Model-based fault diagnosis of a pump-displacement-controlled actuator with a multidisciplinary approach using bond graph

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ABSTRACT
In this chapter, firstly, the pump-displacement-controlled actuator system with applications in aerospace industries is modeled using the bond graph methodology. Secondly, an approach is developed towards simplification and model order reduction for bond graph models that can usually use in conceptual representation or design procedures. The model order reduction process indicates which system components have the most bearing on the frequency response, and the final model retains structural information. Finally, the state space form of mathematical model of the system based on the bond graph model is presented. By associating bond graph model, it becomes possible to design fault detection and isolation (FDI) algorithms, i.e. the generation of fault indicators, and to improve monitoring of the actuator.

1. INTRODUCTION

An important aspect of mechatronic systems is that the synergy realized by a clever combination of a mechanical system and its embedded control system leads to superior solutions and performances that could not be obtained by solutions in one domain. Models of mechatronic systems are often large and complicated, with many parameters, making the physical interpretation of the model outputs, even by domain experts, difficult. This is particularly true when unnecessary features are included in the model. In mechatronics, where a controlled system is designed as a whole, it is advantageous that model structure and parameters are directly related to physical structure in order to have a direct connection between design or modeling decisions and physical parameters.

The bond graph methodology is a convenient and useful complimentary tool for obtaining both the behavioral and the diagnostic models. Moreover, the method presents the unique feature of being able to model systems in different energy domains using the same approach with a single model, thus it becomes ideal for modeling and simulation of mechatronics and control systems. Because of the multi-domain energies involved in the actuators, the bond graph methodology as a multidisciplinary and unified modeling language proves a convenient tool for the given purpose. The advantage of the bond graph modeling compared to other methods is the good visibility of power transfers between all elements, and even between several subsystems in which we can measure efficiency of the system.

The proposed model guarantees the reversibility of power flows, at the opposite of other approach for example transfer function. By the bond graph method, it is easy to see the impact of changing one parameter in the complete model of the actuator system. The model structure can also be modified, taking care of the causality. Respecting the causality, computing convergence troubles due to causality conflicts are avoided. The analysis of causal paths highlights variable links. This is an advantage of bond graph method, in order to have a view of energetic dependences and resonances in the model.

1.1. BOND GRAPH MODELING METHODOLOGY

The bond graph methodology as a graphical modeling language is a convenient and useful tool for obtaining both the behavioral and the diagnostic models. Table 1 defines the symbols and constitutive laws for energy storage and dissipative elements ("energetic" elements), sources, and power-conserving elements. Here we concisely introduce bond graph method and for a more thorough development of bond graphs, we refer the reader to (Thoma, 1975); (Karnopp et al., 2000); and (Borutzky, 2009).

Energy is transported among source, storage and dissipative elements through power-conserving junction structure elements. Such elements include power-continuous generalized transformers TF and gyrators GY that algebraically relate elements of the effort and flow vectors into and out of the element. The constitutive laws of modulated transformers and gyrators *MTF* and *MGY* are functions of external variables, for example coordinate transformations that are functions of generalized coordinates. Transformers are created using linked sources. For example, considering a *TF* with a ratio *r*, the input effort e_1 is measured, and the output effort e_2 is calculated such as e_1/r. In the same way, the output flow f_2 is measured, and the input flow f_1 is calculated as f_2/r. The element is very simple, but it must be set conveniently to respect the causality of the circuit.

Kirchoff's loop and node laws are modeled by power-conserving *1*- and *0*-junctions, respectively. Elements bonded to a *1*-junction have common flow, and their efforts algebraically sum to zero. Elements bonded to a *0*-junction have common effort, and their

