method is given in Fig. 2.

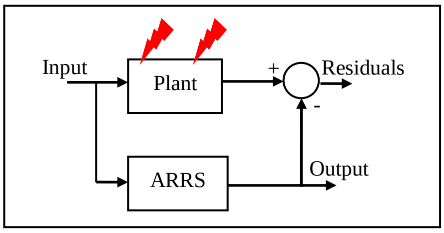

Fig. 2. Block diagram of the fault detection based ARR

III. Actuator Fault Etimation

In [18], K. Zhang et al. propose a fault estimation using adaptive fault diagnosis observe. In this paper, we have inspired this idea using the residual generated through an analytical redundancies relations (ARRs).

A. *Fault Signature Matrix*

The information which component parameter contributes to which ARR in some system mode can be described in a structural Fault Signature Matrix that is called FSM [17].

TABLE I. STRUCTURAL FAULT SIGNATURE MATRIX OF THE BG MODEL

Residuals	ARR_1	ARR_2
Msf (pump)	1	0
R_1	1	0
R_2	1	1
R_3	0	0
R_4	0	0
C_1	1	0
C_2	0	1
De_1	1	1
De_2	1	1

As it shows in (Table 1) on the FSM, the components Msf, C_1 and R_1 have the same signature "10". The sensibility of the residuals to these faults is not the same, so these three faults can be isolated using the developed procedure of fault estimation and isolation. That is, the parametric fault cannot be isolated by inspecting the structural FSM. Considering an estimate of the actuator fault.

B. Actuator Fault Estimation Design

Before showing the main results, this theorem proposed by [18] is given herein.

Theorem 1: If there exist symmetric positive definite matrices $P \in \mathbb{R}^{n*n}$, $Q \in \mathbb{R}^{r*r}$ and matrix $F \in \mathbb{R}^{r*p}$ which check up the following conditions:

$$A^T P + PA - PCR^{-1}CP + Q < 0 \tag{5}$$

$$E^T P = FC \tag{6}$$

Then the fault estimation algorithm is presented (7):

$$\dot{\hat{f}}(t) = -\psi Fr(t) \tag{7}$$

Where $\psi \in \Re^{r\times r}$ is the learning rate matrix. The actuator fault estimate using the above method can be written as :
The proof of Theorem 1 can be referred to [18]. Actuator fault estimate using the Theorem 1 can be written as

$$\hat{f}(t) = -\psi F \int_t^{t_f} r(\tau) d\tau \tag{8}$$

Further, in view of the previous expression, the estimation of the actuator fault magnitudes can be achieved with a little delay in the estimation task. Nevertheless this latter which appears in the estimation step may affect fault effects compensation. For this reason, [18] has adopted another expression that guarantees a fast adaptive fault estimation reaching theorem 2.

Theorem 2: Given scalars $\sigma, \mu > 0$ if there exist symmetric positive definite matrices $P \in \Re^{n\times n}$, $G \in \Re^{r\times r}$, $Y \in \Re^{n\times p}$ and $F \in \Re^{n\times p}$ satisfying the two following conditions:

$$\begin{bmatrix} PA + A^T P - YC - C^T Y^T & -\frac{1}{\sigma}\left(A^T PE - C^T Y^T E\right) \\ -\frac{1}{\sigma}\left(A^T PE - C^T Y^T E\right) & -2\frac{1}{\sigma} E^T PE + \frac{1}{\sigma\mu} G \end{bmatrix} < 0 \tag{9}$$

$$E^T P = FC \tag{10}$$

Where $Y = PL$.
Then, we obtain the fault variation given by:

$$\dot{\hat{f}}(t) = -\psi F(\dot{r}(t) + \sigma r(t)) \tag{11}$$

From theorem 2, we can write the fast adaptive estimation $\hat{f}(t)$ for our actuator fault $f(t)$ as :

$$\hat{f}(t) = -\psi F(\int_t^{t_f} r(\tau) d\tau + \sigma r(t)) \tag{12}$$

F is solved by LMI toolbox resolution whereas r is the residual vector.

Furthermore, we can confirm that fault estimation with the residual integration, obtained by Theorem 2 ameliorate considerably estimation fastness.

