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Energetic Approach to Parametric Fault Detection and Isolation

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***Abstract*— This paper concerned with the diagnosis and identification of parametric fault which may occur in a physical system. The method uses a bond graph system model to generate residual signals for fault diagnosis. Fault identification of system parameters is obtained by the analysis of the bond graph model topology.**

I. Introduction

Fault detection methods are becoming year by year of great importance in industry application, especially in robotic and mechatronic applications [8], because economical and human concerns as well.

Fault diagnosis and identification (FDI) literature has treated many approaches to diagnosis problem (i.e. to recognize that a *fault occurred somewhere* in the monitored system), starting from seminal papers on analytical redundancy by Willsky [11], [1], to more recent approach through parity space [5], and non–linear observer [4]. Furthermore, many authors have investigated the robustness of the fault detection algorithms ([7], [3]).

However, despite many results on fault detection, the problem of fault identification (i.e. find *where* is the fault), remains open to a large extent. In fact, model used in the analytical redundancy method has often low or none relation with the physical structure of the monitored system (i.e. it is often obtained from black box identification procedure) and, therefore, it is quite difficult to understand which physical system component has been damaged.

This paper investigates the fault detection and identification problem starting form a *physical model* of the real system, to directly detect any fault which can occur in system components. The authors believe that Bond Graph modeling formalism [9] is a natural candidate for describing real system for FDI purposes, as it preserves physical insights of system components.

Bond graph modeling is based on observation of energetic exchanges among system components, thus it can be applied to either linear or non-linear systems and to any physical domain (electrical, hydraulic, mechanical, etc.). The basic idea is to monitor any energetic variation in the system, searching for any energy modification which can be linked to a parameter variation (i.e. to a fault). Once the fault is detected, bond graph network topology is then exploited in order to identify the actual fault source.

The paper is organized as follows: in Sec.II we discuss the bond graph approach to system modeling; the fault detection and identification algorithm is developed in Sec.III. In Sec.IV we provide a simulative example in order to show the validity of our approach.

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II. Modeling Strategy

A. The Bond Graphs

In each physical domain there is a pair of dual variables (power conjugated variables) whose dual product gives the power. This pair of variables are generally called effort and flow. In the mechanical domain these variables are force and velocity, in the electrical one are voltage and current. The lumped parameters physical systems can be seen as an interconnection of three kind of elements:

- Elements storing energy
- Elements dissipating energy
- Sources of energy

The dynamics of a physical system are due only to the exchange of energy between the various components through the interconnection.

Bond graphs are a modeling language, introduced by [9] that takes directly into account the energetic properties of the physical system and that shows explicitly the network structure along which the various elements exchange energy. The power exchanges are represented by *bonds*: an effort and a flow are associated to each bond and their dual product represents the power exchanged through the bond. The network structure is represented by the interconnection of the various bonds by means of junctions, whose behavior is governed by Kirchhoff-like laws, and of energy preserving transformations (transformers, gyrators). The network structure can be mathematically represented by a Dirac structure [2],[10].

There are two kinds of elements storing energy: elements storing kinetic energy (inductors, masses, ...) and elements storing potential energy (capacitors, springs, ...). Each (and *only*) element which can store energy has a state associated to it and the structure of any storage element is the following (see fig. 1):

$$\begin{cases} \dot{x} = u \\ y = \dfrac{\partial E}{\partial x} \end{cases} \tag{1}$$

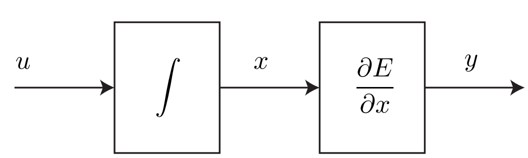


Fig. 1. Energy storing element behavior

where x is the state associated to the element, $E(x)$ is a lower bounded function defined on the state manifold and with real values which represent the stored energy, u is the input (an effort for the kinetic energy storing elements and a flow for the potential energy storing elements) and y is the output (dual to the input, a flow for the kinetic energy storing element and an effort for the potential energy storing element).

