Robust Diagnosis of a DC Motor by Bond Graph Approach

Abderrahméne Sallami, Nadia Zanzouri and Mekki Ksouri

Laboratory ACS, Department of Electrical Engineering, Box 37, 1002 Tunis Belvedere, Tunisia

Abstract: In this article, a Bond Graph (BG) approach is used for modeling, simulation and robust diagnosis of a DC Motor. The design and calculation of an observer is achieved by using graphical methods taking advantage of the structural properties of bond graph model. Simulation results are used to show the dynamic behavior of the system variables and assessing the performance of the observer. A modeling Bond Graph form Linear Fractional Transformations (BG-LFT) to generate constituted Analytical Redundant Relationship (ARR) two parts perfectly separated: A nominal portion denotes the residual and an uncertain part, which serves both to the calculation of adaptive thresholds for normal operation and to sensitivity analysis.

Keywords: Bond Graph, Robust Diagnosis, DC Motor, Linear Fractional Transformations, Analytical Redundant Relationship

Introduction

The diagnostic system is primarily intended to issue alarms which aims to draw attention of the supervising operator of the occurrence of one or more events that could affect the proper functioning of the installation.

Given the complexity of the processes, the generation of alarms is the most used way to alert the operator of the occurrence of an "abnormal" event. Alarms are related to malfunctions that may appear on the production system. It is important to clarify the meaning given to the words used to evoke the malfunctions that may occur in the system. We retain, for this, the definitions in (Basseville et al., 1987; Anguilar-Martin, 1999; Cassar et al., 1994; Graishym, 1998; Ploix, 1998; Maquin and Ragot, 2000; Karnopp and Rosenberg, 1983).

These industrial systems are governed by multiple physical phenomena and various technology components, so the Bond Graph approach, based on an energy analysis and multi-physics, is well suited. The Bond Graph modeling tool was defined by Paynter (1961). This approach allows energy to highlight the analogies between the different areas of physics (mechanics, electricity, hydraulics, thermodynamics, acoustics, etc. . .) and represent in a uniform multidisciplinary physical systems (Paynter, 1961; Dauphin-Tanguy, 2000; Ould Bouamama and Dauphin-Tanguy, 2005; Tagina, 1995; Azmani and Dauphin-Tanguy, 1992; Karnopp, 1979; Gawthrop and Smith, 1995; Roberts et al., 1995; Rahmani et al., 1994; Sueur and Dauphin-Tanguy, 1989; Sueur, 1990). The diagnosis of uncertain systems has been the focus of much research work in recent years (Djeziri, 2007; Djeziri et al., 2009). This interest is reflected in the fact that natural systems are complex and non-stationary and manufacturers seek greater safety and efficiency. The Bond Graph approach proposed in this article allows, for its energy structure and multi physics, to use a single tool for modeling, structural analysis and generation of uncertain ARR.

In this study we try to show how the Bond Graph model can be used for modeling, simulation and construction of observers of linear and nonlinear systems (next section) on the one hand and on the other hand the construction of the system elements to be analyzed by bond graph elements as LFT to generate RRAS consist of two parts perfectly separated: A face portion, which is the residue and an uncertain part, which serves both to the calculation of adaptive thresholds for normal operation and sensitivity analysis.

Robust Diagnosis by Bond Graph Approach

Bond Graph Model

Two methods are proposed by Sueur (1990) to build parametric uncertainty by BG. The first is to represent uncertainty on bond graph element as another element of the same type, causally linked to the nominal element (Fig. 1) or the rest of the model. These uncertainties are kept in derivative causality when the model is preferred in integral causality not change the
order of the model. The second method is the LFT form (Linear Fractional Transformations) introduced on mathematical models Redheffer (1994).

The physical aspect of the multi-hop graphs comes from the fact that from any physical system, it is possible to obtain an independent graphical representation of the studied physical realm. Building a bond graph model can be done in three levels:

- The technological level
- The physical level
- The structural and mathematical

![Fig. 1. Representation BG with the nominal element](image)

- Storage elements: potential (C) or inertial (I)
- Dissipation elements: R
- Junction elements: parallel (0), serial (1), transformation and gyrator
- Sources elements: Sources effort or sources flow
- Detectors elements: Detectors effort or detectors flow

**LFT Representation**

Linear Fractional Transformations (LFTs) are very generic objects used in the modeling of uncertain systems. The universality of LFT is due to the fact that any regular expression can be written in this form after Oustaloup (1994; Alazard et al., 1999). This form of representation is used for the synthesis of control laws of uncertain systems using the principle of the μ-analysis. It involves separating the nominal part of a model of its uncertain part as shown in Fig. 2.