IV. CASE STUDY: TWO TANK SYSTEM

A. System description

In order to demonstrate these previous theoretical results, an hydraulic system with two tanks is described in Fig.3. The two-tank system is adapted from [19]. The process is shown in Fig. 2. This system is composed of:

- Two tanks T_1 and T_2 with the same section S are connected by pipes which can be controlled by different valves.
- A pump P that delivers a liquid to tank T_1.
- Three switching valves V_1, V_2 and V_3.
- Two level sensors: one level sensor that measures h_1 and the other level sensor measures h_2, the liquid level in tank T_2.

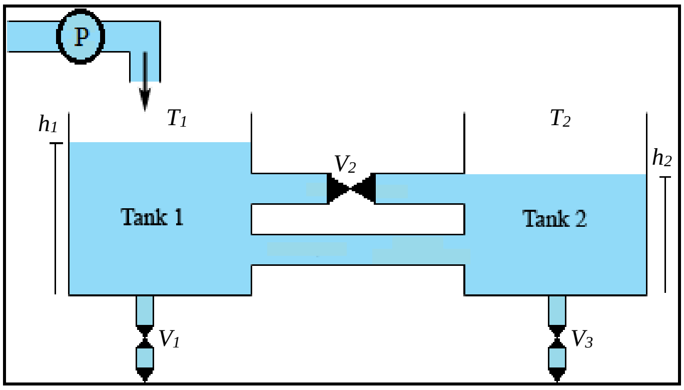

Fig. 3. Two-tank system Scheme

The first tank T_1 is feeded by a controlled pump modeled as a source of a flow MSf: u to keep water level constant. Each tank has an hydraulic capacity $C_1 = \frac{A_1}{\rho.g}$, $C_2 = \frac{A_2}{\rho.g}$ respectively, A_1 and A_2 are the section of each tank, ρ is the density of water, g is the gravity. The two sensors are represented by De_1 and De_2 (water level in each tank). The bond graph model of the system is given in Fig.4.

The failure here is represented by an additive actuator fault. The state equation of the faulty bond graph model is written as (13).

$$\begin{cases} \dot{x}_1 = A_1 x_1 + B_1 x_2 + u + f \\ \dot{x}_2 = A_2 x_1 + B_2 x_2 \\ y_1(t) = C_1 x_1 \\ y_2(t) = C_2 x_2 \end{cases} \tag{13}$$

With

$A_1 = -\frac{1}{C_1}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$, $B_1 = \frac{1}{C_2 R_2}$, $A_2 = \frac{1}{C_1 R_2}$, $B_2 = -\frac{1}{C_2 R_2}$,

$C_1 = \frac{1}{C_1}$ and $C_2 = \frac{1}{C_2}$.

The system matrices A, B, C and E are given as follows:

$$A = \begin{bmatrix} -40 & 16.66 \\ 20 & -16.66 \end{bmatrix},\ B = \begin{bmatrix} 1 \\ 0 \end{bmatrix},$$

$$C = \begin{bmatrix} -40 & 16.66 \\ 20 & -16.66 \end{bmatrix} \text{ and } E = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

In this paper, it is assumed that $E = B$ because only actuator fault are considered.

TABLE II. NUMERICAL VALUES OF SYSTEM PARAMETERS

Parameters	***Description***	***Values***	***Units***
C_1	Tank section C_1	0.05	$m^4.s^2/Kg$
C_2	Tank section C_2	0.06	$m^4.s^2/Kg$
R_1	Resistance	1	$pa.s/m^3$
R_2	Resistance	1	$pa.s/m^3$

The numerical values of system parameters are presented in table II.

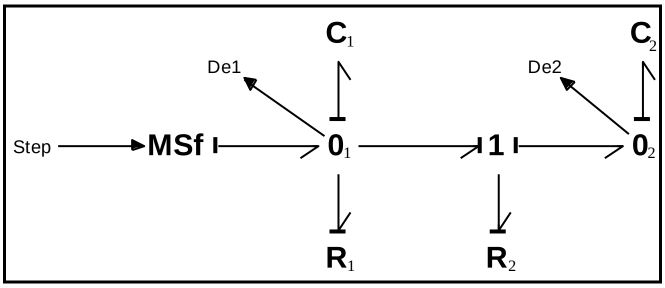

Fig. 4. Bond graph model of two-tank system

In table II, it is given the structural equations deduced from bond graph modelling of process presented in Fig.3. For each mode, we have generated the ARRs for FDI by bond graph model. We combined the equations presented in table II to eliminate unknown variables. The known variables are available from sensors and actuators, so we generate the set of residuals in which the appeared variables are all known.

