FLATNESS FOR ACTUATORS MONITORING:
APPLICATION IN PROCESS ENGINEERING DOMAIN

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Abstract: Process engineering systems encountered in many risky industries (nuclear, chemical…) are complex because of their multidomain energy character. Actuators are the main elements for their control design. They need for their safety a monitoring system. The monitorability model based analysis (ability to detect and to isolate an actuator fault) is based on the structured residual analysis using analytical redundancy or covering causal path based on bond graph methodology. The present paper proposes a new approach based on flatness topology for actuator monitorability analysis. The developed approach is illustrated by a thermofluid application (a non-linear multienergy system).

Keywords: Bond graphs, Multiport, Structural analysis, Flatness, Fault Detection and Isolation (FDI).

1. INTRODUCTION

Actuators are complex and non linear systems characterized by the coupling of several energies (thermal (heater), electrical, mechanical,...). Furthermore, the complexity of modern plants makes them more sensitive to failures. The safety and availability of these plants depends on Fault Detection and Isolation (FDI) procedures, consisting of the comparison between actual behavior of the system (provided by the sensors) with reference behaviors describing the normal operation (for fault detection) or different kinds of faulty ones (for fault isolation/estimation).

One of the most frequently used approaches in the monitoring domain is redundancy, which consists in finding the over determined system variable values by different ways and checking if all the results coincide. This redundancy may be either physical or analytical. The first one is easy to apply and very reliable, but is expensive and cumbersome (Brunet *et al*., 1990). Analytical redundancy aims to find relations between the known variables of the system (Declerck and Staroswiecki, 1992; Cocquempot, 1993). Comparing with any classical model based methods, the Bond Graph (BG) tool allows the Analytical Redundancy Relations (ARRs) to be determined directly from the BG before writing the equations describing the system.

For the actuator and sensor faults diagnosis, the BG use for the design and the improvement of instrumentation architecture has already delivered interesting results based on the linearized models (El Osta *et al*., 2004 (a)). The proposed methods allow the diagnosability study with no need to generate the ARRs. For components monitoring in industrial processes, the reader may refer to (El Osta *et al*., 2004 (b)). However, in the non-linear case, the detection and isolation of faults on actuators is based on signature matrix deduced from a complex calculation of ARRs. Based on a quantitative bond graph approach, the developed FDI procedure concerns the monitoring of actuators (control sources) in non-linear systems. The innovative interest of the paper consists in the diagnosability (ability to detect and isolate faults) analysis using flatness without the ARRs generation. Indeed, flatness topology makes a valuable contribution to the system-monitoring domain of flat models. It will be shown how a well instrumentation architecture design, i.e., a well placement of sensors, assures in a generic way the diagnosability of actuators. In fact, placing sensors on flat outputs provides better insight into the effect of actuator faults and consequently their diagnosability can easily be analyzed.

The paper is organized as follows: after the description of the developed methodology in the second section, the following one treats the case of thermofluid systems, where the monitored process is a complex non linear model combining thermal and hydraulic energies. Finally, this approach is applied to a thermofluid system of three tanks in order to analyze the isolation ability of the actuators considered in bond graph methodology as control sources. In (Achir *et al.*, 2003) a new point of view of bond graphs in terms of differential algebra, modules and differential fields was introduced for the identification of flat outputs in non linear systems. While bond graphs seem to be well adapted for the study of flatness, further works should apply the existent techniques to identify flat outputs for coupled multienergy systems modeled by BGs.