Table 1 Basic bond graph elements

	SYMBOL	CONSTITUTIVE LAW (LINEAR)	CAUSALITY CONSTRAINTS
SOURCES			
Flow	Sf ⊢⇀	$f = f(t)$	fixed flow out
Effort	Se ⇀|	$e = e(t)$	fixed effort out
ENERGETIC ELEMENTS			
Inertia	⇀| I ⊢⇀ I	$f = \frac{1}{I}\int e\,dt$ $e = I\frac{df}{dt}$	preferred integral
Capacitor	⊢⇀ C ⇀| C	$e = \frac{1}{C}\int f\,dt$ $f = C\frac{de}{dt}$	preferred integral
Resistor	⊢⇀ R ⇀| R	$e = Rf$ $f = \frac{1}{R}e$	none
2-PORT ELEMENTS			
Transformer	1 ⇀| TF 2 ⇀| (n)	$e_2 = n\,e_1$ $f_1 = n\,f_2$	effort in-effort out or flow in-flow out
Modulated Transformer	⇀| MTF ⇀| ↓θ, n(θ)	$e_2 = n(\theta)\,e_1$ $f_1 = n(\theta)\,f_2$	
Gyrator	1 ⊢⇀ GY 2 ⇀| (n)	$e_2 = n\,f_1$ $e_1 = n\,f_2$	flow in-effort out or effort in-flow out
Modulated Gyrator	⊢⇀ MGY ⇀| ↓θ, n(θ)	$e_2 = n(\theta)\,f_1$ $e_1 = n(\theta)\,f_2$	
CONSTRAINT NODES			
1-junction	1 ⇀| 1 2 ⇀| ; 3	$e_2 = e_1 - e_3$ $f_1 = f_2$ $f_3 = f_2$	one flow input
0-junction	1 ⊢⇀ 0 2 ⊢⇀ ; 3	$f_2 = f_1 - f_3$ $e_1 = e_2$ $e_3 = e_2$	one effort input

flows algebraically sum to zero. The power bonds contain a half-arrow that indicates the direction of algebraically positive power flow, and a causal stroke normal to the bond that indicates whether the effort or flow variable is the input or output from the constitutive law of the connected element. Full arrows are reserved for modulating signals that represent powerless information flow, such as orientation angles for coordinate transformation matrices.

The three basic passive elements, i.e. *R*, *I* and *C* also have an equivalent definition in the different physical domains. Therefore, it is easy to translate any bond graph into an electrical circuit. In this manner, whatever their physical field all passive elements are changed into electrical elements inserted in an equivalent circuit. For example, mechanical torque source becomes a voltage source, and angular velocity becomes a current.

The bond graph modeling methodology allows for the generation of not only a behavioral model (Karnopp et al., 2000); (Thoma & Ould Bouamama, 2000), but also it can be used for the structural analysis of the system. For instance, they have been used to study the structural control properties (observability, controllability, etc.) (Sueur & Dauphin-Tanguy, 1991) and monitorability analysis (Tagina et al., 1995).

Yet, on the other hand, the causal properties of the bond graph language enable the modeler to resolve the algorithmic level of modeling (e.g. singularities, invertibility, etc.) by assigning adequate derivative or integral causality in the formulation stage, even in conceptual stage as early stage of design before the detailed equations have been derived (Toufighi et al., 2008).

1.2. MODEL ORDER REDUCTION

The approximation of high-order plant and controller models by models of lower order is an integral part of control system design. Until relatively recently model reduction was often based on physical intuition. For example, chemical engineers often assume that mixing is instantaneous and that packed distillation columns may be modeled using discrete trays. Electrical engineers represent transmission lines and the eddy currents in the rotor cage of induction motors by lumped currents.

Mechanical engineers remove high-frequency vibration modes form models of aircraft wings, turbine shafts and flexible structures. It may also be possible to replace high order controllers by low-order approximations with little sacrifice in performance.

The bond graph methodology is widely used for modeling purposes, but only few works deal with model order reduction of complex systems using bond graph models.

Ref. (Louca, 2006) describes a method for calculating the modal power of lumped parameter systems with the use of the bond graph representation, which is developed through a power conserving modal decomposition. Element activity index is a scalar quantity that is determined from the generalized effort and flow through each element of the model. As an application, this approach was used for order reduction of the fuel cell model (McCain & Stefanopoulou, 2006).

Negligible aggregate bond power at a constraint equation node indicates an unnecessary term, which is then removed from the model by replacing the associated bond by a modulated source of generalized effort or flow (Rideout et al., 2007).

Ref. (Moin & Uddin, 2004) uses tree-structured transfer functions derived from bond graphs, maintains a subset of the original state variables in the reduced order model and maintains structural significance in the state variable coefficients. The advantage of the tree structure is that the reduced order models are available directly from a single transfer function.

Ref. (Louca et al., 2005) demonstrates how the algorithm increases the scope and robustness of existing physical-domain model reduction techniques, monitors the validity of simplifying assumptions based on decoupling as the system or environment changes, and can improve computation time.

Model simplifications or order reduction methods are usually derived from one of the following principles (Ljung & Glad, 1994); separation of time constants (segregation), aggregation of state variables, or neglect of small effects.

1.3. FAULT DIAGNOSIS

Electro-hydraulic actuators are complex and non-linear systems characterized by the coupling of different forms of energy and used usually in processes where the environment is harsh. This puts them at high risk to failures.