By using coordinates, we have that:

$$\dot{E} = (\frac{\partial E}{\partial x})^T \dot{x} = y^T u \tag{2}$$

Therefore the product $y^T u$ corresponds to the power delivered to the element and it is always the (dual) product of an effort and a flow.

Dissipation in the system is modeled by means of elements that fix an algebraic relation between flow and effort. No state is associated to these kind of elements and we have that:

$$P_{diss} = e^T f \geq 0$$

The relation established between effort and flow must be such that $P_{diss} \geq 0$ in order to model energy dissipation instead of energy injection.

Source of energy can be modeled in two ways: by means of sources of flow, which fix the flow to a certain value, and by means of sources of effort, which fix the effort to a certain value.

Summarizing, we can see a generic physical system as illustrated in fig. 2, in which half-arrowheads indicate the bonds, $\mathbb{I}$ indicates a kinetic energy storing element, $\mathbb{C}$ a potential energy storing element, $\mathbb{R}$ an energy dissipating element, $\mathbf{S}$ a generic source of energy which can be either source of effort or source of flow. $\mathcal{D}(x)$ represents the Dirac structure (the network interconnection) of the system which is usually state dependent.

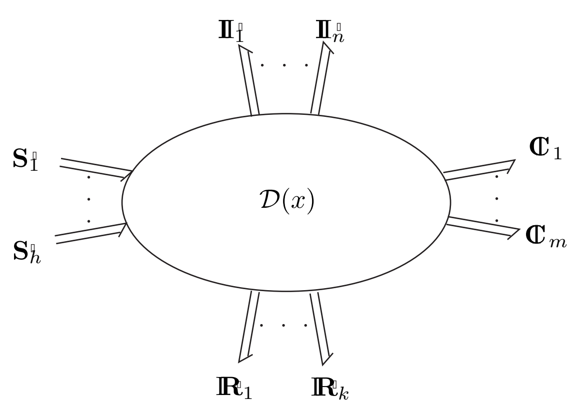


Fig. 2. Generic physical system

We can interconnect two physical systems through a *power port*. A power port is characterized by a vector space $\mathcal{V}$ and by its dual $\mathcal{V}^*$. We can therefore write:

$$P = V \times V^*$$

where $\mathcal{V}$ is the space of flows and $\mathcal{V}^*$ is the space of efforts.

B. The Port-Hamiltonian Formalism

Port-Hamiltonian formalism [10] is a very suitable way to formalize the bond graph model of a lumped parameters physical system. In the most general form, a port-Hamiltonian system can be described as:

$$\begin{cases} \dot{x} = (J(x) - R(x))\dfrac{\partial H}{\partial x} + G(x)u \\ y = G^T(x)\dfrac{\partial H}{\partial x} \end{cases} \tag{3}$$

where x is the state of the system, associated at the energy storages, $J(x)$ is a skew-symmetric matrix representing the Dirac structure of the system, $R(x)$ is a symmetric positive semidefinite matrix, representing the energy dissipation of the system and H is the energy of the system, which is a function of the state. The input u and the output y are power conjugated variables representing the system power port.

Between system input and output and the energetic behavior of the system there is the following relation:

$$\begin{aligned} \dot{H} &= (\frac{\partial H}{\partial x})^T \dot{x} = (\frac{\partial H}{\partial x})^T ((J(x) - R(x))\frac{\partial H}{\partial x} + \\ &+ G(x)u) = (\frac{\partial H}{\partial x})^T J(x)\frac{\partial H}{\partial x} - (\frac{\partial H}{\partial x})^T R(x)\frac{\partial H}{\partial x} + \\ &+ (\frac{\partial H}{\partial x})^T G(x)u = -P_{diss} + y^T u \end{aligned} \tag{4}$$

thus, we can write:

$$y^T u = P + P_{diss}$$

The main advantage of bond graph modeling language and, consequently, of the port controlled Hamiltonian formalism is that the physics of the system is directly taken into account. The parameters which appear in the energy function are physical parameters (masses, resistances, inductances,...). Furthermore, every physical system, even if it acts in more than one energetic domain (i.e. electrical motor), can be represented by a bond graphs model.