Ratings are aggregated into an augmented matrix denoted \( M \), supposedly clean and uncertainties regardless of their type (structured and unstructured parametric uncertainties, modeling uncertainty, measurement noise ...) are combined in a matrix structure \( \Delta \) diagonal. In the linear case, this standard form leads to a state representation of the form (1):

\[
\begin{align*}
  x &= Ax + B_1 w + B_2 u \\
  z &= C_1 x + D_{11} w + D_{12} u \\
  y &= C_2 x + D_{21} w + D_{22} u
\end{align*}
\]

With:
- \( x \in \mathbb{R}^n \): System state vector
- \( u \in \mathbb{R}^m \): Vector grouping system control inputs
- \( y \in \mathbb{R}^p \): Vector grouping the measured outputs of the system
- \( w \in \mathbb{R}^l \) et \( z \in \mathbb{R}^l \): Respectively include inputs and auxiliary outputs. \( n, m, l \) and \( p \) are positive integers

The matrices \( (A, B_1, B_2, C_1, C_2, D_{11}, D_{12}, D_{21} \text{ and } D_{22}) \) are appropriately sized matrices.

**BG Modeling Elements by LFT Representation**

Modeling linear systems with uncertain parameters was developed in C. Sie Kam, we invite the reader to view the references for details on the modeling of uncertain BG components (R, I, C, FT and GY) Fig. 3. We therefore limit this part to show the two methods of modeling uncertain BG elements and the advantages of BG-LFT for robust diagnosis.

Full BG-LFT can then be represented by the diagram in Fig. 3.

![Fig. 2. Representation LFT for physical system](image)

![Fig. 3. Representation of BG-LFT](image)
Generate Robust Residues

The generation of robust analytical redundancy relations from a clean bond graph model, observable and over determined be summarized by the following steps:

1st step: Checking the status of the coupling on the bond graph model deterministic preferential derived causality; if the system is over determined, then continue the following steps

2nd step: The bond graph model is made into LFT

3rd step: The symbolic expression of the RRA is derived from equations junctions. This first form will be expressed by:

- For a junction 0:
  \[ \sum b_i f_i + \sum Sf + \sum w_i \]
  \[ (2) \]

- For a junction 1:
  \[ \sum b_i c_i + \sum Se + \sum w_i \]
  \[ (3) \]

With the sum \( \Sigma Sf \) of sources flows due to the junction 0, the sum \( \Sigma Se \) of the sources of stress related to junction 1, \( b = \pm 1 \) at the half-arrow into or out of the junction, and \( e \) in and \( f \) in purpose are unknown variables, the sum \( \Sigma w_i \) of modulated inputs corresponding to the uncertainties on the junction-related items:

4th Step: The unknowns are eliminated by browsing the causal paths between the sensors or sources and unknown variables

5th step: After eliminating the unknown variables, are uncertain as \( \text{RRA}_s \):

\[ \text{RRA}: \Phi \left\{ \sum Sc, \sum Sf, De, Df, De, Df, \right\} \]

\[ \sum w, R, I, C, TF, GY \]

- \( TF \) and \( GY \) are the nominal values of the elements and modules, respectively \( TF \) and \( GY \)
- \( R, C \) and \( I \) are the nominal values of the elements \( R, C \) and \( I \)

Analysis of Residuals Sensitivity

Analysis of residuals sensitivity has been developed in recent years. Indeed, the methods are proposed to evaluate these residuals. When residuals are assumed normal around a known average statistical methods to generate normal operating thresholds are well suited (Basseville et al., 1987). In the event that the uncertainty does not operate at the same frequency as defects, filtering methods are suitable property (Han et al., 2002). While the actuators and sensors faults are determined using parity space (Henry et al., 2001; Henry and Zolghari, 2006). Unfortunately, these residues generation methods are not effective since they neglect the inter-parametric correlation (the thresholds are often overvalued and may differ).

The Bond Graph tool provides an effective solution to the problem of parametric dependencies since the generation BG-LFT automatically separates tailings and adaptive thresholds.

Generation of Indices Performance

To improve diagnostic performance, determine the indices performance (sensitivity index and defect detectability index).