The causal properties of the bond graph methodology can help to derive state space form of the governing equation of the system and design fault detection and isolation (FDI) algorithms, i.e. the generation of fault indicators (Ould Bouamama et al., 2005); (Khemliche et al., 2006). In this way, by associating bond graph models, it becomes possible to obtain the behavioral knowledge of the actuator, and to improve their monitoring.

2. BOND GRAPH MODELING OF THE ELECTRO-HYDRAULIC ACTUATOR

Because of the multi-domain energies involved in the actuators, the bond graph methodology as a multi-disciplinary and unified modeling language proves a convenient tool for the given purpose.

Electro-hydraulic actuators are used aboard aircrafts and missiles (Langlois et al., 2004). In particular, they become often used for actuating control surfaces (Bossche, 2003). From the power distribution's point of view, a flight control actuator is a dynamic load with fluctuant power consumption, which has to impose an accurate position control while pushing heavy loads at low speeds.

The main class of electrical actuators for control surfaces is constituted of electro-hydraulic actuators. As shown in Fig.1, the structure of such actuators involves several physical domains that are coupled from the electrical input (connected to the electrical network) to the output (mechanical control surface) (Habibi, 1999). First, electricity is converted to rotational mechanic with a dc motor. Then, a volumetric pump transforms mechanical power into hydraulic power. A hydraulic jack is in charge of transforming hydraulic to translation mechanic. Finally, the rod translation drives the rotation of the flight control surface. Therefore, many different transformations and field crossings are involved in electro-hydraulic actuators. That is a reason why bond graph is particularly convenient to represent this actuator. All physical domains can be drawn on the same design, with the same schematic elements, which greatly facilitates the system's analysis.

We consider the electro-hydraulic actuator system that was studied and modularly implemented for its sub-systems in bond graph methodology in Ref. (Toufighi et al., 2007). In this manner, each sub-system constituting the electro-hydraulic actuator can be separately modeled through power variables (efforts and flows) and parameters used in these sub-models are introduced in tables 2 and 3 respectively. Here we roughly describe the bond graph modeling procedure of the sub-systems.

2.1. ELECTRICAL MOTOR

The electro-hydraulic actuator is supplied with a constant DC voltage source. The DC motor is simply modeled by a gyrator (GY- element) for the electromechanical conversion, with a ratio equal to the electro-magnetic flux (Φ). On the electrical side, armature inductance and resistance are transcribed in bond graph respectively with I- and R-elements (L_M and R_M). That is the same on the mechanical side, for moment of inertia and viscous friction coefficients (respectively J_{MP} and B_{MP}).

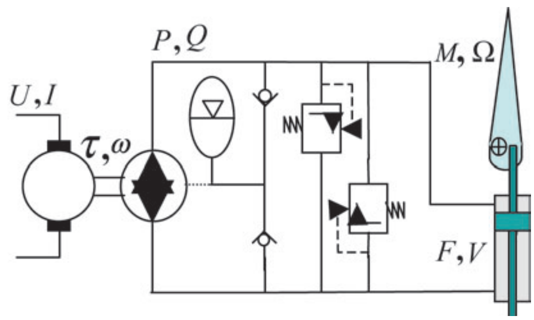

Figure 1 Diagram of an electro-hydraulic actuator and control surface.

2.2. HYDRAULIC PUMP

The equivalent inertia and friction of the mobile parts are modeled by I and R elements. That is why they are grouped together with those of the motor (J_{MP} and B_{MP}). The core of the hydraulic pump is made of two TF elements with a transformer ratio equal to the pump volumetric displacement (D). Internal hydraulic leakages (R_{LP}) are modeled by a R-element placed between the two hydraulic lines. The compressibility of the fluid in both hydraulic lines as the pump hydraulic stiffness is obtained with two C-elements; K_{HP1} and K_{HP2}. The additional viscous friction coefficient (B_{PE}) takes into account other losses in the pump, assumed to be proportional to the rotational speed.

2.3. ACCUMULATOR, PRESSURE LIMITER AND LINE

The accumulator can be commonly modeled using a C-element. However, a constant effort source Se set to the pressure P_{Acc} has been preferred for simplification purpose. Due to its high dynamics, each re-feeding valve is modeled using non-linear R-element (R_{CV}). The overpressure (saturation) function is performed due to a combination of two pressure relief valves that limit the pressure difference between the two hydraulic lines. Once again, their high dynamic allows representing this function by a static model, using only a non-linear R-element (R_{RV}). The pressure losses into the lines are taken into account with two non-linear dissipative elements (R_{L1} and R_{L2}).

