A Robust Bond Graph Model Based Real Time Monitoring and Fault Diagnosis for CNC Machines

Mohamed Arezki Mellal [1]*, Edward J. Williams [2]

[1] Faculty of Engineering Sciences (FSI), M'Hamed Bougara University, Boumerdès, Algeria

[2] Decisions Sciences, University of Michigan, Dearborn, Michigan, USA

* mellal.mohamed@gmail.com; mellal-mohamed@umbb.dz

Abstract- **The bond graph (BG) is a modeling and simulation tool, providing many possibilities which are used in mechatronics. Mechatronics is a multidisciplinary engineering field necessitating a unified method for the monitoring. This paper deals with a model based real-time simulator for CNC machines in order to detect eventual failures. A versatile methodology based on bond graph analysis to build a dynamic icon model library which is successful implemented for the Fault Detection and Isolation (FDI). The developed approach is investigated using SYMBOLS2000 software.**

Keywords*- Bond Graph; Fault Detection and Isolation Matrix; Model Library; Monitoring; CNC Machines*

I. INTRODUCTION

The modern CNC machines are multidisciplinary systems, called “mechatronic systems”. Mechatronics is the synergistic and systemic combination of mechanics, electronics and computers in real time [1]. A unified modeling approach is necessary for the analysis and mode. The graphical tool is well suited for this purpose. This methodology allows the display of the power exchange system, which includes storage, dissipation and transformation.

In addition, this tool takes into account not only the generation of a behavior of the system, but it can also be used for the structural and the causal analysis which are essential for designing control systems and the monitorability.

The flexibility of this tool allows us to add more elements such as losses or thermal effects. The causal and structural properties of the graphic language allows the modeler to solve the algorithmic level model in the formulation stage before the detailed equations have been derived, this context has been developed in [2].

These properties can be used for the design of systems, for the monitoring and the supervision, these methods are illustrated in [3−6]. Therefore, this graphical method can be considered as an integrated tool for computer-aided design. The bond graph (BG) are [7]: representation graphs of the dynamic behavior of systems regardless of the considered field, graphs based on energy flow, an object-oriented modeling of systems and a powerful modeling tool for engineers.

To model a system using bond graph, several elements are considered and two unified variables are used: effort and flow. These elements are classified into three categories [2]: three passive elements (R, C and I), two active elements (Se and Sf) and four junctions (1, 0, TF and GY). The notion of causality has been illustrated in [2, 7].

In this paper, we propose a model for monitoring the parameters of CNC machines in real time. We develop a model library implemented for the symbols software and a configuration for the controllability.

This paper is organized as follows: The next section contains description of the proposed model; shows the model library implemented in the software; describes the controllability and establishment of commentaries. Finally, in the latest section some conclusions are proposed.

II. MODEL BASED REAL TIME MONITORING FOR CNC MACHINES

A. System Description

In [8], a CNC machine was studied in order to develop equations using bond graph. In this paper, we propose a more realistic model and introduce the implementation of capsules for the real time monitoring using SYMBOLS2000 software for the piece porter part. This machine contains two parts:

- Control part for machining program, instrumentation and monitoring display.
- Operative part for piece machining.

In Fig. 1, an electric motor drives through: a set of reductor, screw/nut and the table for the piece porter which moves horizontally. The engine is powered by a voltage V_{in} and the table is marked with its position $Pos(t)$. Figure 2 shows the bond graph of the system by representation of each element.

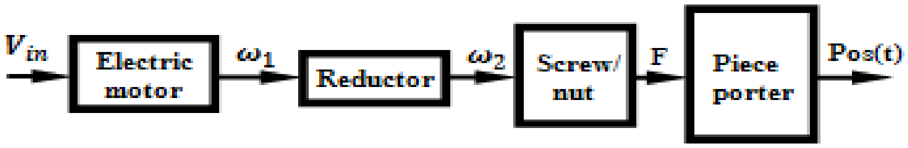

Fig. 1 Piece porter par

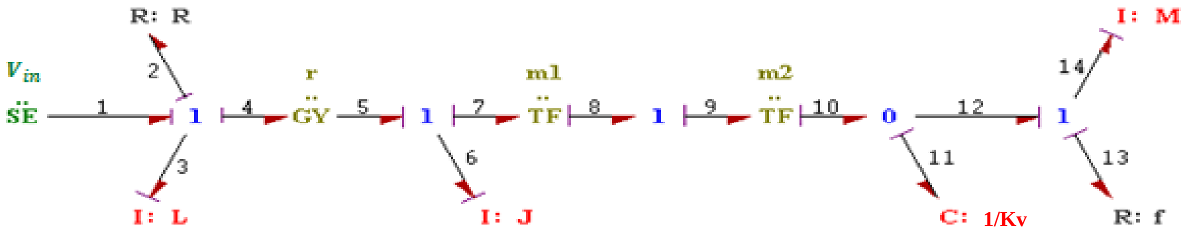

Fig. 2 Modeling of the system using bond graph

B. Bond Graph Modeling

In [8] the equations were analytically developed, simulated using SYMBOLS2000 software and it was proved that the rank of the bond graph is equal to four (I:L;I:J;C:$1/k$;I:M). The parameters of the table are illustrated in Table 1 [9].

