Process Monitoring Using Bond Graph Approach

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Abstract: This article presents the use of the Bond Graphs approach as a tool for the monitoring of complex processes. This approach is based on the generation of analytic redundancy relations (indicatory of failing) at junctions of the Bond Graphs model of the process in question. A case study on an installation of electric pumping of water illustrates the efficiency and performances of the approach.

Key-Words: Bond graphs, Modelling, complex processes, Faults, detection and isolation, Analytic redundancy relations.

1 Introduction

Constraints of competitiveness accentuated by internationalization and translated in terms of production cost, security of the technological systems and quality of the object produces represent a major preoccupation of the industrial world. In this setting, the monitoring occupies an essential position, since it permits, from the observation of the system, to take a decision on their modes of running allowing to ameliorate the conduct of the process or to prevent a drifting can take to failures of manufacture or the catastrophic damages.

However, the bond graphs tool since its invention in 1961[1], don't stop enlarging their domains of use, to the modelling at the analysis of the systems. In Bond Graphs approach, the stage of modelling is indeed, an important stage for the conception of the monitoring systems.

The paper is organized as follows: the section 2 gives a brief exhibition of monitoring functions, as well as methods the more used in the literature. Then, one finds in the section 3 a small presentation of the Bond Graphs tool with his mathematical aspect of the causality.

The section 4 presents the use of the Bond Graphs for the residual generation. In section 5 is illustrated an example of application of the procedure shown in section 4 and a comparison with the procedure used in [4] for the diagnosis of fault.

A conclusion is given, at the end of this paper, to put the point on the use of bond graph in the fault detection and isolation.

2 Steps and features of monitoring

The goal of the monitoring is to design a system able to produce an alarm defining the presence of a fault in one or several parts of the studied process, as soon as possible, in presence of noises, perturbations and uncertainties Fig.1.

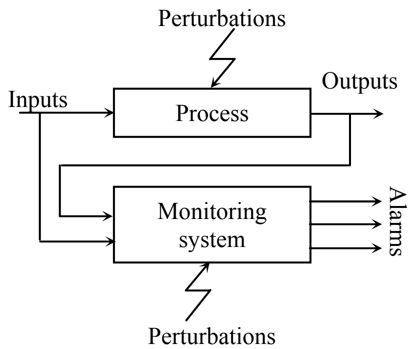

Fig.1: General scheme of monitoring system

A monitoring system must achieve the following tasks:

- Faults Detection,
- Faults isolation,
- Faults Diagnosis.

There are several methods for the design of monitoring systems; they may be classified as follows:

- Methods with model: they serve to use a model of behavior of the process to supervise. The gap between the model and the real running triggers an alarm.

Several approaches are known for this type of monitoring, as:

- Parameter or state estimation (θ or x) [2][3],
- Parity space methods [2],
- Bond graph approach [4] [5] [7].

➢ Methods without model: they consist in building a basis of data by measures gotten up during the normal working to compare it to measures gotten up at the time of the working of the process.

In the same way, we distinguish several approaches:

- Statistical approach [2],
- Artificial Intelligence approach (AI) [6],
- Pattern recognition.

Contrary to the methods without model, the methods of surveillance with model allow a precision and a sufficient efficiency for risk processes. In the category of the methods with model, the modelling by bond graphs permits by its modularity to integrate an optimal precision level according to the compromise between veracity and efficiency.

3 Bond Graphs Modelling

The Bond Graph representation is a technique of modelling based on exchanges of power between systems. The idea of start is that the instantaneous power of any system can be calculated from two variable conjugated, that are: the effort and the flow, as:

$$P(t) = e(t).f(t) \qquad (1)$$

Where: $P(t)$ is the instantaneous power, $e(t)$ and $f(t)$ are respectively the effort and the flow at the instant t.

These two variables are represented implicitly on bond graph by a half arrow indicating the sense supposed of the power exchange.

For example, if a subsystem *(A*) exchange of the power with another subsystem *(B)*, the representation of this transfer is given by the following figure Fig.2:

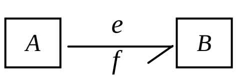

Fig.2: Bond graph representation of the power exchange

Variables (***e*** and ***f***) have some physical significances according to the domain of the system to model, as the pair (*tension* ***u*** and *current* ***i***) in electricity, (*Pressure* ***P*** and *volume flow* ***Q***) for the hydraulic domain, (*couple* ***τ*** and *rotational speed* ***ω***) for the rotational mechanics. More details on the physical significance of power variables are given by [1]. Bond graphs elements can be classified of the following manner:

- Passive Elements (receive the power) :
  - *R Element (Resistance) : who represents the phenomenon of energy dissipation,*
  - *C Element (Capacitance) and I (Inertia): represent the storage of the energy.*
- Active Elements (supply the power) :
  - *Effort source Se,*
  - *Flow Source Sf.*
- Multi ports junction Elements:
  - *0 Junction : common effort,*
  - *1 Junction : common flow,*
  - *Power Transformer: directed TF and mixed GY.*

Elements *Se Sf*, *TF* and *GY* can hold constant or variable values. If it is the case, one adds a ' M ' before every element that represents the abbreviation of Modulated. The physical significance of these elements is given for every domain of the physics by [1].