2.4. HYDRAULIC JACK

The main element constituting the jack is a TF with a transformer ratio equal to the piston surface (A). Internal hydraulic leakages can be modeled like in the hydraulic pump by a R-element (R_{LJ}). However, it may be considered as infinite due to the dynamic sealing. The compressibility of the fluid in both chambers is obtained in bond graph with two C-elements ($1/K_{HJ1}$ and $1/K_{HJ2}$) that are equal to V_{JP1}/β and V_{JP2}/β respectively. An efficient way to represent the jack dissipation is found by introducing an expansion viscosity effect, modeled by an R-element on a 1-junction (R_{HJ1} and R_{HJ2}). On the mechanical side, the mass of the jack rod is placed on a I-element (m_J), and the dry friction force is modeled by an effort source (F_{DJ}).

2.5. CONTROL SURFACE

Due to the mass constraints, the jack attachment to the control surface is not rigid. It is modeled by a finite stiffness represented by a C-element ($1/K_{MJ}$). The associated structural damping is modeled by an R-element (B_{MJ}). The transformation from rod translation to surface rotation is modeled using a *MTF*-element with a variable ratio equal to the lever arm component ($l.cos\theta$). Finally, the control surface inertia is taken into account with an I-element (J_{CS}). Fig. 2 illustrates the bond graph of the control surface.

Considering the causalities, it can be seen that the electro-hydraulic actuator model allows computing the surface deflection in response to the position set point and the hinge moment applied to the surface (M_{CS}) as a source of effort. According to the flight mission of the aircraft or missile, hinge moment and position order are fixed.

3. EVOLUTION, SIMPLIFICATION AND MODEL ORDER REDUCTION OF THE MODEL

3.1. EVOLUTION OF THE BOND GRAPH MODEL

With respect to the reference behavioral model, the main advantage of the bond graph model is due its capability of evolution. In fact, it represents a design model, whose parameters are directly linked to physical phenomena. Knowing system components, it is easy to modify the parameter values. This is convenient to resize an actuator, in order to use the same model structure for different sizes of actuators. On the other hand, the complexity of the bond graph model can progressively evolve its structure and can be modified as much as needed, taking care of the causality.

Contrarily to a behavioral model, there is no specific calculation (transfer function, state model, etc) in the model, because each physical element is graphically represented. Therefore, adding a new element in the model does not involve recalculation; modifications can be carried out. Furthermore, the causality analysis also allows facilitating convergence by ensuring the compatibility of element couplings, and avoiding algebraic loops.

The advantage of the bond graph modeling compared to other methods is the good visibility of power transfers between all elements, and even between several actuators.

The proposed model guarantees the reversibility of power flows, at the opposite of other approach for example transfer function. By the bond graph method, it is easy to see the impact of changing one parameter in the actuator model on the complete electrical network. The model structure can also be modified, taking care of the causality. Respecting the causality, computing convergence troubles due to causality conflicts are avoided. The analysis of causal paths highlights variable links. This is an advantage of bond graph method, in order to have a view of energetic dependences and resonances in the model.

3.2. SIMPLIFICATION

Actually, the bond graph model briefly described above owns two hydraulic lines, but it is possible to create an equivalent one-line bond graph with a low loss of information. On this model, hydraulic parameters have the mean values of real parameters. In particular, the jack piston chamber volume (V_{JP}) is average of V_{JP1} and V_{JP2} to calculate hydraulic stiffness; $1/2K_{HJ}$ that equals to $V_{JP}/2\beta$. Simplifications are also obtained by ignoring hydraulic jack leakage coefficient, and hydraulic pump stiffness. Accumulator and overpressure limiter are not represented on this figure. Concerning the accumulator, there is no working on a single-line schematic.

The challenge for controlling the system is to position the control surface with a sufficient performance level. In the special practice, the linear position of the hydraulic jack is

Table 2 Power variables (effort, flow)

