Modeling Approach of Functional Model for Multidomain System∗

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Modeling approach to obtain unified, hierarchical and legible model for multidisciplinary system is very important for performance prediction and analysis in complex system design. In this paper, graphic modeling methods, such as the use of block diagrams, bond graphs, functional models and object-oriented models, are reviewed firstly. Then, the modeling methods of bond graphs and functional models are compared, and a set of simplified fundamental items and a systematic modeling procedure to establish functional models are proposed. Finally, the proposed modeling method of functional models is applied to several examples of electrical, mechanical and hydraulic systems, and simulations performed on Simulink verify the practicability and effectiveness of the proposed modeling approach. The proposed modeling approach of functional models helps engineers to carry out modeling in an orderly way, so that the functional modeling method can be used by more engineers and applied in engineering analysis.

Key Words: Modeling, Simulation, Power Flow, Functional Model, Block Diagram, Bond Graph

1. Survey of Graphic Modeling Methods

The graphic modeling approach to bridge the gap between the physical and mathematical descriptions of engineering systems is one solution to establish a legible system model. In this section, several graphic modeling and simulation methods are reviewed.

1.1 Block diagram method

The use of block diagrams, as a kind of graphic modeling approach, can conveniently express mathematical equations in a graphic way. Blocks, the main components of a block diagram, represent a certain mathematical function and are connected to each other by directional lines used as block inputs and block outputs. The capability of a block diagram to group blocks into a subsystem allows a hierarchical model to be built for a complex system. Even though a block diagram can be quickly established from a system equation using a block network of mathematical operators, it is hard to create directly from a physical system. Furthermore, it is difficult for a block diagram to illustrate the physical structure of a system and to express a multidomain system in a unified way. The computation of a block diagram model is directly performed block by block at each time step. When the input of one block is driven by the output of the same block or by a feedback path through another block, an algebraic loop generally occurs. An algebraic loop arises when a DAE (differential algebraic equation) system is modeled or when the model includes an algebraic constraint due to the physical interconnectivity in the system. Block diagram simulators, such as Simulink and SystemBuild(1),(2), are particularly useful in designing a control system. The capability of Simulink to solve algebraic loops helps to work out general engineering problems relevant to both ODEs (ordinary differential equations) and DAEs.

1.2 Bond graph modeling method

The dynamics of a physical system stems from the power exchange among system components. Effort and flow are the general power variables of a multidomain
system, whose product is interpreted as power\(^3\). Power exchanged among the components of a physical system is described as power flow. The bond graph approach developed by Paynter\(^4\) in 1961 is a power-flow-based graphic modeling method with the capability to establish a domain-independent model in a unified form on the basis of power conservation and the analogy of power descriptions among different systems. The system state-space equation derived from the bond graph model is used for numerical analysis. The bond graph approach has evolved into a lot of simulators, such as Enport (Rosenberg, R., 1974), MSI (Lorenz, F., 1997), CAMP-G (Granda, J.J., 1985), 20-SIM (Broenink, J.F., 1990), MTT (Gawthrop, P.J., 1991)\(^4\)--(9). However, a highly organized modeling schematic of a bond graph is far from being understood at a glance of model due to its special modeling symbols and structure, and such difficult readability influences the acceptance of the bond graph and its application in engineering. A hybrid model of a bond graph and a block diagram will be a more powerful programming tool for many practical simulations\(^{10}\).