**Index Sensitivity (IS)**

The index of parametric standardized sensitivity explained the evaluation of the energy provided by the residue uncertainty on each parameter by comparing it with the total energy provided by all uncertainties:

\[ IS = \left[ \frac{\partial \varphi}{\partial a_i} \right] \left[ \frac{\partial d}{\partial w_i} \right] \]

\[ (4) \]

- \( a_i \): Uncertainty on the parameters
- \( i \in \{ R, C, I, TF, GY \} \)
- \( w_i \): Modulated entry for Uncertainty in the \( i \)th parameter

**Index Defect Detectability (ID)**

The index defect detectability index represents the difference between the efforts (or streams) provided by defects in absolute terms and that granted by all the uncertainties in absolute value:

Junction 1:

\[ ID = [\| f_{1i} \| + 1] - d \]

\[ (6) \]

Junction 0:

\[ ID = [\| f_{1i} \| + 1] - d \]

\[ (7) \]

While defects detectability conditions will be:

- Undetectable fault: \( ID \leq 0 \)
- Undetectable fault: \( ID > 0 \)

Robust Diagnosis of DC Motor by Bond Graph Approach

**Bond Graph Model of DC Motor**

Consider the circuit diagram of a DC motor and its bond graph model given in Fig. 4. On this system, we will detect and locate defects in the flow sensors (current by sensor \( D_f \) and speed by sensor \( D_f \)).

Figure 5 shows the waveform of the current absorbed by the motor (a) and rotational speed of the motor (b).
Abderrahmine Sallami et al. / American Journal of Engineering and Applied Sciences 2016, 9 (2): 432-438
DOI: 10.3844/ajeassp.2016.432.438

Fig. 4. (a) DC motor, (b) Bond Graph model of DC motor

Fig. 5. (a) Current of the DC motor, (b) Speed of the DC motor DC motor

Fig. 6. Residual $r_1(t)$ in the normal operation, Residual $r_2(t)$ in the normal operation
Figure 6 shows the shape of the residues $r_1$ and $r_2$ in the case of normal operation. We note that residues paces converge to zero.

The Fig. 7 shows the modeling of the DC motor by the bond graph approach with two detectors, the current sensor ($Df_1$) and the speed sensor ($Df_2$).

The Fig. 8 below shows the bond graph model in integral causality of the system using the LFT form. To determine the residues, we must put the system in the form derivative and also put sensors under dualized form (Fig. 9).

We have introduced two four parametric defects ($Y_L$, $Y_R$, $Y_J$ and $Y_b$) and structural defects ($Y_{s1}$ and $Y_{s2}$)

**Simulation of the DC Motor**

The simulation of the current and the speed of the DC motor by the software 20-sim intended for industrial systems modeled by the bond graph approach in Fig. 4.

**The Equations BG Model before Default**

Junction 1:

$e_2: SSf_i \to \Psi_{fo}(f_8, e_8) \to e_2 = R_n . SSf_i$

$e_3: SSf_i \to \Psi_{fo}(f_1, e_1) \to e_3 = L_n . SSf_i$

$e_4: SSf_i \to \Psi_{gi}(f_3, e_3) \to e_4 = m . SSf_2$

The ARR1 equation before default can be written:
Conclusion

The choice of the LFT form for modeling with parametric uncertainties the bond graphs allowed to use a single tool for the systematic generation of indicators formal uncertain defects. These parametric uncertainties are explicitly introduced on the physical model with its graphics architecture, which displays clearly on the model of their origins.

Uncertain ARR generated are well structured, showing separately the contribution Energy uncertainties fault indicators and facilitating their evaluations in the step of decision by the calculation of adaptive thresholds for normal operation. The diagnosis performance is monitored by an analysis of the residues of sensitivity to uncertainties and defects. The defect detectability index is defined to estimate a priori detectable value of a default and to measure the impact of default on an industrial process. The parametric sensitivity index is used to determine parameters that have the most influence on the residues. From a practical standpoint, the fields of application of this method are very broad due to the energy aspect and multi physics of bond graphs and the LFT form used to model the influence of uncertainties about the system. The developed procedure is implemented on a software tool (controllab products 20-sim version 4.0) to automate the generation of LFT models and uncertain ARR.

Acknowledgment

We thank the National School of Engineers of Tunis, University of Tunis El Manar to support our work.

Financing Information

The author support or funding to report.

Author’s Contributions

Abderrahmene Sallami: Author made considerable contributions and design, analysis and data interpretation.

Nadia Zanzouri: Author contributes to the review of article critical of his important intellectual content.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of other authors have read and approved the manuscript and no ethical issues involved.

References

Alazard, D., C. Cumer, P. Apkarian, M. Gauvrit and G. Fereres. 1999. Robustesse et Commande Optimale. 1st Edn., Cépadues-Editions, Toulouse, ISBN-10: 2854285166, pp: 348.
Anguilar-Martin, J., 1999. Knowledge-based supervision and diagnosis of complex process. Proceedings of the IEEE International Symposium on Intelligent Control/Intelligent Systems and Semiotics, Sept. 15-17, IEEE Xplore Press, Cambridge, MA., pp: 255-230. DOI: 10.1109/ISIC.1999.796659

Azmani, A. and G. Dauphin-Tanguy, 1992. ARCHER: A Program for Computer Aided Modelling and Analysis. In: Bond graph for Engineers, Dauphin-Tanguy, G. and P. Breedveld (Eds.), Elsevier Science Pub, pp: 263-278.