2. FLATNESS FOR DIAGNOSABILITY IN THE NON LINEAR CASE

Different approaches for the design of FDI procedures have been developed, depending on the kind of knowledge used to describe the plant operation. One of them rests on the use of quantitative dynamical models, which lead to the determination of ARRs, allowing the real time monitoring. However, the ARRs generation is not easy for systems, where the monitored process is a complex non linear model combining several energies. Based on flatness theory introduced by (Fliess *et al.*, 1992; 1995), this section deals with the monitoring of actuators for flat systems. Recall some basic definitions:

Definition 1. A system $\dot{x} = f(x,u)$, $x \in R^n$, $u \in R^m$, is said to be flat if there exist m functions of the state variables (flat outputs), of the inputs and of theirs derivatives to an order $r \le n$ such that the state variables and the input variables can be expressed in terms of these flat output variables, meaning that there exist three mappings:

$$h : R^n \times \underbrace{R^m \times \ldots \times R^m}_{r+1} \mapsto R^m,\ \ \chi : \underbrace{R^m \times \ldots \times R^m}_{r} \mapsto R^n$$

$$and\ \ \vartheta : \underbrace{R^m \times \ldots \times R^m}_{r+1} \mapsto R^m$$

such that $y = h(x, u, \dot{u}, \ldots, u^{(r)})$, $x = \chi(y, \dot{y}, \ldots, y^{(r-1)})$ and $u = \vartheta(y, \dot{y}, \ldots, y^{(r-1)}, y^{(r)})$.

One major property of flat models is that the output, the state (first condition of flatness) and the input variables (second condition of flatness) can be parameterized without integrating any differential equations, in terms of the flat outputs and a number of their derivatives. This interesting property gave rise to many control applications and encourages using this property for the monitoring analysis and the control synthesis in nonlinear bond graph models. Consider the monitorability of actuators in non-linear systems, the next theorem can be stated based on the definition of a flat system:

Theorem 1. The m actuators (control sources) of a flat system are monitorable if we dispose of m sensors placed at flat outputs and if $m > 1$.

Proof. Two cases can be distinguished:

If $m = 1$ (we dispose only of one actuator), then the relation $u = \chi(y, \dot{y}, \ldots, y^{(r-1)}, y^{(r)})$ relates the control source to the flat output and its r derivatives and thus even by having a sensor measuring this output the actuator is not monitorable. In fact, this relation constitutes a basis of ARRs, and then any other analytic redundancy relation is proportional to this relation and does appear the same variables (source and sensor). Both variables will have the same signature and consequently are not monitorable.

If $m > 1$, we have at least two measured flat outputs, the relation $u = \chi(y, \dot{y}, \ldots, y^{(r-1)}, y^{(r)})$ constitutes a basis of ARRs allowing the isolation of an actuator fault because the signature of each actuator fault is different from the signatures of the other variables. Table 1 shows the corresponding signature fault matrix. "1" ("0") in the ith row and jth column means that the ith ARR (ARR$_i$) is sensible (not sensible) to the jth failure. u_j and $\underline{y}_j$ (j=1..m) designate respectively the jth element of the control source vector u and the jth output with its derivatives to the order $r_j \le n$. The Boolean failure signature vectors of control sources are all different, thus the failures which may affect them can be detected and isolated.

Table 1 Signature fault matrix

ARRs	u_1	u_2		u_m	$\underline{y}_1$	$\underline{y}_2$	$\underline{y}_m$
ARR$_1$	**1**	**0**	**…**	**0**	1	1	1
ARR$_2$	**0**	**1**	$\ddots$	$\vdots$	1	1	1
	$\vdots$	$\ddots$	$\ddots$	**0**	1	1	1
ARR$_m$	**0**	**…**	**0**	**1**	1	1	1