III. Parametric Fault Detection and Isolation

A. Problem Statement

Model parameters obtained through black box or grey box identification methods seldom correspond directly to well identified real system properties, making difficult the straightforward use of such model for fault identification.

In particular [6], since a fault on a single physical parameter could reflect in a change on several model parameters,

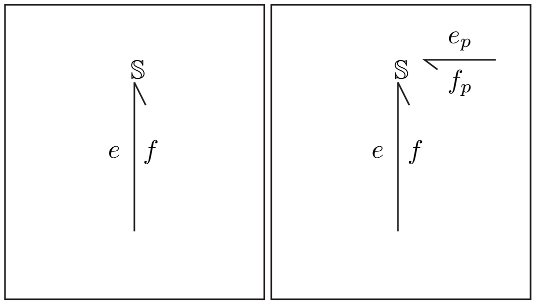
[hbp] 

Fig. 3. Energy Storing Elements

the fault identification algorithm should be able to detect multiple changes in the model parameters, referencing these changes to a single physical fault source.

On the other hands, parameters in the bond graph model corresponds directly to physical characteristics. Thus, we propose to tackle the parametric FDI problem starting by a bond-graph model since any detection of parametric variation can be directly linked to a fault in a physical system parameter. In the remaining part of the paper, we suppose the system state is available through direct measurement or by means of suitable state observer (see for example [12]).

B. Parametric fault from an energetic point of view

In a physical system parametric faults may affect elements which store or dissipate energy. In this case the parameter appear either in the energy expression of the storage elements or in the power dissipated function in case of dissipating elements. Fig. 3 shows the model a parametric fault, left picture and right corresponding to fault–free and faulty case, respectively. In the pictures $\mathbb{S}$ represents a generic element (either energy storing or energy dissipating).

The elements in figure interact energetically with the rest of the world through the power port by means of power conjugated variables effort e and a flow f. If such components store energy, they can be described as:

$$E = \int e^T f$$

E being the energy stored in the element. If the components dissipate energy, then:

$$P_{diss} = e^T f$$

where P_{diss} is the dissipated power.

In fault-free case, the bond graph model parameters are constant, otherwise, any variation in parameter values can be interpreted as a parametric fault. The right picture of fig. 3 shows a power port which models the fault (i.e. the parameters variation), by means of dual variables e_p and f_p. This variables have not a physical meaning, but they represent an "extra energy" in the system, which models the fault occurrence on a physical system parameter. As the power port (e_p, f_p) is not a real power port, but has been defined to represent the fault effect over the system, we name it *parameter port*.

C. A Fault Detection Strategy

Let us consider a port-Hamiltonian model of our physical system and consider the power port variables u and y as input and output respectively. From Eq.(4) it follows that:

$$\int y^T u dt = \int (P + P_{diss}) dt = H + H_{diss} \tag{5}$$

H and H_{diss} are the stored and the dissipated energy of the system in fault-free case. When a parametric fault occurs, quantity of "power" flows through the parameter ports. Since the parameter ports are not real, the energy flow due to the parametric fault is not directly measurable. However, when a parametric fault occurs, we can write:

$$\begin{aligned} &\int [y^T u + \textstyle\sum_{i=0}^{m} (e_{pi} f_{pi})] dt = \\ &= \int (\tfrac{\partial H_F}{\partial x} \dot{x} + \tfrac{\partial H_F}{\partial \theta} \dot{\theta} + P_{dissF}) dt = \\ &= H_F(x) + H_p(x) + H_{dissF}(x) \end{aligned} \tag{6}$$

where m represents the number of parameter power ports and e_p and f_p are the power variables relative to the ports; the subscript F refers to to faulty case.

