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***Abstract*— The first advantage for studying dynamic model structural properties lies in the fact that results are available for every parameter numerical value. Much research has already been carried out on this notion of structural analysis. This article focuses on this approach in a bond graph context and more particularly to conclude about the model's structural invertibility. After having introduced the subject, section II establishes three necessary conditions for a model to fulfill structural invertibility. Section III shows an additional necessary structural condition if one desires to obtain an inverse model of minimal order and, section III presents the notion of the essential order for output specifications. Section IV shows how such a structural invertibility diagnostic can be beneficial for sizing mechatronic systems. Finally section V summarizes the main features of this approach and gives some directions that are worth investigating.**

I. Introduction

The need for a structural approach has appeared with the analysis of systems for which some parameters were numerically unknown or difficult to measure. The key idea of this approach is thus to focus on the determination of the system's structural properties which have the specificity to depend only on the types of physical phenomena involved in the system and on the way they are energetically connected to one another. In this way, the results of the analysis do not depend anymore on the parameter numerical values and give a deeper insight of the system's structure and behavior.

Even if this point of view is not yet well established industrially, much research has already been done on this subject. Up to now several methods or tools have been used to conduct this type of structural analysis. There are: the determination of the system's infinite structure [1], the geometric approach [2], an analysis of the 'system matrices' [3] or the use of the graph theory [4], [5].
However, as highlighted in [6], [7], the two last methods have the following drawbacks:

- These methods generally lead to a loss of information since the construction of the matrices (or the graph) is based on the state-equation which does not explicitly express the different physical phenomena involved and the way they are energetically interconnected.
- And so, by shadowing the system's physical structure, the results of the structural analysis are more difficult to match with physical interpretations.

Compared to these two disadvantages, bond graph language appears an efficient tool for managing structural analysis for at least two reasons. Firstly, as bond graph modelling is based on the representation of energy exchanges in the system, the bond graph model intrinsically incorporates the model structure from the energy point of view. Secondly, with its concept of multidisciplinarity and its graphical aspect, bond graph language seems to be more attractive since it facilitates the reading and the physical interpretation of the structural properties.
In the bond graph context, some research has already be done. Just to cite few of them, some research has proved the usefulness of a structural analysis for: controllability/observability [6], [8], monitorability [9], decoupling [10], pole assignment [11] and invertibility [7], [12].

This paper has been written precisely in the context of invertibility. Its aim is simply to present results extracted from literature with their interpretation and applications. For more details on the proofs, see the references quoted. Our main objective is to show how a bond graph-based structural analysis can be conducted and to what extend this approach can contribute to System Engineering, in particular for mechatronic system sizing. Based on previous works [12]–[17], this article summarizes the sizing methodology proposed by the AMPERE[1] laboratory and enlarges it to an additional time-differentiability condition for output specifications. In fact, the key idea is to consider the notion of the essential order of each output on the bond graph model.
The paper is organized as follows. After having recalled some definitions of structural properties and what they correspond to on a bond graph model, the second section states the necessary conditions for a model to be structurally invertible. In the third

[1]Since January 1, 2007, the LAI has merged with the CEGELY and a team of environmental microbiology to become the AMPERE laboratory (UMR CNRS 5005).

section, the concept of the causal path order is introduced and establishes a fourth condition if one desires to obtain an inverse model of minimal order. Then with the notion of the essential order of an output, a supplementary condition is given not to conclude about the model's structural invertibility but for correctly specifying outputs when simulating the resulting inverse model. Section IV briefly presents AMPERE's sizing methodology and shows the advantages of structural invertibility diagnostic in this type of sizing context. Finally section V summarizes the most important points and suggests directions of future research.

II. Necessary structural conditions for invertibility

In this section, it is shown how structural analysis can be carried out on a bond graph model in order to characterize its structural invertibility (for a given problem). Some bond graph concept definitions are briefly recalled and then necessary conditions for structural invertibility are formulated and illustrated by simple examples. Finally a graphic and systematic procedure for concluding about the model's structural invertibility is given.

A. Definitions

Before defining model inversion by bond graph approach, it is worth defining the following concepts.