Symbol	Quantity	Unit
I	DC motor current	A
U	DC motor voltage	V
ε	DC motor electromotive force	V
ω	Motor-pump angular velocity	rad/s
τ_{EM}	Motor-pump electro-magnetic torque	N·m
τ_M	Motor-pump mechanical torque	N·m
τ_P	Pump internal torque	N·m
ΔP_s	$(= P_{S1} - P_{S2})$ Pump output pressure	Pa
Q_{LP}	Pump internal leakage flow	m^3/s
Q_S	Pump output flow	m^3/s
Q_L	Line flow	m^3/s
P_{ACC}	Accumulator pressure	Pa
Q_{ac}	Accumulator flow	m^3/s
ΔP_J	$(= P_{J1} - P_{J2})$ Jack input pressure	Pa
Q_{LJ}	Jack internal leakage flow	m^3/s
Q_J	Jack internal flow	m^3/s
$F_J{}'$	$(= F'_{J1} - F'_{J2})$ Jack internal force	N
F_J	Jack output force	N
V_J	Jack output velocity	m/s
F_{DJ}	Jack dry friction force	N
V_T	Transmission velocity	m/s
M_T	Transmission hinge moment	N·m
M_J	Control surface inertia hinge moment	N·m
M_{CS}	Control surface hinge moment	N·m
Ω_{CS}	Control surface angular velocity	rad/s

controlled instead of the surface angle. The lever arm links the relation between the position angle and the linear position: in fact, the lever arm has a variable value depending on the position, but this can be easily taken into account, given the installation kinematics.

The parameter of a simplified element is a combination of the parameters of the elements it is composed of all elements have a variable that contains the transformation factor (n) of the parameter, such that a controller developed for the simplified model can immediately be connected to the original non-simplified model; i.e. input and output variables of the original plant model are preserved. A transmission can be eliminated from the model by joining it with a single port element, as in Figure 3.

The parameter value and the type of element may change by this simplification. Propagation of transmission and composing of transmissions will lead to a model without transmissions and dependent elements, if the model does not contain power loops. After installation of the sub-models and mentioned simplification and other simplification for TF and GY elements, we have simplified bond graph model as shown in Figure 4. The elements in this model are defined as

$$R_4 = R_M + \frac{\left(D/A\right)^4 \Phi^2}{B_{MP} + B_{PE}} \qquad C_3 = I_{MP}\left(\frac{A}{D}\right)^2 \Phi^2$$

$$R_9 = 2R_{H/1}, A^2 \approx 2R_{H/2}, A^2 \qquad C_7 = \frac{1}{2A^2 K_{H/1}} \approx \frac{1}{2A^2 K_{H/2}}$$

$$R_{14} = R_{MJ} \qquad C_{15} = \frac{1}{K_{MJ}}$$

$$I_2 = L_M$$

$$S_{e1} = U$$

$$I_{11} = M_J$$

$$S_{e10} = -F_{DJ} = -\mu M_J g \, sgn(V_J)$$

$$I_{17} = \frac{Jcs}{(l\cos\theta)^2}$$

$$S_{e19} = -F_{FC} = -\frac{M_{CS}}{l\,cos\,\theta}$$

Table 3 Parameters

Symbol	Quantity	Unit
L_M	DC Motor inductance	H
R_M	DC Motor resistance	Ω
Φ	DC Motor electromagnetic flux	Wb
J_{MP}	Motor-pump inertia momentum	$Kg.m^2$
B_{MP}	Motor-pump viscous friction coeff.	N.m.s
D	Pump displacement	m^3
B_{PE}	Pump mec. efficiency friction coeff	N.m.s
K_{HP}	Pump hydraulic stiffness	Pa/m^3
R_{LP}	Pump internal leakage resistance	$Pa.s/m^3$
R_{CV}	Check valve resistance	$Pa.s/m^3$
R_{RV}	Relieve valve resistance	$Pa.s/m^3$
R_L	Nonlinear Line resistance	$\sqrt{Pa.s/m^3}$
R_L	Linear Line resistance	$Pa.s/m^3$
K_{HJ}	Jack hydraulic stiffness	Pa/m^3
V_{JP}	Jack piston chamber volume	m^3
β	Fluid bulk modulus	Pa
R_{HJ}	Jack dissipation resistance	$Pa.s/m^3$
A	Jack piston active area	m^3
R_{LJ}	Jack internal leakage resistance	$Pa.s/m^3$
m_J	Jack rod mass	kg
K_{MJ}	Jack mechanic stiffness	N/m
B_{MJ}	Jack structural damping resistance	N.s/m
l	Lever arm length	m
J_{CS}	Control surface inertia momentum	$Kg.m^2$
x	Jack rod position	m
θ	Control surface rotation angle	rad

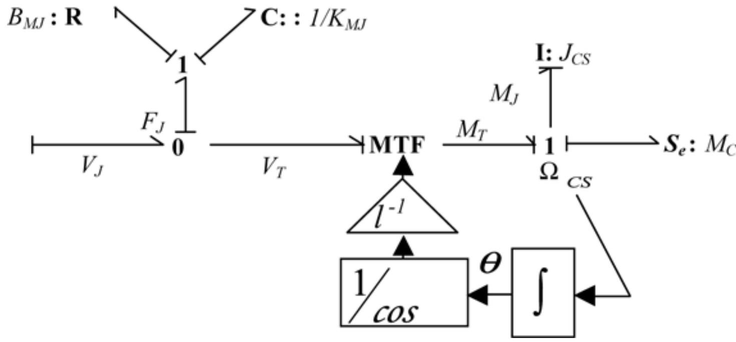

Figure 2 Bond graph of the control surface.