The set of instrumentation and of elements of measures (sensors, devices of measure) can be modeled in bond graph by detectors. One distinguishes detectors of effort De and of flow Df, that doesn't consume the power (supposed ideal), feed therefore by signals represented by the full arrows. They are placed respectively on junctions 0 and 1, according to the necessity of information on the effort or the flux in the wanted position Fig.3.

Bond graphs represent the architecture of the system, where appears exchanges of power between its elements. They also permit to define the structure of calculation with stake in evidence of cause relations to effect within the system by the notion of causality, which is represented by a causal stroke put on the half arrow, defining the sense where the effort (e) is known Fig.4.

In this figure we have coupled two subsystems A and B, with two situations:

- A sends to B a flow (f), that answers by sending to A an effort (e),
- A applies to B an effort (e), that reacts by sending to A a flow (f).

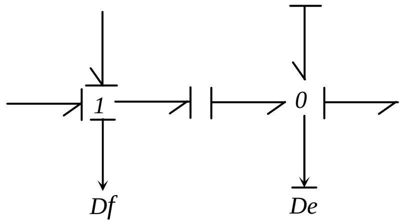

Fig.3 : Effort and flow detectors

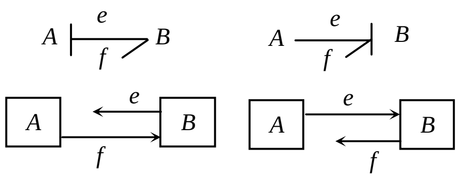

Fig.4 : Two cases of causality

It is necessary to notify that the position of the causal stroke is quite independent of the sense of the half arrow [1].

The notion of causality conditioned by rules of assignment permits the passage of the bond graph model of a system given to the other forms of representation as the function of transfer, the state space equation of and the diagram block [1].

4 Bond Graphs Monitoring

The bond graph tool is used for the generation of analytic redundancy relations. These relations, function only of variables known can provide information on the consistency of the model with the real working of the system of the system. Therefore they are equal to zeros in normal running, different of zero at the time of a failing of one or several components of system.

By the passage of the bond graph model to the state space model, one can use bond graph as support of diagnosis, as it been shown in [4], or by the generation of analytic redundancy relation by the direct or indirect method [7] (in the case of the simple energy) or multi energy as in [5].

For the generation of analytic redundancy relations directly from the bond graph model, one exploits the constituent relations of set of junctions of the model, that are function of known variable (Se, Sf, De and Df) or unknown (the effort and the flow in link with the considered junction), that are deduced by the covering of causal path.

The procedure of analytic redundancy relations generation (ARRs) is expressed as follows:

1. From variables to supervise, chose a type of junction,
2. Chose a junction of this type,
3. Write the constituent relation and express the unknown variables according to the known variables by covering the possible causal paths,
4. Pass to the following junction and repeat the step 3. until the obtaining of sufficiently of analytic redundancy relations (until the obtaining of different signature for the different variable or depletion of junctions).

One gives the definition of the causal path as being an alternation of links and basis elements (R, C or I). According to the causality, the variable crossing is the effort or the flow. To change this variable it is necessary to pass by a GY element or by a passive element [1].

5 Case Study

Either the system describes by the following figure Fig.5. This system is composed of (4) interconnected subsystems: (1) an electric circuit, (2) a motor with an inertia and friction, (3) a pump with mass and friction (4) a reservoir system with pipe.

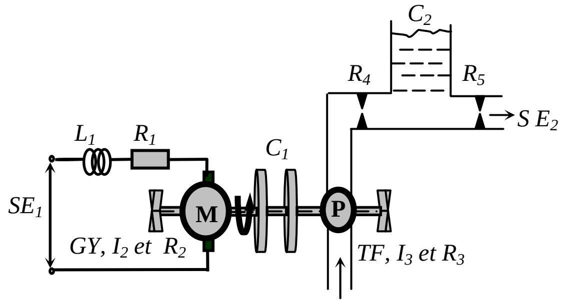

Fig.5: Control system of the water flow

The bond graph model of the system is given by the following figure Fig.6 :

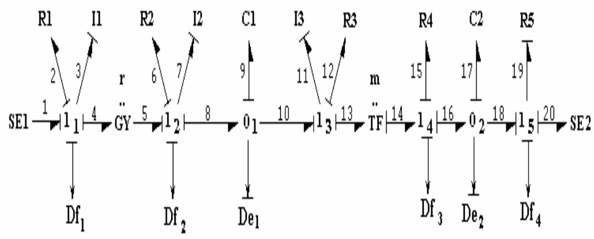

Fig.6 : Bond graph model of the system.