TABLE II. STRUCTURAL EQUATIONS FOR NORMAL MODE

N	Junction	Structural equations
1	Junction 0_1	$\begin{cases} e_1 = e_2 = e_3 = e_4 = De_1 \\ Msf - f_{C_1} - f_{R_1} - f_4 = 0 \end{cases}$
2	Junction 1	$\begin{cases} f_4 = f_5 = f_6 \\ e_4 - e_5 - e_6 = 0 \end{cases}$
3	Junction 0_2	$\begin{cases} e_6 = e_7 = De_2 \\ f_6 - f_7 = 0 \end{cases}$

By replacing the flow f by its expression generated from the BG after eliminating the unknown variables, the residuals are obtained as follow:

$$r_1 = Msf - C_1 \frac{dDe_1}{dt} - \frac{De_1}{R_1} - \frac{De_1 - De_2}{R_2} \tag{14}$$

$$r_2 = \frac{De_1 - De_2}{R_2} - C_2 \frac{dDe_2}{dt} \tag{15}$$

B. *Simulation results*

The simulation have been performed by the software 20-sim. The normal evolutions of residuals are presented in Fig.5 and Fig. 6. Simulation time is fixed to 10s. There are disturbances in the residual 1 which lead us to choose a detection threshold.

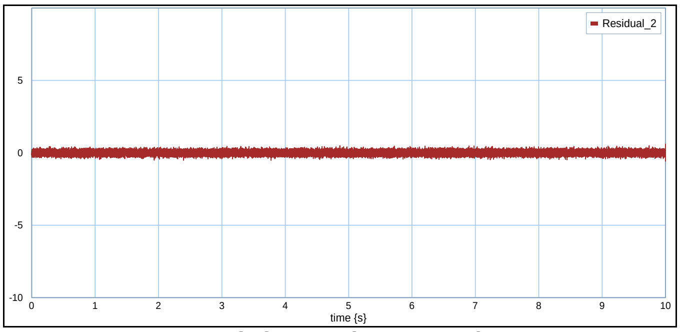

Fig.5. Residual in normal operation with noise

In the faultless case, the residual is close to zero. If there is at least one ARR residual that exceeds a given fault threshold in the system, where threshold depends on user defined specifications for example noise. A non-zero residual indicates that one single fault has happened.

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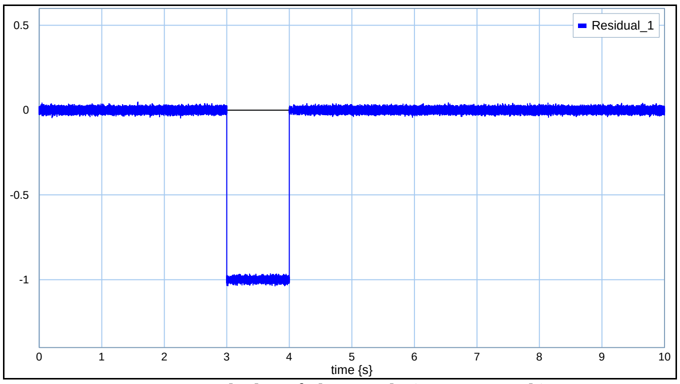

Fig.6. Residuals in failure mode (Actuator Fault)

Fault detection and estimation are illustrated by figures Fig.5 and Fig.6. A fault is simulated at the pump (modelled by MSf in BG). Fig. 6 shows that residual 1 is sensitive to the introduced fault. This is confirmed by the FSM presented in table I.