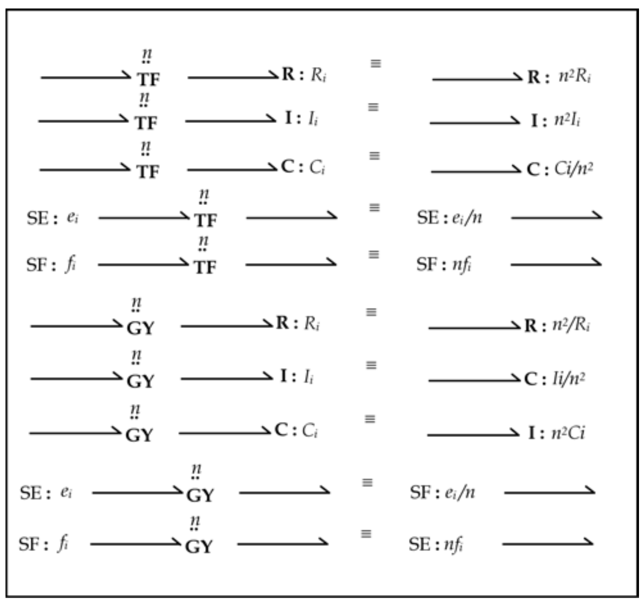

Figure 3 Composition of an element and a transmission.

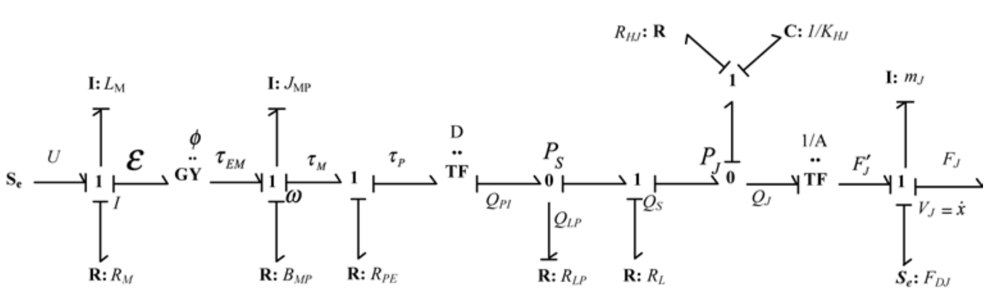

Figure 4 Simplified bond graph model with one line hydraulic part.

3.3. DERIVATION OF THE GOVERNING EQUATIONS

The governing equation of the whole of system can be derived from simplified causal bond graph model shown in Fig. 5 using bond graph methodology. Then, we have six state variables P_2, P_{11}, P_{17}, q_3, q_7, and q_{15}. The state space equations of the system are

$$\begin{aligned}
P_2 &= -\frac{1}{l_2}(R_4 + R_8)P_2 + \frac{R_8}{l_{11}}P_{11} - \frac{1}{C_3}q_3 - \frac{1}{C_7}q_7 + S_{e1} \\
P_{11} &= \frac{R_8}{l_2}P_2 - \frac{1}{l_{11}}(R_8 + R_{14})P_{11} + \frac{R_{14}}{l_{17}}P_{17} + \frac{1}{C_7}q_7 - \frac{1}{C_{15}}q_{15} + S_{e10} \\
P_{17} &= \frac{R_{14}}{l_{11}}P_{11} - \frac{R_{14}}{l_{17}}P_{17} + \frac{1}{C_{15}}q_{15} + S_{e18} \\
q_3 &= \frac{1}{l_2}P_2 \\
q_7 &= \frac{1}{l_2}P_2 - \frac{1}{l_{11}}P_{11} \\
q_{15} &= \frac{1}{l_{11}}P_{11} - \frac{1}{l_{17}}P_{17}
\end{aligned} \tag{1}$$