3. DIAGNOSABILITY IN THERMOFLUID PROCESSES

Dynamic models in process engineering are non-linear. The non linearities mainly result from coupling of different energies (thermal, chemical, mechanical,…). The bond graph as a multidisciplinary and unified language tool is well suited for the modeling purpose. The bond graph modeling methodology is based on the characterization of power exchange phenomenon in a system. Thermal and mechanical systems can be modelled by true bond graphs (Dauphin-Tanguy, 1999). However, the complexity of the thermodynamic phenomena requires a careful choice of the power variables. Indeed, in process engineering, true bond graphs introduce thermal effort variables of complex natures. They are not well adapted for simulation problems (they do not respect the simple conservation laws). Consequently, pseudo bond graphs are used (the product effort by flow is no more a power (Karnopp *et al.*, 1990)). However, the classical properties of true bond graphs stay available for pseudo bond graphs. The selection of power variables and constitutive relations for the different multiports in such process depends on the modeled physical phenomena (saturated, under saturated…) (Thoma and Ould-Bouamama, 2000). As power variables, the temperature T or the specific enthalpy h are used for the thermal effort variable e_T and the pressure P is used as the hydraulic effort variable e_H. The mass flow $\dot{m}$ is the hydraulic flow variable f_H and the thermal flow variable f_T is the thermal flow $\dot{Q}$ (for thermal conduction) or the enthalpy flow $\dot{H}$ (for thermal convection).

As illustration of the multienergy BG modeling let us consider the example illustrated by the three-tanks system disposed as shown in figure 1. The tank $\mathbf{C_1}$, filled by the mass flow $\dot{m}_1$, contains water heated by a warming resistance supplying an electric power $\dot{Q}$. The tank $\mathbf{C_2}$ is filled by the mass flow $\dot{m}_2$. The valves $\mathbf{R_1}$ and $\mathbf{R_2}$ are on-off valves.

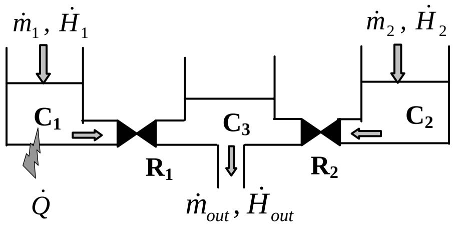


Fig. 1. Scheme of the system.

The nonlinear multienergy bond graph is drawn on figure 2. In the thermodynamic bond graph, the coupled power (hydraulic and thermal) exchanged between two sub systems is indicated by small rings around the bonds and the junctions are vectorials. The "0" junctions are represented in vectorial form (underlined) to express a

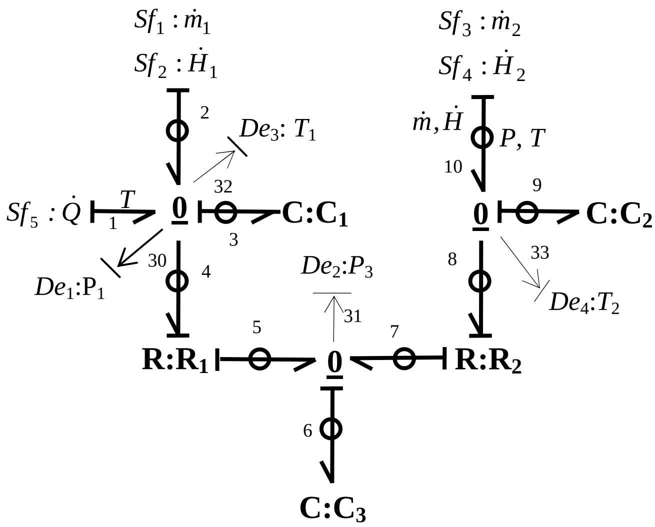


Fig. 2. Multienergy Bond Graph Model.

conservation law of energy in two forms (thermal and hydraulic). As the simple junction elements, the vectorial junctions are also power conservative. The storage item accumulators are modeled by **C** multiports and the valves by **R** multiports. While the thermofluid sources (sources by convection) are modeled in vectorial way, the thermal sources by conduction participate only in the thermal balance (for more details, see (Thoma and Ould-Bouamama, 2000)). Let u_H, u_T, y_H^{flat} and y_T^{flat} be respectively the vector of hydraulic inputs, thermal inputs, hydraulic flat outputs and thermal flat outputs. Consider the under saturated case, where only hydraulic sub model Σ_H can influence thermal sub model Σ_T (figure 3), an interesting result can be stated:

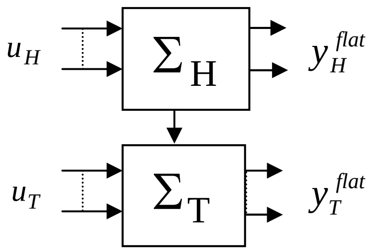


Fig. 3. Coupled power exchange (hydraulic-thermal).