Definition 1. *A* **power line** *is defined as a path for energy transmission between two points of the system. It corresponds to a series of powers related each one to another without a power appearing more than once in the sequence. Thus, on an acausal bond graph model, a power line between two components can be seen as a series of power bonds and multiport elements connecting these two components [16], [18].*

Definition 2. *A* **causal path** *is an ordered sequence of variables related each one to another by the equations of the model without a variable appearing more than once in the sequence. On a causal bond graph model[2], a causal path is then a series of effort and flow variables successively related according to the model causality assignment [13], [18].*

Definition 3. *An* **input/output (I/O) power line** *(resp.* causal path*) is a power line (resp. causal path) between an input and an output of the model. On a bond graph model, an I/O power line (resp. causal path) starts from a modulated element and goes to a detector (De or Df-element).*

Definition 4. *Two power lines (resp. causal paths) are said to be* **disjoint** *only if there is no power (resp. variable) in common [13]. This translates, by graphical disjunction of these two power lines (resp. causal paths), into the bond graph model.*

[2] *i.e.* on a bond graph model where the conventional causality has been assigned.

B. Necessary condition 1: Existence of disjoint *I/O power lines*

Necessary condition 1. *In order to be structurally invertible, there must be* at least *one set of* disjoint *I/O power lines on the acausal bond graph model.*

1) Interpretation: From a graphical point of view, bicausality assignment [19] (which is the extension of classical causality and which is used for constructing inverse models) is necessarily propagated along the bonds of the I/O power lines. Thus, for MIMO systems, the existence of partially joined power lines will cause more than one strong causality on one junction and then a causal conflict during the bicausality propagation: existence of at least one set of *disjoint* I/O power lines is necessary to avoid this type of causal conflict during the inverse model construction.
From a physical point of view, this simply means that if one desires to control a specific degree of freedom y from a specific input u, a path for energy transfer between this specific pair (u, y) must exist. For MIMO systems, the same reasoning can be applied for each specific pair (u_i, y_i) (so the problem has to be square) with the supplementary condition that paths for energy transfer have to be disjoint. Verifying the I/O power line disjunction thus enables a part of ill-posed problems in the sense of invertibility to be detected.

2) Examples: Fig. 1 and Fig. 2 illustrate this first condition for structural invertibility. The same bond graph model is considered for the two figures but with two different inverse problems:

- in fig. 1, the aim is to control the pair of outputs (y_1, y_2) from the pair of inputs (u_1, u_3).
- while in fig. 2, the aim is to control the same pair of outputs (y_1, y_2) but this time from the pair of inputs (u_1, u_2).

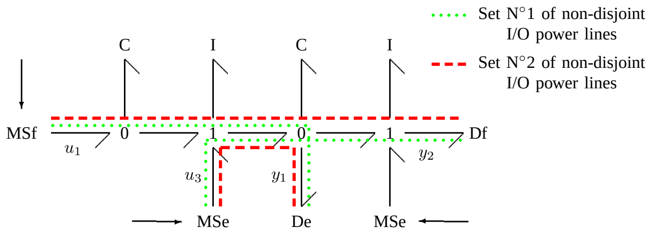


Fig. 1. Example of a non-existence of disjoint I/O power lines

Analysis of the I/O power lines leads then to the following results. In the case of fig. 1, there are two sets of I/O power lines between the inputs and outputs under consideration: $\{u_1\text{–}y_1, u_3\text{–}y_2\}$ and $\{u_1\text{–}y_2, u_3\text{–}y_1\}$. Unfortunately these couples of power lines are not *disjoint*: the model is not invertible with respect to the pair of inputs (u_1, u_3) and to the pair of outputs (y_1, y_2).

On the contrary, in fig. 2, there are also two sets of I/O power lines, $\{u_1\text{–}y_1, u_2\text{–}y_2\}$ and $\{u_1\text{–}y_2, u_2\text{–}y_1\}$, but one of them is composed of *disjoint* power lines. This model satisfies the first condition: it is potentially structurally invertible with