1.3 Functional model method

The functional model method proposed by Sumida, S., Nagamatu, A. and Nagamatu, M. in 1998\(^{10}\)--(14), as another kind of power-flow-based modeling method, illustrates power flow transmission by the effort-flow structure of the functional model. The simulation process of the functional model is to solve system equations derived from the functional model, which is similar to that of the bond graph method. Both the functional model and bond graph can show the topology of a physical system, while the functional model is more acceptable to engineers because its modeling symbols and structure are closer to those used in engineering. The expansion and unification of functional models make it easy to set up hierarchical models from small-scale to large-scale systems. The functional model can only describe a linear system, nevertheless an additional mechanism model representing nonlinear property can cooperate with the functional model to solve the nonlinear problem by controlling the element parameter in the functional model during the simulation process. From this point of view, the functional model approach to solving the nonlinear problem is indirect. Moreover, special tools are indispensable for translating the functional model into a system state space equation, which limits the practicability of the functional model method in engineering. Some investigations in the modeling and simulation of engines, powertrains, and the virtual testing of automobiles demonstrate the power of the functional model in the virtual product and prototype development of automobile\(^{15}\)--(21).

1.4 Object-oriented modeling method

The object-oriented modeling approach, another kind of graphic modeling method developed after the late 1980s, builds noncausal modeling on an object-oriented construct stemming from modern software, and performs simulation using a system equation derived from an object-oriented model. Noncausal modeling allows the object interface to be defined as pairs of variables that are not committed to an input or output role, and allows the internals of an object to be completely encapsulated. The object-oriented construct facilitates the reuse of models and model parts by the sharing of description parts among objects according to a hierarchical relationship. Based on these modeling technologies, the modeling of a physical system is performed as follows. Firstly, the object model is built up in a textual program using an object-oriented modeling language and is encapsulated into a graphic icon, and then the graphically represented model is set up as interconnected object icons. Even though the final system model is displayed graphically, most modeling procedures are performed to make textual programs that describe the physical properties of objects rather than to use a graphic description to get a graphic model of the physical property directly. Moreover, a mathematical expression of the object has to be derived in advance and be written into the program, which will make the user a software builder rather than a modeler of a physical system. Many object-oriented modeling languages have been developed, such as Dymola (Elmqvist, H., 1978), ASCEND (Piela, P.C., 1989), Omola (Mattsson, S.E. and Andersson, M., 1988 – 1998), ObjectMath (Fritzson, P., Engelson, V. and Viklund, L., 1993), NMF (Sahlin, P., Bring, A. and Sowell, E.F., 1994), gPROMS (Barton, P. and Pantelides, C., 1994), Smile (Kloas, M., Friesen, V. and Simons, M., 1995), ULM (Jeandel, A., Ravier P. and Buhsing, A., 1995), SIOOPS+ (Breunese, A.P.J. and Broenink, J.F., 1997), Modelica (1997), and VHDL-AMS (IEEE Std. 1076.1-1999)(22)--(31). Based on these object-oriented languages, many modeling and simulation environments are developed, such as Dynasim (Dymola-based), Omsim (Omola-based), ObjectMath (ObjectMath-language-based), Modelica (Modelica-language-based), SIMPLORER 6 (VHDL-AMS-based)\(^{32}\), and Saber software (VHDL-AMS-based)\(^{33}\). Model representation and modeling concepts in some of these tools are only practical in one physical field not yet suitable in obtaining a unified model for a multidisciplinary system. Multidomain modeling tools such as Modelic are still being developed for practical use in engineering. Although the bond graph approach can also be regarded as a form of object-oriented approach in that its port- and equation-based modeling concepts are similar to those in the object-oriented approach\(^{34}\), their fundamental modeling methods are different, that is, bond graph modeling is based on the graphic description of physical properties, while object-oriented modeling is based on the language description of physical properties.
2. Comparison of Bond Graph and Functional Model Methods

In this section, bond graph and functional models are compared with each other.

2.1 Comparison of basic element

The bond graph is composed of nine basic elements: 1-port elements of resistor, inertia and capacitor representing a constitutive law between the power variables of effort and flow respectively; 1- and 0-junctions named common effort junction and flow junction, respectively, representing the relationships among the variables of effort and flow attached together; 2-port elements of TF (transformer) and GY (gyrator) representing the power transmission relationship between two neighboring bonds; the source elements of \( S_f \) and \( S_e \) supplying power input into the system. On the other hand, the functional model, as stated in Refs. (11) – (14), is composed of two sets of main symbols for linear and nonlinear modeling respectively and a set of main unit functional elements. Main unit functional elements correspond to 1-port elements in the bond graph. Main symbols represent some mathematical operations. The combination of symbols of plus and partition can act as junctions in the bond graph, and the symbols of multiply can play the roles of \( TF \) and \( GY \) in the bond graph.