Theorem 2. (Under Saturated Regime) A well-insulated thermofluid system of order 2*n* is flat if and only if the sub hydraulic model of order *n* is flat (*n* is the number of potential storage elements, tanks for instance). In this case, the thermal flat outputs are those placed at heated tanks.

Sufficient Condition: Any thermofluid process can be considered as interconnected components. Consider a well-insulated thermofluid system of order 2*n*, the state vector $x = (x_H, x_T)^t$ is associated to the storage plant items (the existent *n* accumulators), where x_H and x_T are respectively the vector of the stored mass variables and the enthalpy variables in the *n* accumulators. If the hydraulic model is flat, there exists a flat output vector at the hydraulic level $y_H : y_H^{flat}$ verifying equation (1) with $r \le n$.

$$x_H = \chi_H(y_H, \dot{y}_H, ..., y_H^{(r-1)})$$
$$u_H = \vartheta_H(y_H, \dot{y}_H, ..., y_H^{(r-1)}, y_H^{(r)}) \tag{1}$$

In the thermodynamic BG, the state variables of an accumulator *i* are related by equation (2),

$$x_{iT} = x_{iH} C_P T_{iC} \tag{2}$$

where x_{iT}, x_{iH} and T_{iC} are respectively the total stored enthalpy (H_{iC}), the stored mass (m_{iC}) and the temperature variables associated to the accumulator *i*. Based on expression (2) and definition (1), we conclude that the first condition of flatness for the thermal system is equivalent to express T_{iC} in terms of flat outputs for *i*(1..*n*). This is possible if one has a thermal sensor (a thermal flat output) at each accumulator heated by a thermal source (thermal source by conduction or convection).

In fact, considering the bond graph model of an accumulator (figure 4) one can write:

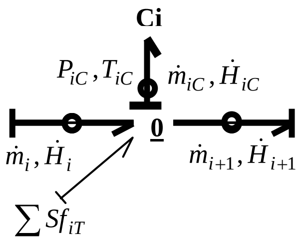


Fig. 4. BG model of an accumulator (integral causality).

$$\dot{x}_{iT} = \dot{H}_{iC} = \dot{H}_i - \dot{H}_{i+1} + \sum Sf_{iT} \tag{3}$$

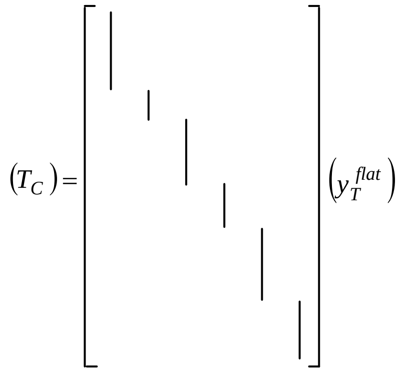
with:

- $\dot{H}_i$ the inlet enthalpy flow (thermal flow by convection) acting on the accumulator *i*:
  $$\dot{H}_i = \dot{m}_i C_P T_{i-1C}$$
- $\sum Sf_{iT}$ the sum of the thermal flow source variables by conduction or resulting from the external thermofluid sources (non installed in the circuit) acting on the *i* component
- $\dot{H}_{iC} = (\dot{m}_i - \dot{m}_{i+1}) C_P T_{iC}$ which represents the thermal energy stocked in the accumulator