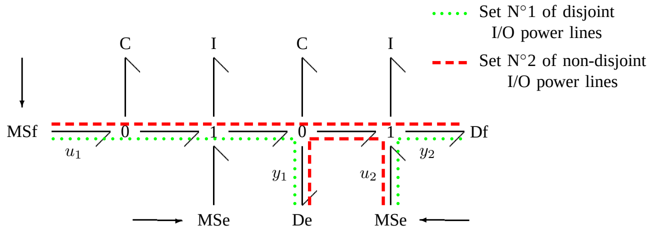
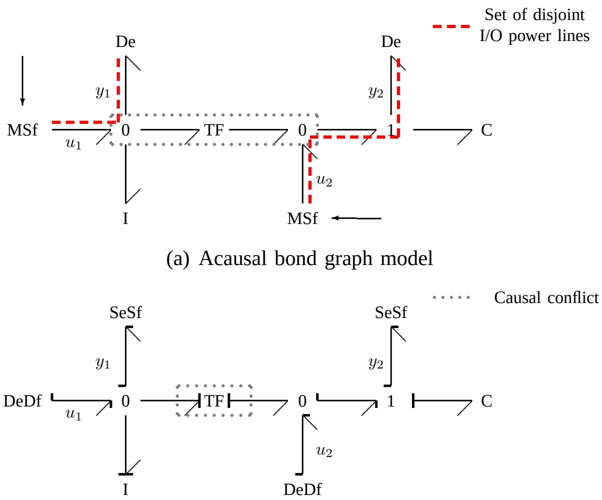


Fig. 2. Example of two sets of two I/O power lines

respect to the pair of inputs (u_1, u_2) and to the pair of outputs (y_1, y_2).

3) Comments: The adjective 'potentially' is of prime importance in the latter sentence and highlights the fact that the first condition is only necessary but not sufficient. In fact, the I/O power line disjunction does not lead necessarily to a correct bicausality propagation during the inverse model construction. Such a case is illustrated in fig. 3(a): there is one set of *disjoint* I/O power lines (they have no power bond in common) but the TF-element will not ensure a correct bicausality propagation (appearance of a causal conflict as in fig. 3(b)).



(a) Acausal bond graph model

(b) Bicausal bond graph model

Fig. 3. Example of two disjoint I/O power lines which do not ensure a correct bicausality propagation

However, the non-conflictual bicausality propagation can be *a priori* checked in two different ways:

- on an acausal level with the analysis of *independent* I/O power lines as introduced in [16] (but these kinds of power lines may be difficult to detect in practice).
- or on a causal level with the study of *disjoint* I/O causal paths, as it will be explained in the following section.

C. Necessary condition 2: Existence of a set of disjoint *I/O causal paths*

Necessary condition 2. *In order to be structurally invertible, there must be* at least *one set of* disjoint *I/O causal paths on the causal bond graph model.*

1) Interpretation: From a graphical point of view, if a set of *disjoint* I/O causal paths exists, this shows that bicausality can be correctly assigned without any conflict and then that it is possible to graphically construct the corresponding inverse model.
From a mathematical point of view, if no set of *disjoint* I/O causal paths exists, this means that the inputs could not be simultaneously expressed in terms of the outputs and thus that the model is not invertible for the given problem.

2) Example: Fig. 4 illustrates this second condition for structural invertibility. The same bond graph model and inverse problem as in fig. 2 are being considered. From the causal assignment, it can then be deduced that there is only one set of *disjoint* I/O causal paths: $\{u_1\text{–}f_2\text{–}e_2\text{–}e_3\text{–}e_4\text{–}f_4\text{–}f_6\text{–}f_7\text{–}e_7\text{–}y_1, u_2\text{–}e_{10}\text{–}f_{10}\text{–}y_2\}$. The model satisfies the first and the second condition: it is potentially structurally invertible with respect to the pair of inputs (u_1, u_2) and to the pair of outputs (y_1, y_2).