2.2 Comparison of structure orientation

In the bond graph, the half arrow of the bond indicates the direction of the power flow, and the bond stroke assigned by causality analysis indicates which variable is the input of the bond and which is the output. In the functional model, the directions of effort and flow signal lines correspond to the arrow of the bond, and the element direction corresponds to the bond stroke. Therefore, causality analysis in the bond graph can be adopted in the functional model modeling in assigning the directions of effort and flow and that of the element unit.

2.3 Comparison of modeling and simulation procedures

Modeling procedures to set up unified bond graph model directly from different physical systems have been summarized as modeling guidance\(^\text{(4)}\). However, to date, a general modeling approach for establishing a functional model directly from a physical system has not been investigated. When all bond strokes in a bond graph are assigned, the system equation can be automatically derived from the bond graph model. The simulation of the bond graph is used to solve the derived system equation. As to the functional model, a similar simulation process is carried out to derive the system state equation from the functional model and to solve the equation to obtain numerical analysis results.

3. Modeling Approach of Functional Model

Based on the comparisons between the bond graph and functional model, a set of simplified symbols to describe the necessary requirements for the functional model structure and constitutive relationship, and a systematic procedure to generate a functional model directly from a physical system are summarized in the following sections.

3.1 Fundamental items of functional model

1. Effort-flow structure: the power variables of effort and flow used in both the bond graph and functional model are the same. The main graphic frame of the effort-flow structure in the functional model is composed of two signal lines representing effort and flow in opposite directions to indicate power flow transmission in the same way as bond illustrates power flow transmission in the bond graph. Therefore, the effort-flow structure can describe a multidisciplinary system in a unified format based on power conservation and modeling analogies involving in various energy types.

2. Element unit: The element unit connected between the effort and flow lines represents the constitutive law of the element, as shown in Table 1. The physical parameter and mathematical operations representing the constitutive law of the element are embedded in one block, the same as the 1-port elements of the bond graph. Both linear and nonlinear physical properties can be melded into a block of the element unit. This block description of the element unit is different from the main functional unit in the original functional model as stated in Refs. (11) – (14), which can only demonstrate linear constitutive properties in that the constitutive law of the element unit is described in terms of constant physical parameters and in-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Element unit in various physical systems</th>
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<tbody>
<tr>
<td>Translatory system</td>
<td>Rotational system</td>
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<tr>
<td>Inertia unit</td>
<td>Force ( \rightarrow ) ( \dot{X} \rightarrow ) Velocity ( \rightarrow ) ( \dot{F} \rightarrow ) ( \dot{F} \rightarrow ) ( \dot{F} \rightarrow ) Angular Velocity</td>
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<tr>
<td>Capacitor unit</td>
<td>Velocity ( \rightarrow ) ( \dot{X} \rightarrow ) Force</td>
</tr>
<tr>
<td>Resistor unit</td>
<td>Velocity ( \rightarrow ) ( \dot{X} \rightarrow ) Force</td>
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tegrals or derivative operations. Therefore, the presented block description of the element unit can simplify nonlinearity modeling with no need to set up a mechanism model for nonlinear properties.

(3) Connector: a pair of connectors, distribution connector and sum-to-zero connector, are used as the general connections to attach signals together as 1-junction and 0-junction attach bonds in the bond graph. All signals attached to the distribution connector are identical; the algebraic sum of all signals attached to the sum-to-zero connector is zero and there is only one output signal. The sum-to-zero connector corresponds to the general Korchhoff’s current law. When an element unit is connected with an effort-flow structure, a pair of distribution and sum-to-zero connectors are attached to both ends of the element unit. The pair of flow distribution and effort sum-to-zero connectors corresponds to the 1-junction in the bond graph, and the pair of effort distribution and flow sum-to-zero connectors is equivalent to the 0-junction in the bond graph.