The term $\frac{\partial H_F}{\partial \theta}\dot{\theta}$ in Eq.(6) represents some extra power coming from the parameter ports because of the parameters variation. Therefore, considering only the input u and the output y we have that:

$$\int u^T y = H_F(x) + H_{dissF}(x) \tag{7}$$

H_F and H_{dissF} are different from the nominal energy and dissipated energy functions since parameters changed. Though, by the knowledge of the model, we can compute nominal values for functions $H(x)$ and $H_{diss}(x)$ corresponding to the parameters nominal values.

In case of any parametric fault we will have that the following *parametric fault detection condition* holds.

$$\int y^T u dt \neq H(x) + H_{diss}(x) \tag{8}$$

We detect the action of the parameter ports simply looking at the energetic behavior of the power port (u, y).

It's noteworthy that no assumption has been made on the parametric fault, and both abrupt and slow parameters variations can be detected.

D. A Fault Identification Strategy

Physical parameters, in a bond graph model, can be associated either to energy storing elements or to dissipating elements. Using the port-Hamiltonian formalism to represent the system, we can show that the parameters can enter either in the energy function (in the term $\frac{\partial H}{\partial x}$) or in the dissipation matrix $R(x)$.

Each element storing energy, which it is always associated a system state, is directly connected to a junction. Thus, a variation of a parameter caused by a fault directly influences the energetic flow through the associated junction and, therefore, the behavior of the correspondent state variable.

On the other hand, each dissipative element is connected to a 1-junction and, therefore, a fault on its associated parameter influences the value of the associated states.

Therefore in order to detect the origin of the fault, we design a procedure seeking in the bond graph model for any possible influence of a physical parameter fault over a system state variation, allowing so the identification of the occurred fault. The deliverable of the procedure is a "fault isolation signature table" showing the relations between each fault and the states of the system. It's noteworthy to remark that multiple faults could not be separately identified, however they still detectable.

In order to actually isolate the parametric fault, we compute the energy function $H(x)$, its partial derivative $\frac{\partial H}{\partial x}$ and the dissipation matrix $R(x)$ with the nominal value of the parameters. In fault-free case, the computed state matched with the real state of the system, otherwise, if there is a fault on system parameter, the behavior of the state involved is different with respect to the computed one. Thus, using the isolation signature table, we can identify which parameter has changed.

We can summarize the Isolation strategy by the following algorithm:

1) Compute $H(x)$, the energy of the system, with nominal parameters.

2) Compute $\frac{\partial H}{\partial x}$.

3) Compute $R(x)$, the dissipation matrix, with nominal parameters.

4) From the topology of the Bond Graph model obtain which states are directly influenced by each parameter variation, taking into account that
   - If the physical element associated to the parameter is a dissipative one, the influenced state is the one attached to the same 1-junction to which is connected the dissipative element.
   - If the physical element associated to the parameter is an energy storing one, the influenced states are the ones relative to the junctions directly connected (disregarding any transformers or gyrators along the interconnection) to the one of the state associated to the faulty parameter.

5) Build a table (*Isolation Table*) which associate to each possible parametric fault the states influenced by it.

6) Calculate x_H, the state in case of nominal value of the parameters, by means of the Hamiltonian model of the system using $\frac{\partial H}{\partial x}$ and $R(x)$ obtained at points 2. and 3.

7) Compare x, the real state of the system, with x_H and, by means of the table obtained in 5. isolate the fault.

Fig. 4 shows the proposed FDI strategy. Using input and output system measurements u and y, we calculate functions $H + H_{diss}$. On the other hand, we calculate again quantity $H + H_{diss}$ using system state obtained (for example) from a state observer, using the nominal values of the parameters (whence the subscript H, healthy, namely with no faults on parameters). Residuals R_d are obtained by comparing these two variables; a fault is detected if the residual is greater than zero.

Fault identification is achieved using the nominal state value (no fault) x_H, which is compared to the actual state. Then we use an Identification Logic function to compare the real and computed states and to isolate the fault taking into account the isolation table.