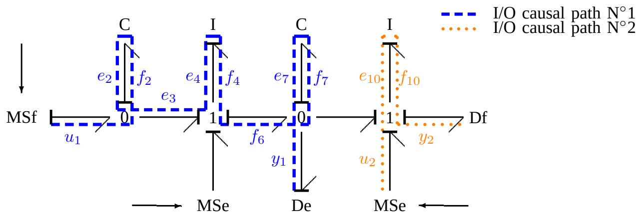
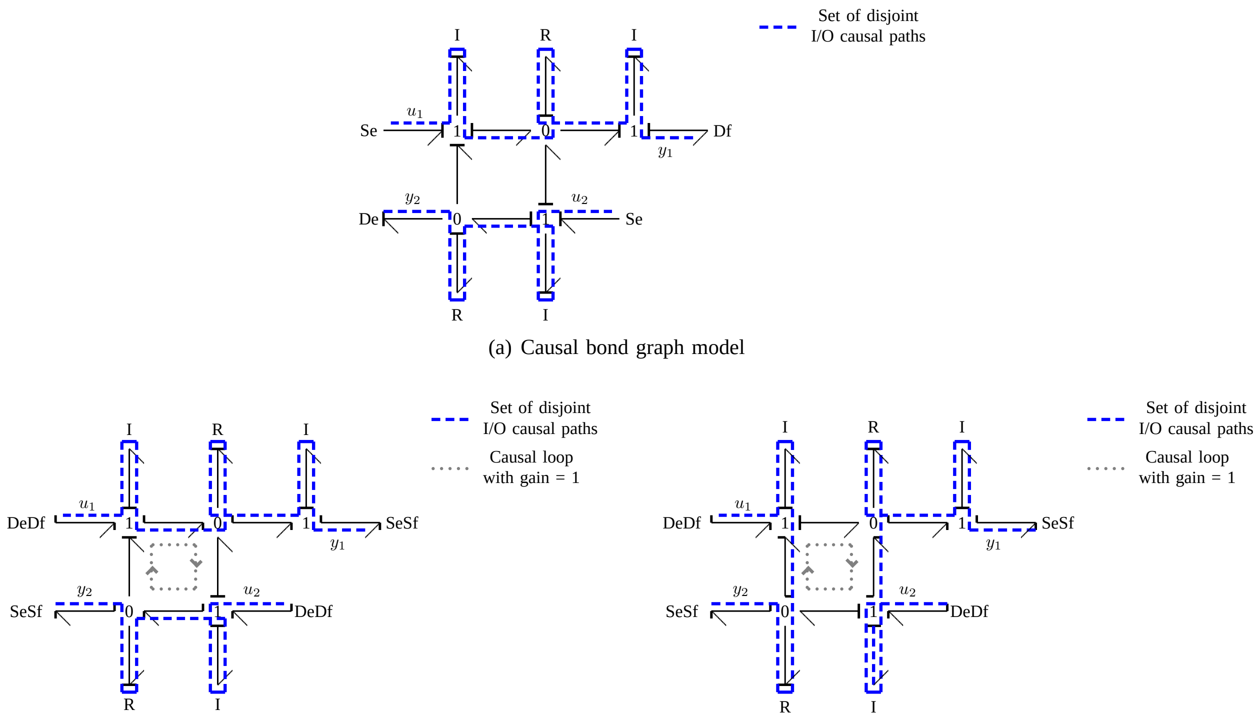


Fig. 4. Example of one set of two I/O causal paths

3) Comments: Once again it is worth noting the importance of the adjective 'potentially' because even if this second condition is more restrictive than the first one and it rejects some ill-posed problems that have not been detected with the I/O power line analysis, this condition is not sufficient for concluding about the model's structural invertibility. For instance, consider the causal bond graph model shown in fig. 5(a). There is at least one set of *disjoint* I/O power lines and one set of *disjoint* I/O causal paths. However any bicausality assignment in fig. 5(b) and in fig. 5(c) leads to a causal loop with a gain equal to 1: the junction structure is non-solvable and so the model is non-invertible for the sets of inputs and outputs under consideration. In fact the existence of a set of *disjoint* I/O causal paths on the causal bond graph model ensures only the bicausality propagation along the I/O power lines during the construction of the corresponding inverse model. But this existence does not guarantee that causality assignment, applied to the rest of the representation, will not lead to a non-solvable junction structure (even in the inverse model, external cycle and co-cycle constraints must be respected [20]). A test of this last condition must be conducted to conclude about the model's structural invertibility.

D. Necessary condition 3: Notion of solvable junction structure

Necessary condition 3. *The junction structure of the resulting inverse bond graph model must be* solvable.



(a) Causal bond graph model

(b) Inverse bond graph model 1

(c) Inverse bond graph model 2

Fig. 5. Example of a model satisfying the two first conditions but which is not invertible

1) Interpretation: From a mathematical point of view, this means that there is a sequence of causal assignments, which are *a priori* resolvable, between the set of inputs $\{u_i\}$ and the set of outputs $\{y_i\}$ and thus there is a way to determine each unknown u_i from one specified y_j: the model is structurally invertible (*i.e.* the model will in practice be effectively invertible on condition that the constitutive relations representing involved physical phenomena are mathematically invertible).

2) Example: Let consider the model shown in fig. 4 again. If we construct the corresponding inverse model, we will note that this leads to a solvable junction structure and so the model is structurally invertible with respect to the pair of inputs (u_1, u_2) and to the pair of outputs (y_1, y_2).