(4) Transformer: A transformer is inserted into the signal lines of both effort and flow, respectively, between two effort-flow structures to conserve power between different components within the same domain or between different physical domains. Such a description of a transformer is different from that stated in Refs. (11)–(14), in which only one matrix is adopted to implement the transmission relationship of power. The two transformer connections of effort with effort and flow with flow in functional model play a role as $TF$ in bond graph, while two transformer connections of effort with flow and flow with effort act as $GY$ in the bond graph.

(5) Signal source: Signal sources, that is, the effort and flow sources corresponding to $S_e$ and $S_f$ in the bond graph, respectively, represent the interaction of a system with the environment and supply energy input into the system.

(6) Causality: The directions of the effort-flow structure and element unit depend on causality analysis, by which the computational directions of the effort and flow input and output of the element unit are assigned. Such assignment of direction is similar to the assignment of bond stroke in the bond graph. The procedure for causality analysis in the functional model can be summarized in accordance with the causality analysis process in the bond graph, and it can be performed in the following sequence. Firstly, the directions of effort and flow connected to the power source are assigned in the positive power direction. Secondly, the causality of the inertia and capacitor units is assigned. Integration causality rather than derivative causality is recommended. One important limitation inherent in derivative algorithms is that the time step for derivative causality must be smaller than that for integral causality to achieve computational convergence and accuracy. Finally, the resistor unit is inserted directly between the effort and flow in a direction compatible with its neighbors.

In summary, these simplified basic elements of the functional model can find their counterparts in the nine basic elements of the bond graph, that is, element units correspond to 1-port elements in the bond graph, a pair of general connectors play the role of 1-junction or 0-junction; two transformers act as $TF$ and $GY$; effort and flow signal source correspond to $S_f$ and $S_e$ in the bond graph, respectively. Therefore, the functional model and bond graph can be interconverted by replacing their corresponding basic elements.

3.2 Modeling procedure of functional model

A systematic procedure for generating a functional model directly from a multidomain physical system is generalized on the basis of the modeling procedure of the bond graph and similarities between the functional model and bond graph. In this procedure, the modeling processes for the mechanical domain and nonmechanical domain are the same; however, the variable used as a reference to establish the effort-flow structure in the nonmechanical or mechanical system is different, that is, effort is regarded as the reference variable in the nonmechanical domain and velocity the reference variable in the mechanical domain. The modeling procedure is as follows.

(1) A lumped-parameter model that describes physical properties of the engineering system is established, which should be simple if the accuracy requirement of engineering is met. The different physical domains and their relative element units are identified and modeled into one subsystem, and each subsystem can be built up individually according to steps 2 to 5. Hierarchical modeling arrangement can be carried out if a subsystem is complicated.

(2) The effort-flow structure is set up for each reference variable. In the nonmechanical domain, the effort-flow structure for each effort variable is set up with the attachment of a pair of flow sum-to-zero and effort distribution connectors; in the mechanical domain, the effort-flow structure for each velocity variable is built up with the attachment of a pair of force sum-to-zero and velocity distribution connectors.

(3) The element unit and signal source connected to the reference variables are attached to their corresponding effort-flow structure in accordance with causality analysis. Parameters in the elements are determined by parameter identifications corresponding to the physical properties.

(4) The difference between two neighboring reference variables is taken into consideration if some element units are relevant. In the nonmechanical domain, a pair of effort sum-to-zero and flow distribution connectors are inserted between the two neighboring effort-flow structures to indicate such a difference; in the mechanical domain, a
pair of velocity sum-to-zero and force distribution connectors are inserted. Then, the element unit relating to such a variable difference is attached in accordance with causality analysis.