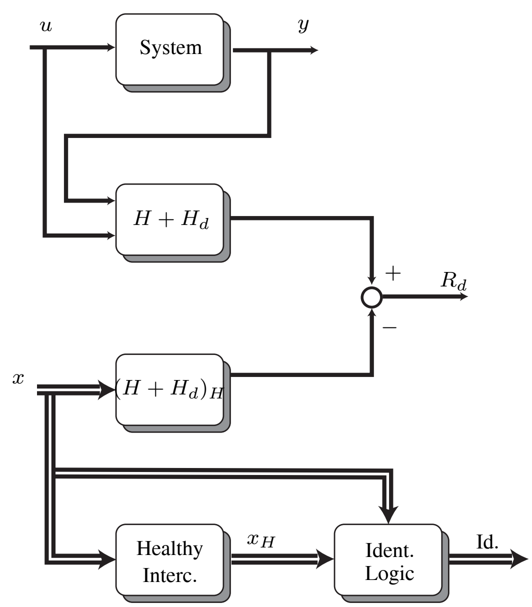


Fig. 4. The FDI strategy

IV. An Example: DC motor

This section reports a simulation example of the proposed methodology applied to the parametric fault diagnosis and identification in a DC motor. The equations governing the behavior of the system are:

$$\begin{cases} V_a = R_a i_a + L_a \dfrac{di_a}{dt} + k\phi_e \omega \\ \\ V_e = R_e i_e + L_e \dfrac{di_e}{dt} \\ \\ J\dot{\omega} = k\phi_e I_a - b\omega \end{cases} \tag{9}$$

In order to apply our strategy we build a bond graph model of the system, which is illustrated in Fig.5.

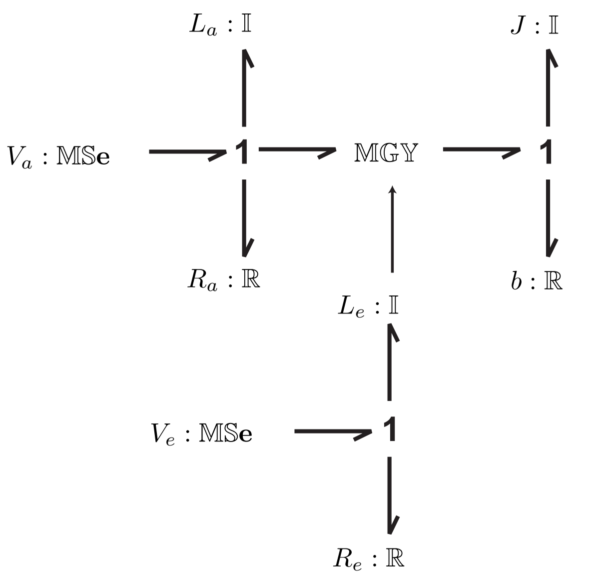


Fig. 5. Bond graph model of a DC motor

The model of the system in a port-Hamiltonian formalism can be easily deduced and it is:

$$\begin{cases} \begin{bmatrix} \dot{\phi}_a \\ \dot{\phi}_e \\ \dot{p} \end{bmatrix} = \left(\begin{bmatrix} 0 & 0 & -k\phi_e \\ 0 & 0 & 0 \\ k\phi_a & 0 & 0 \end{bmatrix} - \begin{bmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & b \end{bmatrix} \right) \begin{bmatrix} \frac{\phi_a}{L_a} \\ \frac{\phi_e}{L_e} \\ \frac{p}{m} \end{bmatrix} + \\ + \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_a \\ V_e \end{bmatrix} \\ \\ y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \frac{\phi_a}{L_a} \\ \frac{\phi_e}{L_e} \\ \frac{p}{m} \end{bmatrix} \end{cases} \tag{10}$$

The system has three elements storing energy (two inductors and the mechanical load) and three elements dissipating energy (two resistors and the mechanical friction on the load). The energy stored in the system is:

$$H(x) = \frac{\phi_a^2}{2L_a} + \frac{\phi_e^2}{2L_e} + \frac{p^2}{2J}$$

and the energy dissipated by the system is:

$$H_d = \int [R_a(\frac{\phi_a}{L_a})^2 + R_e(\frac{\phi_e}{L_e})^2 + b(\frac{p}{J})^2]dt$$

where ϕ_e and ϕ_a are the magnetic fluxes of the circuits and p is the momentum of the load.