And, the matrix form of the state space equations of the system is

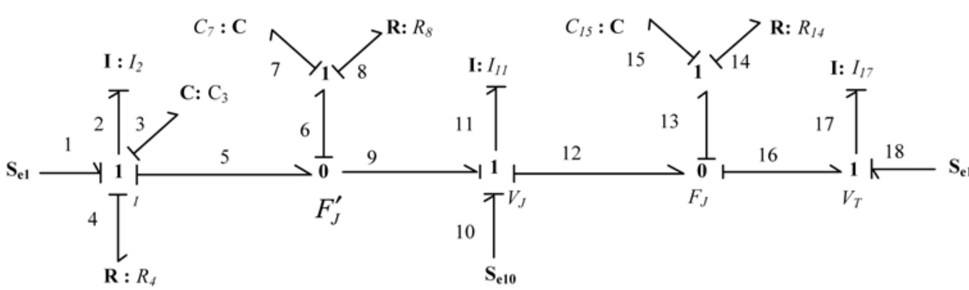

Figure 5 Simplified bond graph model of the system.

$$\begin{Bmatrix} \dot{P}_2 \\ \dot{P}_{11} \\ \dot{P}_{17} \\ \dot{q}_3 \\ \dot{q}_7 \\ \dot{q}_{15} \end{Bmatrix} = \begin{bmatrix} -\frac{1}{l_2}(R_4+R_8) & \frac{R_8}{l_{11}} & 0 & -\frac{1}{C_2} & -\frac{1}{C_7} & 0 \\ \frac{R_8}{l_2} & -\frac{1}{l_{11}}(R_8+R_{14}) & \frac{R_{14}}{l_{17}} & 0 & \frac{1}{C_7} & -\frac{1}{C_{15}} \\ 0 & \frac{R_{14}}{l_{11}} & \frac{R_{14}}{l_{17}} & 0 & 0 & \frac{1}{C_{15}} \\ \frac{1}{l_2} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{l_2} & -\frac{1}{l_{11}} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{l_{11}} & -\frac{1}{l_{17}} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} P_2 \\ P_{11} \\ P_{17} \\ q_3 \\ q_7 \\ q_{15} \end{Bmatrix} + \begin{Bmatrix} S_{e1} \\ S_{e10} \\ S_{e18} \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{2}$$

4. FAULT DIAGNOSIS ANALYSIS USING DETECTORS IN BOND GRAPH MODEL

Owing to its causal properties, a bond graph model can greatly contribute to the design and the development of the process monitoring and fault diagnosis application. For these purposes, we use some effort and flow detectors, De and Df on 0- and 1-junctions respectively in Fig. 4 as shown in Fig. 6. The detectors or sensors can of course provide other services, such as keeping memory of minimum and maximum levels, providing alarms, etc.

The improvement of the actuator's safety is essentially based on the FDI procedures. Different model-based methods for the FDI procedures have been developed, depending on the kind of knowledge used to describe the process (transfer function, state equation, structural model, etc.).

Monitorability analysis (ability to detect and to isolate the faults which may affect the system) is based on the fault signatures deduced from the analytical redundancy relations (ARRs). ARRs are symbolic equations representing constraints between different known process variables (parameters, measurements and sources). ARRs are obtained from the behavioral model of the system through different procedures of elimination of unknown variables. Numerical evaluation of each ARR is called a residual, which is used in model based fault detection and isolation (FDI) algorithms. ARRs represent constraints between different known variables (parameters, measurements and sources) in the process. In other words, ARRs are static or dynamic constraints which link the time evolution of the known variables when the system operates according to its normal operation model. Once ARR are designed, the fault detection (FD) procedure checks at each time whether they are satisfied or not, and when not, the fault isolation (FI) procedure identifies the system component(s) which is (are) to be suspected. For the FDI procedure to work properly, ARRs should be structured, sensitive to faults and robust, i.e. insensitive to unknown inputs and disturbances (McCain & Stefanopoulou, 2006).

System modeling is an important and difficult step in the generation of the ARRs. Because of the multi-domain energies involved in the actuators, the bond graph methodology as a multi-disciplinary and unified modeling language proves a convenient tool for the given purpose.

