8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

Automated Modeling of Complex Mechanical Systems Using Bond Graph

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Key Words: *Automated Modeling, Interconnected Systems, Bond Graph, Lagrangian Systems*

ABSTRACT

For the sake of development of a large scale complicated mechanical systems such as clutch screw press machines manufacturing large blades of gas turbine compressors or steam turbines for power generating system, it is indispensable for engineers to rapidly make virtual prototypes on computer, that is, mathematical models for testing their performance, functioning as well as reliability to ensure product specification and competitiveness. To do this, it is quite essential not only to make an exact model of the whole system of our concern, but also to isolate physical properties to identify them by properly idealized physical elements such as mass, spring, damper and so on. In the mathematical modeling of such complicated mechanical systems, it is inevitable to deal with a large number of variables and physical parameters induced from kinematical and dynamical relations such as kinematical constraints, coordinate transformations and equilibrium conditions of forces. Engineers who design and develop such complicated mechanical systems, therefore, need a computer-oriented modeling method to automatically generate virtual prototypes, namely, mathematical models of the complicated mechanical systems as well as to make realtime simulations by using them on computer for the design and analysis of the original real machines.

In this presentation, we propose an automated modeling methodology of complex mechanical systems by using *bond graph*. First, we show our main strategy of the proposed automated modeling methodology originally developed by Kawase and Yoshimura [1991], Yoshimura and Kawase [1993] and Yoshimura [1995], where a network-theoretical approach to nonlinear mechanical systems such as flexible multibody systems with nonholonomic constraints was presented by fully utilizing the analogy of electric network theory. In this context, we categorize required relations for modeling any mechanical system into the following three ones; namely, (1) *physical*, (2) *structural* and (3) *causal* relations. The physical relations denote physical properties given by constitutive relations of elements such as inertia, flexibility, dissipation and so on, while the structural relations indicate how the physical elements are energetically interrelated, which are to be represented by a set of kinematical and dynamical relations induced from kinematical constraints, coordinate transformations as well as inertia coupling torques. The causal relations allocate input-output relations consistently among physical variables appeared in the structural relations as well as the physical relations. Thus, it is shown that we can regard any complicated mechanical system of our concern as an *interconnected system* that is an aggregation of a system structure and physical elements with causality. Second, we make a virtual prototype on computer, namely, an idealized model of the mechanical system that is symbolically represented as bond graph models, by which one can easily understand how the energy flow of the mechanical system is regulated through the system structure modeled by nonenergic multiports (see Wyatt and Chua [1977]); in other words, the system structure shows how physical elements are energetically interconnected

through nonenergic multiports in bond graph models. Notice that a notion of nonenergic multiports is a generalized idea of *nonenergic systems* that was originally coined by Birkhoff [1927] in the context of Lagrangian mechanics. The physical properties given by constitutive relations of physical elements such as mass, spring and damper can be also symbolically represented by bond graph symbols of physical elements, which are to be incorporated into a set of equations of motion as to *primitive systems*. Here, we utilize the term "primitive system" in the sense of Kron [1963], which indicates a totally torn apart subsystem.

From the viewpoint of analytical mechanics, primitive equations of motion associated with conservative physical elements such as mass and spring may be represented by the Lagrangian or Hamiltonian formalism. When we consider any dissipation due to damping factors as well as nonconservative external forces, we need to make some modifications in order to fit them into the Lagragnain or Hamiltonian equations of motion. When a Lagrangian $L(q,v)$ is given, primitive equations of motion for the physical elements may be given by

$$\dot{q} = v, \quad \frac{d}{dt}\frac{\partial L}{\partial v} = \frac{\partial L}{\partial q} + F + Q,$$

where q denotes generalized coordinates, $\dot{q}$ time derivative of q, v generalized velocities, F nonconservative external forces including damping forces and Q constraint forces associated to kinematical constraints. Note that the Lagrangian L is not necessarily regular but degenerate in general.

Furthermore, the structural relations are to be interconnected with the above-mentioned primitive equations of physical elements, where the interconnection can be given by kinematical constraints and their dual dynamical relations, which can be systematically formulated by the *duality principle* proposed by Yoshimura [1995] (see also Yoshimura and Kawase [2001]) and those structural relations can be effectively represented by using *dual connection matrices* N and B as

$$N(q)\,\dot{q} = 0, \quad B^T(q)\,Q = 0,$$

where the orthogonal complementarity condition $B^T(q)N^T(q) = 0$ holds. As to the causal relations, the *causal connection matrices* $\bar{N}$ and $\bar{B}$ are introduced, which indicate the *input-output relations* in association with N and B.

In the presentation, we will show how the dual connection matrices can be systematically obtained by the duality principle and also how system equations of mechanical systems can be automatically generated in the Lagrangian context along the above modeling strategy. Additionally, we will demonstrate the proposed modeling methodology by some illustrative examples of mechanical systems and electric circuits, together with their bond graph models.

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