3) Comments: A procedure for the detection of non-solvable causal loops can be found in [20], [21] in order to check this third condition. However it is worth noting that the case of non-solvable junction structure can only appear in bond graph models containing bond cycles. So the third condition is automatically verified for bond graph models with tree structures.

E. Bond graph-based procedure for testing model inversion

Criteria for structural invertibility study can then be summed up into these two cases:

Case 1: If the acausal bond graph model contains no set of *disjoint* I/O power lines, the model is not invertible[3].
Case 2: If the causal bond graph model contains multiple sets of *disjoint* I/O causal paths, choose a set of *disjoint* I/O power lines for bicausality propagation. Construct the corresponding inverse model. If it leads to a solvable junction structure, then the model is structurally invertible. On the contrary, if for any chosen set of *disjoint* I/O power lines and for any of the causality assignments, it still remains a non-solvable junction structure, the model is not invertible. The model and/or the inverse problem have to be reformulated.

F. Structural analysis advantages and remarks

As written before, the main advantage of conducting a structural analysis lies in the fact that the resulting diagnostic does not depend on parameter values or on the form of the physical phenomena equations. The study of structural properties is carried out without inspecting the constitutive relations taken into account in the chosen model. Moreover, compared to classical inversion techniques based on mathematical manipulation [22], this approach offers the advantage to be entirely graphical and close to the physical meaning. Finally this is even more attractive since structural analysis can be automated as in the software MS1 [23]. On that subject, note that one of the power line advantages is that their study does not require causality assignment to the bond graph model and this could possibly lead to a gain of computational time.

[3]Attention has to be paid on the fact that we conclude only about the structural invertibility of the model and not of the physical system. Structural analysis is only conducted on how the modeler represents the physical system in his mind.

If the model contains no set of *disjoint* I/O power lines, non-invertibility can be directly concluded and this without assigning causality.

III. Structural condition for obtaining an inverse model of minimal order

This section shows how, after having concluded about the model's structural invertibility, the structural analysis carried out on the causal bond graph model can be used to obtain an inverse model of minimal order and to correctly specify outputs for simulating this inverse model.

A. Definitions

Before establishing the fourth structural condition, some additional notions have to be defined. Let us consider the linear time-invariant right-invertible system:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} = \mathbf{C}\mathbf{x} \end{cases} \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^n$ is the state vector and $\mathbf{u} \in \mathbb{R}^p$ (resp. $\mathbf{y} \in \mathbb{R}^p$) denotes the input (resp. output) vector.

Definition 5. *On a bond graph model in preferential integral causality, two I/O causal paths are said to be* **different** *if they have no dynamic element (I or C) in integral causality in common [7], [24].*

Definition 6. *On a bond graph model in preferential integral causality, the* **length** $l_k(v_i \to v_j)$ *of a causal path* p_k *between a variable* v_i *and another variable* v_j *is equal to the number of dynamic elements in integral causality met on this path [24].*

Definition 7. *On a bond graph model in preferential integral causality, the* **order** $\omega_k(v_i \to v_j)$ **of a causal path** p_k *between a variable* v_i *and another variable* v_j *is defined as the difference between the number of energy storages in integral causality and the number of those in derivative causality along this causal path [12].*

Definition 8. *On a bond graph model in preferential integral causality, the* **order** $\omega(S_k)$ **of a set** S_k *of* disjoint *causal paths is defined as the sum of the orders of the* m *causal paths constituting this set.*

Definition 9. *The* **relative degree** n'_i *of the output* y_i *represents the order of the infinite zero of* $(\mathbf{A}, \mathbf{B}, \mathbf{c}_i)$ *where* $\mathbf{c}_i$ *is the* i^{th} *row of* $\mathbf{C}$*. On a bond graph model, this* relative degree n'_i *is equal to* l_i *the length of the shortest length causal path between the output* y_i *and any inputs [10].*

Definition 10. *On a bond graph model, the number of the system's infinite zeros is equal to the number of* different *I/O causal paths. Moreover each* **infinite zero order** n_j *of* $(\mathbf{A}, \mathbf{B}, \mathbf{C})$ *is computed as follows [25], [26]:*

$$\begin{cases} n_1 = L_1 \\ n_j = L_j - L_{j-1} \end{cases} \tag{2}$$

where L_j *is the smallest sum of the lengths of* j different *I/O causal paths.*