TABLE I PARAMETERS OF THE PIECE PORTER

Value	Definition	Unit
Kv = 0,47	Constant of the motor	(rad/s)/v
L = 0,0019	Inductance of the motor	H
R = 0,61	Resistance of the armature	Ω
J = 0,01	Inertia of the rotating part	kg·m²
n = 0,5	Reduction ratio	--
h = 0,01	Pitch of the screw	m/rad
M = 8	Mass of the table	Kg
f = 6000	Viscous friction	N·s/m
k = 300000	Stiffness	N·m/rad

C. Implementation for the FDI Matrix

This software (SYMBOLS2000) can also make out the Fault Detection and Isolation matrix (FDI). To model the monitoring system, we must build capsules that contain the various components of the system, therefore a capsule is the bond graph of each part of the system that assigns a representative icon with inputs and outputs. These capsules are connected with sensors that are coupled to junctions. Only capsules of process engineering are available, hence, we need to build our own capsule for our system.

1) Capsule of the Motor:

In Fig. 3, the capsule of the motor contains:

- An effort source (1): represents the input of the motor (voltage generator).
- Two sensors of flow: to detect the variation of the internal resistance (10) and inductance (7) of the motor.
- A speed sensor in the Rotating part (8) of the motor.
- Output of the motor (flow output) for the motion transmission (9).

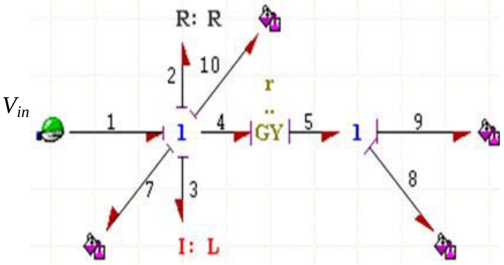

Fig. 3 Capsule of the motor

2) Capsule of the Reductor:

In Fig. 4, the capsule of the redactor contains:

- Input of the reductor , input of the flow energy (7).
- Speed sensor (6).
- Output of the reductor (5).

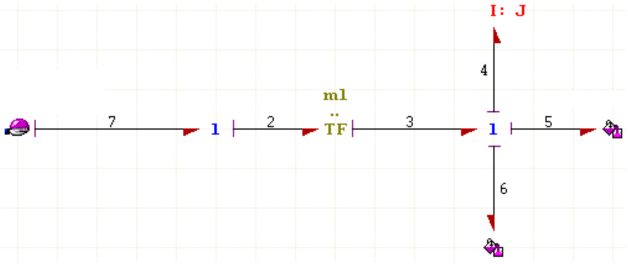

Fig. 4 Capsule of the reductor

3) Capsule of the Set Screw/Nut and the Piece porter:

In Fig. 5, the capsule of the set screw/nut and the piece porter contains:

- Input (1) of the set screw/nut (flow energy input).
- Torque sensor (8) in the set screw/nut.
- Speed sensor (10) of the piece porter.

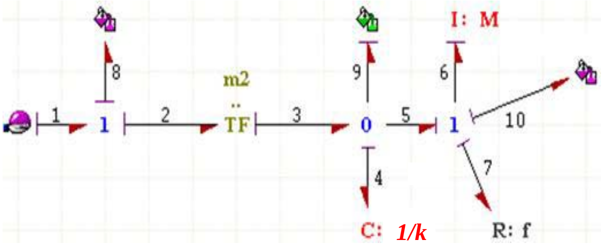

Fig. 5 Capsule of the set screw/nut and the piece porter

D. Monitoring System

After building the library, we can model the system using the capsules represented by icons (see Fig. 6), where:

Df_2: Sensor of the motor’s internal resistance.

Df_3: Sensor of the motor’s inductance.

Df_4: Speed detector of the motor’s rotating part.

Df_5: Speed sensor.

De_7: Torque sensor.

Df_8 : Speed sensor in the set screw/nut.

Df_9 : Speed sensor in the piece porter.

