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The Importance of Physical System Modelling to Industry: System Models That Could Have Prevented Some Costly Mistakes

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Abstract: In order to develop new concepts into prototypes and ultimately into products, physical system modeling is virtually a necessity. At the concept stage, low order models are needed to understand the interactive dynamics of complex systems, and, as development proceeds into prototyping and manufacture, more sophisticated models may be needed to size components, determine fatigue life, plus more.

As the product becomes more and more defined, the modeling depends more and more on special purpose software packages that evaluate stress and strain, magnetic circuit design, fluid flow fields, etc. These packages require that the product is near final form, as the input files for these programs require details about the system that would not be known in the concept development stage.

The modeling discussed in this paper is specifically directed to the concept development of mechatronic systems. These systems typically involve multiple energy domains where electro-mechanical, -pneumatic, and -hydraulic devices are involved. Since the device or system is not well defined at this stage, the modeling must be handled by the inventors using physical principles, and assembling the various pieces of the model into an overall dynamic model that can be simulated.

Bond graphs are particularly well suited for concept development of multi-energy domain systems. This is demonstrated here using several examples where modeling at an early stage of development would have avoided some very costly mistakes.

Keywords: Physical System Modeling, Bond Graphs, Analysis, Simulation

1. INTRODUCTION

In this paper, several examples are presented where production was reached for a particular product only to discover that the product did not work as expected. Production was delayed, in some cases, for months, and the costs were enormous. In some cases, once the physical system was understood, a relatively simple fix could be employed. In other cases, the flaw was not addressable with a simple fix, and costly redesign was necessary. In all cases, physical system understanding at the concept stage would have avoided the problem. It is true that hindsight is perfect, and these examples are not to be misconstrued as criticisms of any particular company or group. These examples point out the necessity for modeling an overall system at the concept level. Since real engineering systems involve many complex components in several different energy domains, tools are needed that allow straightforward representation of complex systems in multiple energy domains and straight forward assemblage of these components into overall, system models ready for simulation.

Bond graphs are a concise pictorial representation of all types of engineering physical systems. With very few symbols, all energetic systems can be represented. Once a bond graph has been derived, state variables are automatically selected and formulation problems are exposed through assignment of causality. Each system component can be derived separately and then the final overall bond graph can be assembled from the components. The end result is an analytical or computational model that contains all the interactive dynamics of the overall, multi-energy domain system. In most cases, the bond graph model is directly interpretable by specialized software such that the modeler does not have to derive any equations his or herself. Instead, equations are derived, simulated, and results plotted, automatically. There is a wealth of literature about bond graph modeling. The Bond Graph Compendium is a website that cites literally thousands of technical papers that use bond graphs. Karnopp et al is a text that develops bond graph modeling from the elementary concepts to the modeling of very complex mechatronic systems. Examples of commercial software that processes bond graphs into simulation programs include CAMP-G, TwenteSim and AMESim.

Modeling and simulation is used extensively throughout industry to aid in system understanding, prototyping, and commercialization. Much of this work is, of course, not published. However, The Bond Graph Compendium is an excellent starting point to locate examples of industrial modeling as are the Transactions of the Society for Computer Simulation.

2. BOND GRAPH BASICS

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It is not possible to understand bond graph modeling in this brief introduction and the interested reader is referred to the text by Karnopp et al. Bond graphs are based on energy flow or power flow between different energy domains in a system model. The power is carried by bond (straight line) connecting subsystems of the model. A half-arrow on a bond end indicates positive power flow direction.

There are only 4 variables that are used. The power variables are effort e and flow f, the product of which is power. There are 2 defined variables called the energy variables: momentum, $p = \int e\,dt$ and displacement $q = \int f\,dt$. Table 1 shows the effort, flow, momentum, and displacement variables for several energy domains typical of physical systems.

There are 9 basic elements that have physical counterparts in the various energy domains. These basic modeling elements are shown in Table 2 and these are all that are needed for a large number of physical system models. The R-element is a dissipative element while the I-element and C-element ideally store and return energy to the system. The source elements S_E and S_F are effort and flow sources that are used to excite the system with a known input or to control the system when the outputs from these elements are set by other variables. TF and GY elements are the transformer and gyrator respectively and these elements allow the crossing of energy domains so that multiple domains can be represented in the same overall model. The 0- and 1-junctions are the junction elements that direct and add power flow according to the model constraints. Assembling a model using these 9 elements follows a procedure described in Karnopp et al.

A unique feature of bond graph modeling is that algebraic issues in formulation are exposed through straight forward assignment of causality. Causality is indicated by the perpendicular mark at a bond end. The causal assignment dictates the state variables regardless of the complexity of the system. The following examples are taken from experiences where bond graph modeling proved to be invaluable.

3. TRUCK ISOLATION SYSTEM

A company developed a vibration isolation system for use on the back of heavy truck cabs. These cabs are pivoted with stiff mounts at the front, and the soft isolators are located on the left and right side of the cab at the rear. The isolators consist of fluid filled displacers (piston/cylinder devices) attached by a fluid filled hose to an air charged accumulator. The displacers are about 10 cm in diameter, the hose is about 2.5 cm in diameter, and the accumulators are 30 cm diameter spheres. A schematic of the system is shown in Fig. 1 along with the system bond graph.

The physical system modeling is completed when the schematic of Figure 1 is drawn. Decisions have already been made as to what dynamics are important and must be included in the model and what dynamics can be neglected. It has been decided that only vertical dynamics of the cab are important, that the cab can be represented as a single point mass, that the fluid inertia of the tube is important as well as the fluid resistance of the valve, and that the volume compliance at the tube termination can be represented as a linear element. The decisions that went into retaining certain dynamic effects while rejecting others are “Engineering Decisions” and come from physical understanding of the system being developed. There really is no mathematics associated with these decisions. However, the schematic is not useful if predictions cannot be made about the system performance and this is where bond graph modeling becomes extremely useful.

The company that proposed this isolation system went on to prototype, test, and commercialize this system. It was assessed by one customer as a superior isolation system and purchased for inclusion in their product. However, when another customer tested the same product, their evaluation determined that the system was extremely poor and that ride was much better without the isolation system installed. Obviously, the developers of this product did not understand the fundamental behavior of their system.

When queried about the effects of "fluid inertia," the company stated that this was considered and deemed not to be a problem because the cab weighs about 1136 Kg and the total weight of the fluid is only 3 Kg. This constituted a fundamental misconception that would not have been made had a hydro-mechanical model of their system been formulated.

From the bond graph of Fig. 1, using procedures from Karnopp et al, we write directly from the bond graph,

$$p_f = I_f A_p \left(v_{in} - \frac{p_m}{m} \right). \tag{1}$$

The state equations become

$$\dot{p}_m = A_p \frac{q_a}{C_a} + A_p R_f \left(v_{in} - \frac{p_m}{m} \right) + A_p \dot{p}_f \tag{2}$$

and

$$\dot{q}_a = A_p \left(v_{in} - \frac{p_m}{m} \right). \tag{3}$$

Since this is modeled as a linear system, a transfer function and frequency response can be analytically evaluated. If the derivative of (1) is substituted into (2) and the transfer function derived, the result is,

$$\frac{v_m}{v_{in}} = G \frac{(s^2 + 2\varsigma_0 \omega_0 s + \omega_0{}^2)}{(s^2 + 2\varsigma_n \omega_n s + \omega_n{}^2)} \tag{4}$$

where,

$$G = \frac{m_e / m}{1 + m_e / m}, \tag{5}$$