Definition 11. *The* **essential order** n_{ie} *of the output* y_i *can be calculated as in [27]:*

$$n_{ie} = \sum_{j=1}^{p} n_j - \sum_{\substack{j=1 \\ j \neq i}}^{p} n'_j \tag{3}$$

Thus, on a bond graph model, the essential order n_{ie} *can be defined as follows [28], [29]:*

$$n_{ie} = L_p - \sum_{\substack{j=1 \\ j \neq i}}^{p} l_j \tag{4}$$

B. Necessary condition 4 for obtaining an inverse model of minimal order

Necessary condition 4. *In order to obtain an inverse model of minimal order, choose a minimal order set of* disjoint *I/O causal paths for propagating the causality during the construction of the corresponding inverse model.*

1) Interpretation: In fact, the term 'minimal order' for a minimal inverse model has two features. Firstly, this order is the minimal order the dynamic part of the inverse system can have. Secondly, this implies that outputs are differentiated (with respect to time) a minimal number of times during the inverse model construction. On a structurally invertible bond graph model, these two features are obtained by choosing a minimal order set of *disjoint* I/O causal paths [12].

C. Necessary condition 5: Output specifications for simulating an inverse model

Necessary condition 5. *In order to simulate an inverse model, one has to specify each output* y_i *so that its time-differentiability must be equal* at least *to its corresponding essential order* n_{ie}.

1) Interpretation: As demonstrated in [30], each essential order n_{ie} is equal to the highest derivation order of the output y_i appearing in the inverse model. Specifying appropriate outputs is thus needed for simulating such a model: if each specified output is not at least n_{ie} time-differentiable, it will be impossible to express (and so to calculate) the corresponding inverse model.

2) Example: In order to illustrate these fourth and fifth conditions, let us consider the fig. 4 causal bond graph again. In section II, structural invertibility has already been proved. Moreover, since there is a unique set of *disjoint* I/O causal paths, the corresponding inverse model will be necessarily of minimal order. Now, let us determine which condition of the output specifications must be satisfied in order to enable the resulting inverse model simulation.

The analysis of the I/O causal paths on the causal bond graph model leads to the conclusion that there are only four I/O causal paths, as shown in tab. I. The unique set of *different* I/O causal paths is $\{p_1, p_3\}$[4], so

[4]This set corresponds in fact to the set of *disjoint* I/O causal paths shown in fig. 4.

Output	Causal path	Order	Length	Shortest path
y_1	p_1	$\omega_1(u_1 \to y_1) = 3$	$l_1(u_1 \to y_1) = 3$	$l_1 = 2$
	p_2	$\omega_2(u_2 \to y_1) = 2$	$l_2(u_2 \to y_1) = 2$	
y_2	p_3	$\omega_3(u_2 \to y_2) = 1$	$l_3(u_2 \to y_2) = 1$	$l_2 = 1$
	p_4	$\omega_4(u_1 \to y_2) = 4$	$l_4(u_1 \to y_2) = 4$	

TABLE I

I/O CAUSAL PATH ANALYSIS FOR THE FIG. 4-EXAMPLE.

$L_2 = l_1(u_1 \to y_1) + l_3(u_2 \to y_2) = 4$. From the length of the two shortest length I/O causal paths, the essential order for each output can be calculated as follows: $n_{1e} = L_2 - l_2 = 3$ and $n_{2e} = L_2 - l_1 = 2$. Thus, to simulate the corresponding inverse model, y_1 and y_2 must be specified so that they are at least three and two times time-differentiable respectively. Finally note that the analysis of the I/O causal path orders is not sufficient to conclude about this output specification condition.

3) Comments: Contrary to classic inversion techniques which first construct a full order inverse model before reducing it, the main advantage of this fourth condition is that the minimal order inverse model is more directly obtainable without order post-reduction. Moreover, note that the notion of the essential order provides information not only about the inverse model but also about decoupling. In fact invertibility is a necessary condition for decoupling. If the essential order n_{ie} of each output y_i is equal to its relative degree n'_i, the system is decouplable by static feedback [27]. Invertible systems not decouplable by static feedback require a dynamic extension to achieve decoupling by static feedback [31]. In this case, the essential order gives the necessary dynamic extension order to decouple the system.