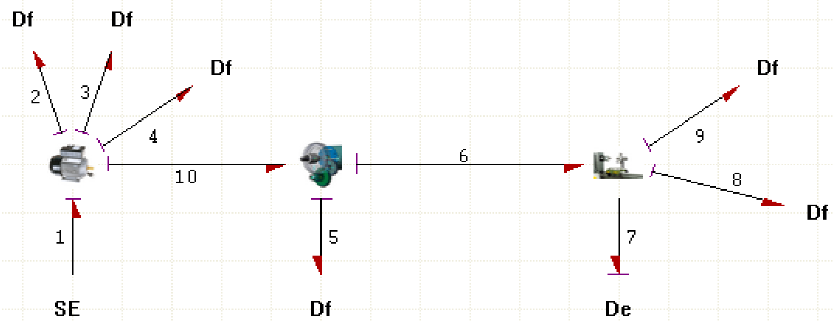

Fig. 6 Modeling of the monitoring system

E. FDI Matrix and ARRs Equations

The generation of robust analytical redundancy relations from the bond graph model is summarized in the following steps:

- 1^{st} step: Verification of the bond graph coupling in the derived preferential causality, if the system is over-determined, then continue the following steps;
- 2^{nd} step: The bond graph model is formed into the LFT (Linear Fractional Transformations) form;
- 3^{rd} step: The symbolic expression of the ARR is derived from the equations at the junctions as follows:

For the Junction 0:

$$\sum b_i \cdot f_{i_n} + \sum S_f + \sum W_i \tag{1}$$

For the Junction 1:

$$\sum b_i \cdot e_{i_n} + \sum S_e + \sum W_i \tag{2}$$

where $\sum Sf$ is the sum of the flow sources in the Junction 0, is $\sum Se$ the sum of the effort sources in the Junction 1, $\sum b_i = \pm 1$ depends on the half-arrow which is entering or leaving from the junction and $\sum W_i$ is the sum of the modulated inputs corresponding to the uncertainties on the elements related to the junction. The unknown variables are f_i and e_i.

- 4^{th} step: The unknown variables are eliminated by traversing the causal paths between sources, detectors and the unknown variables.
- 5^{th} step: After elimination of the unknown variables, the ARRs are expressed as following form:

$$ARRs: \phi(\sum S_e, \sum S_f, D_e, D_f, \sum W_i, R_n, C_n, GY_n, TF_n, I_n, RS_n) = 0 \tag{3}$$

where (TF_n, GY_n) are respectively the nominal values of the modules of the elements (TF, GY) and (R_n, C_n, I_n, RS_n) are the nominal values of (R, C, I, RS).

The structure of the ARRs gives a binary matrix which gives the sensitivity of the residues at component failures in the process physical (sensors, actuators, regulators, etc). The elements of the matrix are given as follows:

$$S_{ji} = \begin{cases} 1, \text{if the } i^{th} \text{ ARR contains} \\ \quad \text{variables of the } j^{th} \text{ component} \\ 0, \text{otherwise} \end{cases} \tag{4}$$

In SYMBOLS2000, we can generate the FDI matrix. First step is to specify the infallible components in order to simplify the model, in our case we exclude the voltage generator which is considered outside of the specifications.

On the matrix of Fig. 7 are displayed the measures variables, sources and components of the process. On this window, it was specified that the components found infallible in the scope of process, so they will not be displayed.

	M_b	I_b	R_1	R_2	R_3	R_4	R_5	R_6	R_7
Df_2	1	1	1	0	1	0	0	0	1
Df_3	1	1	1	0	1	1	1	1	0
Df_4	1	1	0	0	0	0	1	0	0
De_7	1	0	1	1	0	1	0	0	0
Df_9	1	1	0	1	0	1	0	0	0
Df_5	1	1	0	0	0	0	0	1	0
Df_8	1	1	0	0	0	0	0	0	1
Reductor	1	1	1	0	0	1	1	1	0
Screw/nut	1	0	1	1	0	1	0	0	0
Motor	1	1	1	0	1	0	0	0	0

Fig. 7 FDI matrix

It should be noted that R_1, R_2, …, R_7 are the corresponding residues in the ARRs (Analytical Redundant Relationships) and (M_b, I_b) are respectively the detectability and isolability of failures. The rows of the matrix are the signatures of the components (i.e. dependence of residuals in relation to failures of components). A value "1" means that the failure of the component theoretically influence on one response of (or several) residue(s), otherwise "0". When the variable associated with a component appears in at least one residue, then its failure is detectable (M_b=1). If the signature of a component is unique (strictly different to others signatures) its failure is isolated (I_b=1).

From the FDI matrix shown in Fig. 7, we can note that:

- All values of the column are equal to "1", therefore all failures of the system can be detected.
- On the other hand, the signatures of the sensor and the set screw/nut are identical which means that defects affecting these components cannot be isolated therefore the torque sensor cannot contribute effectively to the supervision of the part Screw/Nut.
- The motor and reductor are supervisable as their signature is different.
- The set screw/nut is not entirely supervised.