The power port by means of which we can interact with the system is characterized by an input (V_a, V_e) and an output (i_a, i_e). We generate the detection residual by means of:

$$R_d = (\int (V_a i_a + V_e i_e)dt) - (H(x) + H_d(x)) \tag{11}$$

where $H(x)$ and $H_d(x)$ are the expressions of the energy stored and of the energy dissipated respectively, obtained as function of the state and computed with nominal values of the parameters.

In order to isolate faults, we build a table in specifying the states whose behavior is directly affected by a certain parametric faults. We can immediately deduce from the bond graph which states are affected by faults on parameters, leading to construct the following isolation table:

Fault on	affects states
R_a	ϕ_a
R_e	ϕ_e
b	p
L_a	p ϕ_a
J	p ϕ_a
L_e	ϕ_e

TABLE I

THE CORRESPONDENCE BETWEEN POSSIBLE FAULTS AND SYSTEM STATE.

We simulated a fault on the mechanical damper. We suppose that the damper value changes from $0.5Nsec/m$ to $1Nsec/m$ at time $T = 3.5sec$. Simulation results are shown by Fig.6.

Fig. $6{-}a)$ shows residual signal R_d calculated using Eq.(11). We can see that the residual becomes greater than zero when the damping parameter changes and, therefore, the parametric fault is detected.

In order to isolate the parametric fault we compute *on-line*, the state of the system using the nominal values of the parameters by using the port-Hamiltonian model.

Figures $6{-}b)$, $-c)$ and $-d)$ show by continuous line the real states of the system and by dashed line the states computed using the nominal values of the parameters.

If there were no fault the real and computed state would coincide while in case of fault at least the behavior of one state is different from the behavior of the calculated one. We can see that the real states ϕ_a and ϕ_e are the same as the computed ones while the real state p is different. From the Table (I) it can be obtained that the fault affects the damper.

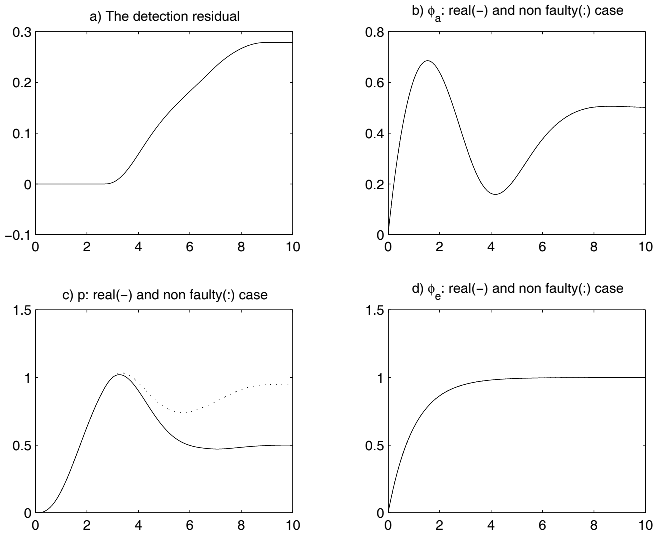


Fig. 6. Simulation results

V. Conclusions and Future Work

This paper concerned with a parametric fault detection and isolation in physical systems. The method is based on bond graphs models and energetic behavior analysis in order to exploit directly the physical properties of the system and the information of the inner structure of the system that the network structure of the bond graph model provide us. Using this approach we are able to detect and isolate the faults on the physical parameters of the system.

The future work will be concerned with a robust implementation of the algorithm with respect to measurement noise and model uncertainties and to test the methods in real applications.

Furthermore we would like to extend the energetic approach for sensors and motors fault. Indeed the condition expressed by Eq.(8) for the detection of a fault is still valid in case of a motor gets stuck and gives a constant torque or a sensor gives a constant output because of fault. Both these situation can be seen as an energetic inconsistency between the port behavior and the states of the system. A proper fault isolation algorithm has to be found.

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