4.1. DERIVATION OF ARRs FROM BOND GRAPH MODEL

The general form of an ARR is given by a relationship between a set of known process variables as

$$f_1 (K_1) = f_2 (K_2), \tag{3}$$

where f_1 and f_2 are two functions relating K_1 and K_2, which are sets of known system variables, and any one side of the equation may be null. In a bond graph based approach, the

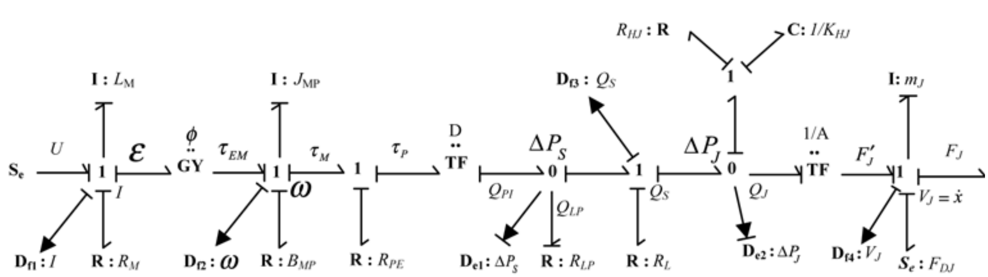

Figure 6 Diagnostic bond graph model of the hydraulic part of the system.

known variables are the sources (*Se* and *Sf*), the modulated sources (*MSe* and *MSf*), the measurements from sensors (*De* and *Df*), the model parameters and the controller outputs (*u*).

Each constraint relation should always be valid within a certain bound of error, when evaluated using measured data from the real system. This error, which is theoretically zero during the normal operation of a system, is called a residual. Any inconsistency in holding one or more of the constraints is an indicator of fault(s) in some system component. A residual, *r*, which represents the error in the constraint, is formed from each ARR,

$$r = f_1(K_1) - f_2(K_2) = f(K) = 0 \tag{4}$$

or;

$$r = f\,(Se,\ Sf,\ MSe,\ MSf,\ De,\ Df,\ u,\ \theta) = 0 \tag{5}$$

where f is the combined constraining function, and $K = K_1 \cup K_2$. For n structurally independent residuals; $ri = fi\ (Ki)$, where $i = 1, \ldots, n$ and K_i is the set of known variables in the argument of function f_i; the following property is satisfied: $K_1 \neq K_j \ \ \forall i \neq j$, where $i, j = 1, \ldots, n$. Residuals are never equal to theoretical zero in any online application involving real measurements. Due to the sensor noises and the uncertainties in the parameters, residual values contain small variances. Residuals lead to the formulation of a binary coherence vector $C = [c_1, c_2, \ldots, c_n]$, whose elements, $c_i\ (i = 1, \ldots, n)$, are determined from a decision procedure, Θ, which generates the alarm conditions. We use a simple decision procedure, $C = \Theta(r_1, r_2, \quad , r_n)$, whereby each residual, r_i is tested against a threshold, ε_i fixed a priori.

$$C_i = \begin{cases} 1, & if\,|r_i| > \varepsilon_i; \\ 0, & otherwise. \end{cases} \tag{6}$$

The coherence vector is calculated at each sampling step. A fault is detected, when $C \neq [0, 0, \ldots, 0]$, i.e. at least one element of the coherence vector is non-zero (alternatively, at least one residual exceeded its threshold).

Residuals are generated using the conservation laws at each junction (1 and 0) and then their structural independence are checked with existing residuals (Ould Bouamama et al., 2005).

5. CONCLUSION

The bond graph structure facilitates the study of parameter variations. This is particularly convenient to size components and optimize a complete system. In this work a new modeling approach using bond graph method is applied. It suggested a new design methodology for automatically synthesizing design for multi-domain, lumped parameter dynamic systems, assembled from mixtures of electrical, mechanical, hydraulic, pneumatic and thermal components.

Through the bond graph representation, multi field and heterogeneous systems such as electro-hydraulic aeronautic actuators can be efficiently modeled. The capability to progressively evolve allows improving accuracy following the system analysis level, without increasing drastically the complexity of the model implementation. The level of complexity of the model has to be chosen according to the needs. Dynamic effects are properly taken into account with a low complexity level.

The second conclusion leads toward simplification and model order reduction. In contrast to the mathematically-derived models, with the bond graph method, the elimination of physical elements from the model constrains the simplified and reduced order model to use state variables and parameters from the original full order model.

The model order reduction has two principal advantages;

1. The final model retains structural information. The first of these features provides a designer with insight in the system behavior for conceptual design purpose.
2. The model order reduction process indicates which system components have the most bearing on the frequency response.

The bond graph methodology is a convenient and useful tool for obtaining diagnostic model rather than the behavioral model. Therefore we use only one representation (the bond graph) for both the modeling, and for the monitoring of the system. One of these depends on the use of quantitative dynamic models, which leads to the determination of ARRs, and allows the real-time monitoring of the actuator. Contrary to other classical model based methods, the ARRs can be directly and systematically determined from the bond graph model.

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