It is important to note that the matrix of failures signatures built from the causal paths is a configuration (or operation mode) well definite and therefore the associated model. The form of equations for each component of the bond graph is the same throughout the period of operation in a given configuration.

The decision procedure is applied to the set of residues R_i to generate a binary coherence vector $V=[V_1, V_2,\ldots, V_7]$, this vector indicates if a failure is present on the process or otherwise.

Each element V_i of V is obtained by applying the corresponding decision procedure $\Phi_i(R_i)$, i.e., $V_i=\Phi_i(R_i)$. Thus, an alarm is triggered when $V_i=1 \Longrightarrow V\neq 0$.

Theoretically, if the system is functioning, the value of the residues R_i ($i=1, 2, 3,\ldots,7$) must be equal to "zero", but in practice and in the simple case, $|\psi\Delta T(R_i)|$ is bounded by a small amount ε_i, where $\psi\Delta T$ is the pre-treatment of each residue (an average value is calculated in the interval of time ΔT. The parameter ε_i is a threshold (by experience). This is due to the measurements noise.

In the presence of failures, each value of residue treated is compared with a fixed threshold value. In our case, each element V_i of V is obtained using the following condition:

$$V_i = \begin{cases} 1, if \ |\psi\Delta T(R_i)| > \varepsilon_i \\ 0, otherwise \end{cases} \tag{5}$$

We note that the value of ε_i must be well calculated to avoid false alarms.

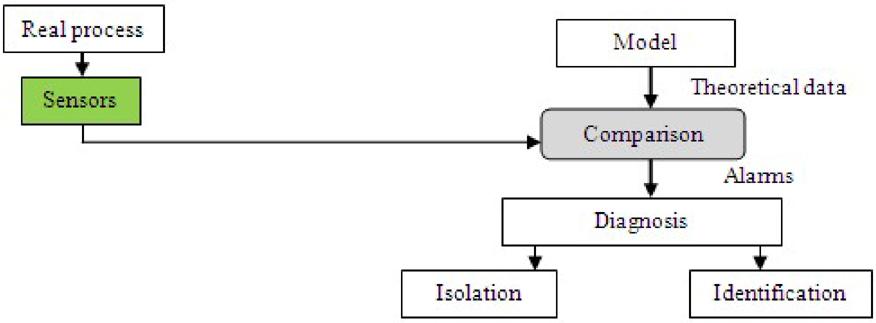

Fig. 8 Monitoring system

III. CONCLUSION

In this paper, we proposed a bond graph model based real-time simulator for CNC machines in order to detect eventual failures using SYSMBOLS2000 software. Figure 8 sum-marizes the design of the monitoring system.

The proposed methodology is technically feasible and economically realizable to be integrated into production lines and it makes to assist the maintenance operators. The advantage of this method is characterized by:

- Direct generation of the FDI matrix in real time.
- Versatile method for modification of the machines parameters.
- An optimal sensor placement was presented.

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Dr. Mohamed Arezki MELLAL was born in Algeria. He earned the B.Sc., M.Sc. and Ph.D. (2007, 2009 and 2013 respectively) in Mechatronics, both from M'Hamed Bougara University, Boumerdès, Algeria. He participated in several national and international conferences: South Korea, China, Poland, Italy, Tunisia, Algeria and he is author of several papers in refereed journals. He completed an internship at Osaka Electro-Communication University, Osaka, Japan. He serves on the editorial board of three international journals. Also, he serves as a reviewer for several journals and conferences. His research interests: Mechatronics, Dependability, Study of complex systems, Bond graph modeling and Optimization using bio-inspired metaheuristics.

Edward J. WILLIAMS is a Senior Technical Specialist. From 1969 to 1971, he did statistical programming and analysis of biomedical data at Walter Reed Army Hospital, Washington, D.C. He joined Ford Motor Company in 1972, where he worked until retirement in December 2001 as a computer software analyst supporting statistical and simulation software. After retirement from Ford, he joined PMC, Dearborn, Michigan, as a senior simulation analyst. Also, since 1980, he teaches at the University of Michigan, USA. He is author or co-author of several papers and technical newsletters.

He is a member of the Association for Computing Machinery [ACM] and its Special Interest Group in Simulation [SIGSIM], the Institute of Electrical and Electronics Engineers [IEEE], the Institute of Industrial Engineers [IIE], the Society for Computer Simulation [SCS], the Society of Manufacturing Engineers [SME], and the American Statistical Association [ASA]. He serves on the editorial board of several journals. During the last several years, he has given invited plenary addresses at several conferences.