This implies:

$$T_{iC} = \frac{\dot{m}_i C_p T_{i-1C} + \sum Sf_{iT}}{\dot{m}_i C_p} \tag{4}$$

For insulated accumulators; it is clear that without thermal sources, the temperature of the outflow is equal to that of the inflow. Among the *n* existent accumulators, consider that only *q* are thermally actuated $(q \le n)$. By associating the *q* thermal flat outputs ($y_T : y_T^{flat} \in R^q$) to the temperatures of the heated accumulators, one would be able to determine T_{iC} in terms of the thermal flat outputs for $i(1..n)$. The matrix relating the thermal sensors to the vector of temperature T_C has the form:



where the segments indicate the placement of values 1. Using equations (2) and (4), one obtains:

$$x_T = \Psi(y_H, \dot{y}_H, ..., y_H^{(r-1)}, y_T) \tag{5}$$
$$u_T = \sum Sf_{iT} = \Theta(y_H, \dot{y}_H, ..., y_H^{(r)}, y_T, \dot{y}_T) \tag{6}$$

with Θ and Ψ two nonlinear functions.

Necessary Condition: For the simple reason that the sub hydraulic model is independent from the thermal one in the under saturated case, it is obvious that if the sub hydraulic model is not flat the global system will not be.

Remark 1. In the thermodynamic BG, flat outputs can be easily expressed in terms of real sensors. In fact, all the state variables in process engineering can be expressed in terms of real sensors of different types (effort sensors are those associated to the pressure and the temperature in the tanks and the existent hydraulic flow sensor measures the hydraulic mass flow $\dot{m}$ across a valve or a pipe).

4. APPLICATION

4.1 Flatness for Actuators Monitoring

Consider the monitoring analysis of the actuators of the process shown on figure 1. Four cases can be treated whether the thermal flow by convection $\dot{H}_1$ ($\dot{m}_1 C_p T_1$, T_1 is the inlet temperature of tank 1) and $\dot{H}_2$ ($\dot{m}_2 C_p T_2$) are considered as dependent or independent variables (T_1 and T_2 are parameters or real actuators (control sources)). As illustration of the developed methodology, only two cases are considered:

Case 1 (T_1 and T_2 are parameters) In fact, the first case is considered if the temperatures of the inflows are constant. While the real actuators are in this case $Sf_1:\dot{m}_1$, $Sf_3:\dot{m}_2$ and the thermal flow by conduction $Sf_5:\dot{Q}$, we will verify that the flat outputs are:

$$y_1 = x_{1H} = m_{1C}\,,\ y_2 = x_{3H} = m_{3C} \text{ and } y_3 = x_{1T} = H_{1C}$$

The corresponding detectors De_1, De_2 and De_3 allow the measurement of the pressure (associated with the mass stored in tank $\mathbf{C_1}$ and $\mathbf{C_3}$) and of the temperature (associated with specific enthalpy h) of tank $\mathbf{C_1}$. Based on theorem 1, $Sf_1:\dot{m}_1$, $Sf_3:\dot{m}_2$ and $Sf_5:\dot{Q}$ are monitorable since we dispose of three sensors placed at the flat outputs.

Case 2 (T_1 and T_2 are control sources) In this case the corresponding flat outputs are:

$$y_1 = x_{1H} = m_{1C}\,,\ y_2 = x_{3H} = m_{3C}\,,\ y_3 = x_{1T} = H_{1C} \text{ and } y_4 = x_{2T} = H_{2C}$$

In this case a new flat output is introduced. The corresponding additional thermal sensor De_4 measures the temperature of tank $\mathbf{C_2}$. All the sensors are supposed to be ideal and are modeled by using signal bonds meaning that no power is transferred. A causality assignment precises the types of the sensors, in our case all sensors are of effort type. Based on theorem 1, all the considered actuators $\{Sf_1:\dot{m}_1$, $Sf_3:\dot{m}_2$, $Sf_2:\dot{H}_1$, $Sf_4:\dot{H}_2$, $Sf_5:\dot{Q}\}$ except $\dot{H}_1$ and $\dot{Q}$ are monitorable. In fact, $\dot{H}_1$ and $\dot{Q}$ are "redundant" (they provide the same function and represent physically one actuator).