The instrumentation system includes 6 sensors: Df1 detector of electric current, Df2 detector of speed of rotation of the arm of the motor, De1 detector of couple of the motor, Df3 detector of the flow liquid entering in the pipe, De2 detector of the pressure in the tank, Df4 detector of the flow liquid leaving the tank. By the exploitation of relations of structure of junction and elements constituting the bond graph model, and while following the affected causality and the set of the causal paths covered, analytic redundancy relations are given as follows:

$$ARR_1 = (R_1 + I_1 s) Df_1 + r.Df_2 - SE_1 \qquad (2)$$

$$ARR_2 = (R_2 + I_2 s) Df_2 - r.Df_1 + De_1 \qquad (3)$$

$$ARR_3 = \left(R_3 + I_3 s + m^2 R_4\right) Df_3 + m\left(De_2 - De_1\right) \qquad (4)$$

$$ARR_4 = R_5 Df_4 - De_2 + SE_2 \qquad (5)$$

With s is the operator of *Laplace*, *m* and *r* are respectively modules of transformation of the *TF* and *GY*. By these relations one can construct the table of signatures for set of actuators and sensors of the system as follows:

	SE_1	SE_2	Df_1	Df_2	Df_3	Df_4	De_1	De_2
ARR_1	**1**	**0**	**1**	**1**	**0**	**0**	**0**	**0**
ARR_2	**0**	**0**	**1**	**1**	**0**	**0**	**1**	**0**
ARR_3	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**1**
ARR_4	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**1**

Table 1 : Faults signatures of the supervised component.

One remarks from this table that the components (Df1, Df2) have the same fault signature, as well as for components (SE2, Df4), what returns the isolation of faults that they affect very difficult. To solve this problem it is necessary to pass (step 4) to the other relations of structure (junctions 0) remaining. It permits to deduce other redundancy relations, while putting possible the isolation of these considered components.

$$ARR_5 = (C_1 s) De_1 + \frac{1}{m} Df_3 - Df_2 \qquad (6)$$

$$ARR_6 = (C_2 s) De_2 + Df_4 - Df_3 \qquad (7)$$

The relation (6) permits to solve the problem of component isolation (Df1, Df2), whereas the relation (7) permits to make it for components (SE2, Df4).

ARR_5	**0**	**0**	**0**	**1**	**1**	**0**	**1**	**0**

ARR_6	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**1**

Table 2 : Additional faults signatures.

The paper [4] uses bond graphs in the same way as support of diagnosis of fault of the same system, after the passage to the state model. By comparison to the gotten up measures and when a fault is detected, the proposed procedure by [4] consists to cut up the bond graph model in subsystems (4 in this example) to compute a quantity called entropy information for every bond of cutout (here 4, 10 and 14), the smallest value of this quantity corresponds to the bond of division.

The procedure of diagnosis serves then to compare measures gotten up on values of variables of the division bond as well as values of elements of subsystems in the two senses of division with values of the model.

This procedure is considerably very slow for the diagnosis by comparison to the method proposed in this paper. Says otherwise, the method that we propose present being's interest a qualitative and symbolic character, adapted therefore well to a computer implementation.

On the supervision point of view this method can be extended to the detection and the localization of faults affecting components of the model (R, C and I) by the use of the constituent relations of these components as support of analytic redundancy relations generation.

Well that we worked in the single energy domain, the method of supervision by bond graph can be used in multi energy domains where components and the bonds link are multi ports and strongly nonlinear.

6 Conclusion

No one can ignore the necessity of the monitoring of the complex industrial processes. The bond graph tool by its multidisciplinary character, replies to the industrial requirements as being a method of modelling, of simulation, of monitoring and even a tool of the design of control laws.

This paper illustrates the industrial application of this tool for the fault detection and isolation of sensors and actuators. This approach is based on the generation of analytical redundancy relations from the bond graph model of the system to supervise.

In views we wish firstly to extend this method to supervise complex systems with coupled energy as those in genius of processes. Secondly, this study permits to open a fruitful research horizon in the integration of the bond graph tool in a decision making system in view of to localize and to diagnose the shortcomings.

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