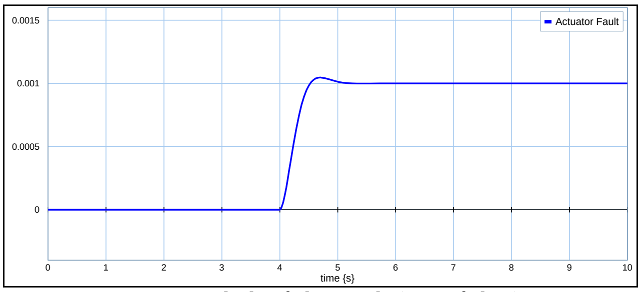

Fig. 7. Residual in failure mode (Pump failure)

Firstly, we have consider that the actuator fault in Fig.7 is represented by an echelon with an amplitude of 0.001 m^3/s starting from $t = 4s$.

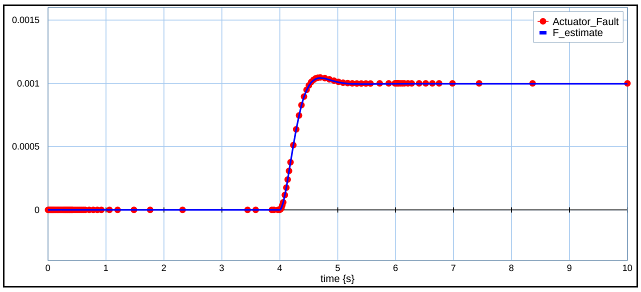

Fig.8. Fault signal and its estimate.

The simulation in Fig.8 display that our approach using the fast estimation is fast and improve the rapidity of the recovery fault. Secondly, we have consider the same actuator fault represented by a pulse signal during 1s (from t= 3s to t= 4s).

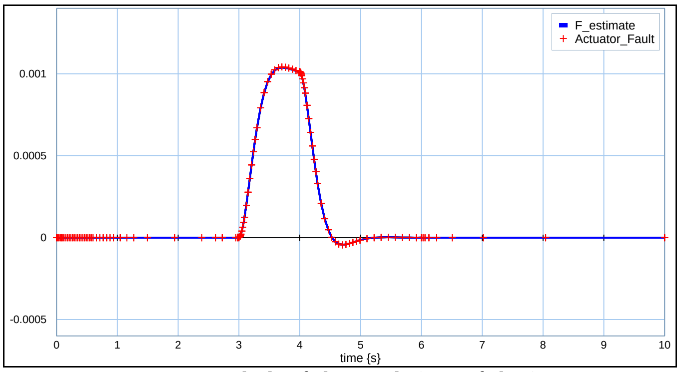

Fig. 9. Residual in failure mode (Pump failure)

We can deduce from Fig. 9 that our actuator fault is detected by the residual signal, and for which value is different from zero. Fig.9 illustrates our failure's estimation and shows that this latter is fast and accurate.

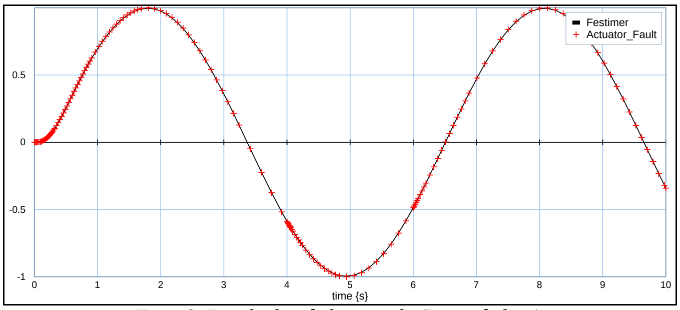

Fig. 10. Residual in failure mode (Pump failure)

From Fig. 10, it can be seen the estimation of actuator failure (pump failure) with a sinusoidal input. Therefore, we can conclude the rapidity of our fault estimation.

V. Conclusion

In this paper, we have shown how to use a bond graph as a dynamic and efficient modelling tool (because of its graphical, structural and causal properties) not only for modelling but also for Fault Detection and Isolation (FDI) and simulation of an electrical system. The state space equations is determined straightforwardly from the model bond graph. An hydraulic system has been utilized for the fault diagnosis by analyzing the residual signal that is generated by an analytical redundancies relations (ARRs). The estimated actuator fault has been adopted. Finally, we have to emphasize that in this manuscript we treat a system with single actuator fault for fault detection and isolation. Some promising future topics include: 1) Sensor or actuator faults treatment with multiple faults case: 2) Fault estimation and Fault tolerant control for hybrid systems based on bond graph approach.

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