IV. USE OF A STRUCTURAL ANALYSIS IN A BOND GRAPH-BASED SIZING METHODOLOGY

In a design context, the study of the I/O power lines enables a better understanding of power exchanges in the chosen model and then can be used for architecture synthesis. In fact, in a context of a technological breakthrough where the modeler has *a priori* no idea about the optimal architecture, he can start with an initial bond graph model, analyze the I/O power lines and then check if the set of given outputs can *a priori* be controlled by a set of given inputs. If one set of such power lines exists, the architecture is *a priori* adapted. On the contrary, if no set exists, the modeler can highlight where his architecture is not suitable and has a graphical guideline for changing the architecture. Analysis of I/O power lines can thus be used for placing actuators and detectors.

In a sizing context, the AMPERE laboratory proposes a methodology based on the use of structural analysis and bond graph inverse models. This methodology aims at aiding an engineer in his design problem for sizing mechatronic systems depending on dynamic and energy criteria. Let us consider an actuated load system and suppose that the design problem is to find an appropriate actuator so that the load follows a given trajectory, this methodology can be summarized as follows [32]:

- Step 1: Load model structure/specifications adequacy: By carrying out a structural analysis on the load model, this step aims at checking if the sizing problem is well-posed in the sense of structural invertibility.
- Step 2: Load input specifications: Assuming that the load model is structurally invertible, this step consists of graphically establishing the inverse load model corresponding to the given sizing problem and simulating it so as to determine variables required at the entrance of the load and which match the specifications.
- Step 3: Component selection: As inputs of the load correspond to the outputs of the actuator, the engineer can thus select, in a library, actuators that appear suitable for the output specifications.
- Step 4: Validation: Finally, since actuators have been selected according to criteria only in terms of output variables, the engineer has to check if the specifications do not exceed the actuator manufacture data in input (and anywhere else in the inside). This step consists of coupling the actuator models to the load model, conducting another structural analysis to check if this new model is structurally invertible, determining the input variables by the use of the new corresponding inverse models and comparing the simulation results for these variables to the manufacturer's data.

Thus notion of structural analysis is, not only used for the adequation step, but for the validation step too. It allows the engineer to have a better insight of his sizing problem and this, at every step of the methodology. It enables him to check if the problem is well-posed in the sense of invertibility (and this without running a simulation) and if not, it gives graphical guidelines to correctly reformulate the problem. Finally, not only useful for checking, structural analysis can be helpful for specification writing with the concept of the essential order. As shown in section III-C, this notion allows the engineer to choose each specified output as sufficiently time-differentiable to be realizable by the chosen model structure.

V. CONCLUSION

Conducting a structural analysis clarifies some advanced aspects on dynamic system behaviour with results independent from any parameter numerical value. Focused on the study of structural invertibility, this paper presents three conditions that a bond graph model has to fulfill in order to be structurally invertible. It must have at least one set of *disjoint* I/O power lines, one set of I/O causal paths and the corresponding inverse model must have a solvable junction structure. Caution must be taken to the fact that this structural analysis concludes only about the model's structural invertibility and not about its invertibility. If one model is structurally invertible, one has to check if the equations involved are mathematically invertible in order to conclude about its effective invertibility.

In fact, this kind of structural diagnostic appears particularly interesting in an engineering context. Firstly for architecture synthesis with the analysis of I/O power lines and secondly for mechatronic system sizing with inverse modelling. The engineer is then able to detect if his sizing problem is well-posed and this, without inspecting the model equations or running any simulation. This represents a great gain of time for engineering departments when ill-posed sizing problems can be detected earlier in the design process. In this case, the engineer will then be able to make the difference between an error due to a structural non-invertibility and one due to simulation. Moreover, with the concept of essential order, structural analysis can help the engineer to write his specifications and then to correctly formulate his sizing problem.

Thus structural analysis appears as an efficient tool upstream of the simulation step and this is all the more attractive since, in fact, without changing the model representation or deriving the model equations, this can be applied for several engineering problems such as parametric synthesis, steady state research, determination of the open loop control, etc. Consequently, even if this kind of approach is not yet well established in engineering departments, efforts have to be made to promote it in companies. This is one of the objectives of the project RNTL SIMPA2 where, in collaboration with the industrial partners (PSA Peugeot Citroën, IFP, EDF), research is currently in progress to enable the structural analysis on a Modelica model to be carried out [32].

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