One can check also that in both cases thermal flat outputs are those placed at the level of the heated accumulators according to theorem 2. In fact each of $\mathbf{C_1}$ and $\mathbf{C_2}$ are heated in the second case which explains the necessity to add a thermal sensor at $\mathbf{C_2}$ level.

4.2 Verification using the State Equations and the ARRs Generation

At the hydraulic level the state equations are written from the BG model (figure 2):

$$\begin{aligned}\dot{x}_{1H} &= \dot{m}_1 - K_1\sqrt{\frac{gx_{1H}}{A_1}-\frac{gx_{3H}}{A_3}}\\ \dot{x}_{2H} &= \dot{m}_2 - K_2\sqrt{\frac{gx_{2H}}{A_2}-\frac{gx_{3H}}{A_3}}\end{aligned}\qquad (7)$$

$$\dot{x}_{3H} = K_1\sqrt{\frac{gx_{1H}}{A_1}-\frac{gx_{3H}}{A_3}} + K_2\sqrt{\frac{gx_{2H}}{A_2}-\frac{gx_{3H}}{A_3}} - \dot{m}_{out}$$

K_1 and K_2 are the constant of the valves, A_1, A_2 and A_3 are the cross section of the tanks (considered uniform) and g is the gravity acceleration. Hydraulic flat outputs are $y_1 = x_{1H}$ and $y_2 = x_{3H}$.

Let $\varphi_{1/2}(y_i - y_j) = \sqrt{\frac{g.y_i}{A_i}-\frac{g.y_j}{A_j}}$

From equations (7):

$$\begin{aligned}\dot{m}_1 &= y_1 + K_1\varphi_{1/2}(y_1-y_2)\\ K_2\varphi_{1/2}(x_{2H}-y_2) &= \dot{y}_2 - K_1\varphi_{1/2}(y_1-y_2) + \dot{m}_{out}\end{aligned}\qquad (8)$$

One can find:

$$\Rightarrow x_{2H} = y_2 + \varphi_2\left(\frac{1}{K_2}(\dot{y}_2 - K_1\varphi_{1/2}(y_1-y_2) + \dot{m}_{out})\right) = F(y_1, y_2, \dot{y}_2)$$

This implies:

$$\begin{aligned}\dot{m}_2 &= \left(\frac{\partial F}{\partial y_1}\dot{y}_1 + \frac{\partial F}{\partial y_2}\dot{y}_2 + \frac{\partial F}{\partial \dot{y}_2}\ddot{y}_2\right) +\\ &K_2K_2\varphi_{1/2}(F(y_1,y_2,\dot{y}_2) - y_2) = G(y_1,\dot{y}_1,y_2,\dot{y}_2,\ddot{y}_2)\end{aligned}\qquad (9)$$

The flatness is therefore verified at the hydraulic level. According to theorem 1, while the sub hydraulic model is flat the global system will be. In fact, the thermal state equations are:

$$\begin{aligned}\dot{x}_{1T} &= \dot{H}_1 + \dot{Q} - K_1\sqrt{\frac{gx_{1H}}{A_1}-\frac{gx_{3H}}{A_3}}C_P\frac{x_{1T}}{x_{1H}}\\ \dot{x}_{2T} &= \dot{H}_2 - K_2\sqrt{\frac{gx_{2H}}{A_2}-\frac{gx_{3H}}{A_3}}C_P\frac{x_{2T}}{x_{2H}}\\ \dot{x}_{3T} &= K_1\sqrt{\frac{gx_{1H}}{A_1}-\frac{gx_{H}}{A_3}}C_P\frac{x_{1T}}{x_{1H}} +\\ &K_2\sqrt{\frac{gx_{2H}}{A_2}-\frac{gx_{3H}}{A_3}}C_P\frac{x_{2T}}{x_{2H}} - \dot{H}_{out}\end{aligned}\qquad (10)$$

Case 1: from equations (10):

$$\dot{Q} = y_3 + K_1\varphi_{1/2}(y_1-y_2)C_P\frac{y_3}{y_1} - \dot{H}_1 \qquad (11)$$