Basseville, M., A. Basseville, G. Moustakides and A. Rougé, 1987. Detection and diagnosis of changes in the eigenstructure of nonstationary multivariable systems. Automatica, 23: 479-489, 1987. DOI: 10.1016/0005-1098(87)90077-X

Cassar, J.P., R. Litwak, V. Coquempot and M. Staroswiecki, 1994. Approche structurale de la conception de systèmes de surveillance pour les procédés industriels complexes. JESA, RAIRO-APII, 31: 179-202.

Controllab Products, 20-sim version 4.0. http://www.20sim.com

Dauphin-Tanguy, G., 2000. Les Bond Graphs. 1st Edn., HERMES Science Publications, Paris, ISBN-10: 2-7462-0158-5.

Djeziri, M.A., B. Ould Bouamama and R. Merzouki, 2009. Modelling and robust FDI of steam generator using uncertain bond graph model. J. Process Control, 19: 149-162. DOI: 10.1016/j.jprocont.2007.12.009

Djeziri, M.A., 2007. Diagnostic des systèmes incertains par l’approche bond graph. Thèse de Doctorat, École Centrale de Lille.

Gawthrop, P.J. and L.P.S. Smith, 1995. Metamodelling: Bond Graphs and dynamic Systems. 1st Edn., Prentice Hall, ISBN-10: 0134898249, pp: 350.

Graisyhm, A., 1998. Méthodologie de conception des systèmes de supervision. Rapport Région Nord Pas de Calais, Mai, Valenciennes, France.

Han, Z., W. Li and S.L. Shah, 2002. Fault detection and isolation in the presence of process uncertainties. Proceedings of the 15th IFAC World Congress, (WC’ 02), pp:1887-1892.

Henry, D. and A. Zolghari, 2006. Norm-based design of robust FDI schemes for uncertain systems under feedback control: Comparison of two approaches. Control Eng. Pract., 14: 1081-1097. DOI: 10.1016/j.conengprac.2005.06.007

Henry, D., A. Zolghari, F. Gastang and M. Monsion, 2001. A new multi-objective filter design for guaranteed robust FDI performance. Proceeding of the 40th IEEE Conference on Decision and Control, Dec. 04-07, IEEE Xplore Press, Orlando, pp: 173-178. DOI: 10.1109/01.980093

Karnopp, D., 1979. Bond graphs in control: Physical state variables and observers. J. Franklin Instit., 308: 221-234. DOI: 10.1016/0016-0032(79)90114-5

Karnopp, D.C. and R.C. Rosenberg, 1983. Systems Dynamics: A Unified Approach. 1st Edn., MacGraw Hill.

Maquin, D. and J. Ragot, 2000. Diagnostic Des Systèmes Linéaires. 1st Edn., Hermès Science Publications, Paris, ISBN-10: 274620133X, pp: 158.

Ould Bouamama, B. and G. Dauphin-Tanguy, 2005. Modélisation Bond Graph Element de base pour l’énergetique. Technique de L’ingenieur, BE 8: 280-280.

Oustaloup, A., 1994. La robustesse. 1st Edn., Hermès, ISBN-10: 2.86601.442.1.

Paynter, H.M., 1961. Analysis and Design of Engineering Systems. 1st Edn., M.I.T. Press, Cambridge, pp: 303.

Ploix, S., 1998. Diagnostic des systèmes incertains: Approche Bornante. Thèse de Doctorat, Université Henri Poincaré, CRAN.

Rahmani, A., C. Sueur and G. Dauphin-Tanguy, 1994. Pole assignment for systems modelled by bond graph. J. Franklin Instit., 331: 299-312. DOI: 10.1016/0016-0032(94)90102-3

Redheffer, R., 1994. On a certain linear fractional transformation. EMJ. Maths Phys., 39: 269-286.

Roberts, D.W., D.J. Ballance and P.J. Gawthrop, 1995. Design and Implementation of a Bond Graph Observer for Robot Control. Technical Report CSC-95004, Glasgow University Centre for Systems and Control.

Sueur, C. and G. Dauphin-Tanguy, 1989. Structural controllability/observability of linear systems represented by bond graphs. J. Franklin Inst., 326: 869-883.

Sueur, C., 1990. Contribution à la modélisation et à l’analyse des systèmes dynamiques par une approche bond graph. Application aux systèmes poly-articulés plans à segments flexibles. Thèse de doctorat, Université de Lille I, France.

Tagina, M., 1995. Application de la modélisation bond graph à la surveillance des systèmes complexes. Thèse de Doctorat, Université de Lille, France.