(5) The transformer is inserted along the continuous power flow line. Subsystem models are encapsulated and arranged in a hierarchical manner to assemble the entire system model.

Two kinds of simulation process can be performed for functional model simulation. One method is to derive a system equation from the functional model and to perform numerical computation of the equation as in the bond graph approach, however, it is necessary to have a special tool to translate the functional model into a system equation. The other method is to carry out computation directly on the functional model without derivation of the system equation. In this method, block-based numerical computation can be adopted and calculation is performed block by block at each time step. In this paper, we mainly investigate the second simulation method using Simulink.

4. Applications

Several typical examples are investigated to demonstrate the validity and practicality of the proposed modeling approach for the functional model. The modeling and numerical computation of functional models are performed on Simulink. Comparisons of the block diagram, functional model and bond graph model are also presented.

4.1 Electrical system

The functional model of a simple electrical circuit, as shown in Fig. 1 (c), is built up as follows. Firstly, the electrical circuit is divided into three parts: signal source, subsystem 1 with resistor $R_1$ and capacitor $C$ in series, and subsystem 2 with resistor $R_2$ and inductor $L$ in series. Secondly, the effort-flow structure is set up for voltage variables in each subsystem. Two pairs of voltage sum-to-zero and current distribution connectors are established for $R_1$, $C$ and $R_2$, $L$, respectively. Finally, the two subsystems are encapsulated and assembled into a whole system model by the two pairs of current sum-to-zero and voltage distribution connectors built up for each subsystem respectively. This functional model better illustrates the topology of the physical structure than the block diagram set up from the system equation shown in Fig. 1 (b).

4.2 Nonlinear mechanical system

A nonlinear mechanical system with typical nonlinearities of spring stiffness and friction, as shown in Fig. 2 (a), is investigated. The functional model, as shown in Fig. 2 (b), is set up directly from the physical model according to the following procedures. Firstly, the structures of $F_i - V_m$, $F_i - V_0$, and $F_s - V_s$ are set up. Secondly, a pair of velocity sum-to-zero and velocity distribution connectors are inserted to indicate the velocity difference between $V_s$ and $V_0$. Thirdly, force source of $F_i$ is added and the element units of Mass $M$, damper $D$ and Spring $K$ are connected with their corresponding force-velocity structures using force sum-to-zero and velocity distribution connectors in accordance with causality analysis. Fourthly, transformer $R$ is inserted into the effort and flow signal lines respectively between structure $F_i - V_m$ and structure $F_s - V_s$ to conserve power transmitted through the lever. Finally, the element unit of $V_{ars}$ and friction control block are set up using the $S$ function.

Fig. 1 Models of an electrical circuit
In the element unit of Varstiff, two-stage stiffness property is defined. In the friction control block, the friction between $M$ and the ground is divided into two stages: the stage of static friction when $M$ does not begin to move and the stage of coulomb dynamic friction that is proportional to the pressure on the slide surface when $M$ slips on the ground. This example shows that nonlinear property can be conveniently embedded into blocks of element. Such nonlinearity modeling is more direct and simpler than the nonlinear description of the mechanism model presented in Ref. (11), as shown in Fig. 2 (c). The simulation results of the proposed functional model illustrated in Fig. 2 (d), are in agreement with the numerical results from both the system equations and numerical results of Fig. 2 (d) in Ref. (11).