By using equation 2, the thermal state vectors can be obtained while calculating the temperature of each tank:

$$T_{1C} = y_3 \Rightarrow x_{1T} = y_1 C_p y_3$$

In fact, while the second accumulator is not heated one can write:

$$\dot{H}_2 = \dot{m}_2 C_P T_2$$

with $T_2 = T_{2C} = \dfrac{x_{2T}}{x_{2H}.C_p} \Rightarrow x_{2T} = x_{2H} \cdot \dfrac{\dot{H}_2}{\dot{m}_2}$

$$\Rightarrow x_{2T} = \frac{F(y_1, y_2, \dot{y}_2)}{G(y_1, \dot{y}_1, y_2, \dot{y}_2, \ddot{y}_2)} \cdot \dot{H}_2$$

T_{3C} can be calculated by writing the thermal energy equation at tank **C₃**:

$$((\dot{m}_1 - \dot{y}_1) + (\dot{m}_2 - \dot{F}) - \dot{m}_{out})C_P T_{3C} =$$
$$(\dot{m}_1 - \dot{y}_1)C_P T_{1C} + (\dot{m}_2 - \dot{F})C_P T_{2C} - \dot{m}_{out} C_P T_{3C}$$

This implies:

$$T_{3C} = H(y_1, \dot{y}_1, y_2, \dot{y}_2, \ddot{y}_2, y_3)$$

$$\Rightarrow x_{3T} = y_2 C_p H(y_1, \dot{y}_1, y_2, \dot{y}_2, \ddot{y}_2, y_3)$$

The ARRs given by equations (8), (9) and (11) show that the boolean signature vectors of the actuators are different which coincides with theorem 1. Consequently, all the considered actuators $Sf_1 : \dot{m}_1$, $Sf_3 : \dot{m}_2$ and $Sf_5 : \dot{Q}$ are monitorable.

Case 2: from equation (11):

$$\dot{H}_1 + \dot{Q} = y_3 + K_1 \varphi_{1/2}(y_1 - y_2) C_P \frac{y_3}{y_1} \quad (12)$$

$$\dot{H}_2 = \dot{y}_4 - A(y_1, y_2, \dot{y}_2) y_4 \quad (13)$$

The ARRs are now given by equations (8), (9), (12) and (13). The corresponding signature fault matrix is given in table 2. Among the considered actuators { $Sf_1 : \dot{m}_1$, $Sf_3 : \dot{m}_2$, $Sf_2 : \dot{H}_1$, $Sf_4 : \dot{H}_2$, $Sf_5 : \dot{Q}$ }, $\dot{H}_1$ and $\dot{Q}$ are not monitorable.

Table 2 Signature fault matrix

ARRs	$\dot{m}_1$	$\dot{m}_2$	$\dot{H}_1$	$\dot{H}_2$	$\dot{Q}$	$\underline{y}_1$	$\underline{y}_2$	$\underline{y}_3$	$\underline{y}_4$
ARR₁	**1**	**0**	**0**	**0**	**0**	1	1	0	0
ARR₂	**0**	**1**	**0**	**0**	**0**	1	1	0	0
ARR₃	**0**	**0**	**1**	**0**	**1**	1	1	1	0
ARR₄	**0**	**0**	**0**	**1**	**0**	1	1	0	1

5. CONCLUSION

The thermodynamic systems occur in many dangerous processes. The monitoring of such processes is consequently interesting. The classical methods are based on a complex generation of ARRs. The flatness, thanks to its property, is used in the present paper for monitoring of actuators of flat thermodynamic processes. For flat systems, the study of actuators monitoring becomes a question of finding the flat outputs. The method is applied to a three-tank thermofluid system. For a class of thermofluid processes, some of the flat outputs are easily fixed (thermal flat outputs) but not all, the further problem is to develop a technique that helps in finding flat outputs directly from a BG model.

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