### 4.3 Suspended body

A typical suspended body is studied, whose physical model, as shown in Fig. 3 (a), is set up based on the assumptions of small angular and translational motions in the plane while neglecting horizontal motion. Its functional model shown in Fig. 3 (b) can be directly established from the physical model as follows. Step 1, establish effort-flow structures with effort sum-to-zero and flow distribution connectors, one force-velocity structure of $f_g - v_g$ for the translatory motion of $M$, two torque-angle velocity structures of $T_1 - \omega_1$ and $T_2 - \omega_2$ for the rotational motion of $J$ at the suspended points, and two force-velocity structures of $f_1 - \dot{x}_1$ and $f_2 - \dot{x}_2$ for the translatory motions of the two suspensions. Step 2, insert two pair of velocity sum-to-zero and force distribution connectors to connect the structures of $f_1 - \dot{x}_1$, $f_2 - \dot{x}_2$ and $T_1 - \omega_1$, $T_2 - \omega_2$ with the structure $f_g - v_g$. Step 3, a force generator is added and the element units of $K$, $C$, $M$, and $J$ are attached to their corresponding effort-flow structures in accordance with causality analysis. Step 4, insert transformation coefficient blocks of $L_1$ and $L_2$ to indicate the power transmission relationship between the body rotational and translatory motions of the two suspensions. This functional model can also be converted from the bond graph model shown in Fig. 3 (c) by replacing the corresponding items. However, the model topology of the functional model is closer to that used in engineering and is more acceptable for engineers than that of the bond graph model. The simulation results of the functional model under the force source of $f_g$, as illustrated in Fig. 3 (d), are in agreement with the numerical results of its system state-space equation.

### 4.4 Hydraulically damped rubber mount

A typical hydraulically damped rubber mount (HDM)
used in a vehicle powertrain system is chosen to study the modeling of fluid-structure interaction. The HDM is mainly composed of a rubber component, two fluid chambers, a fluid track and a decoupler membrane, as shown in Fig. 4 (a). The rubber component serves as the main support of powertrain load and as a piston to pump fluid to flow between the upper and lower chambers through the fluid track. The fluid track plays a role as tuned isolator damper. The subsystem consisting of fluid inertia in the fluid track and volumetric elasticity of the upper chamber results in the nonlinear frequency- and amplitude-dependent isolation performances of HDM, which leads to a large dynamic stiffness and a high damping that isolate low-frequency and large-amplitude vibrations effectively. The decoupler membrane helps to increase the volumetric elasticity of the upper chamber to achieve good isolation for the high-frequency and small-amplitude vibrations when there is less fluid flowing between chambers. The lumped-parameter model of the physical model, as shown in Fig. 4 (b), includes three subsystems: one is composed of the elastic stiffness $K_r$ and damping $C_r$ of the rubber component; the second one is an oscillatory system composed of fluid inertia $I_f$ and volume stiffness $K_{mp}$ (called inertia track subsystem); the third one is the accumulator subsystem of the lower chamber represented by the volume stiffness $K_{lo}$. The piston pump effect of the rubber component is equivalent to a cylinder piston with a cross section of $A_p$ called the piston area, that is, the fluid volume pumped by the rubber component is equivalent to that pumped by the cylinder piston. The functional model, as shown in Fig. 4 (c), is created according to the following modeling procedures.

1. A force-velocity structure is built for the rubber component subsystem, and a pressure-volume flow rate structure for the inertia track subsystem. The element units of $K_r$ and $C_r$ are attached to the force-velocity structure using the force sum-to-zero and velocity distribution connectors, respectively, and the element units of $I_f$ and $R_f$ to the pressure-volume flow rate structure using the pressure sum-to-zero and volume flow rate distribution connectors.

2. Two pairs of volume flow rate sum-to-zero and pressure distribution connectors are attached to the pressure-volume flow rate structure of the fluid track, and the corresponding element units of $K_{mp}$ and $K_{lo}$ are added.

3. The transformer block of piston area $A_p$ is
(a) Structure of HDM

(b) Physical model

(c) Functional model

Fig. 4 HDM Models

inserted between the force-velocity structure and the pressure-volume flow rate structure to represent the power exchange between the rubber component subsystem and the fluid inertia track subsystem.

(4) Element units are created using the $S$ Function according to parameter identifications: the static characteristics of $K_f$ are estimated by finite element analysis; the dynamic characteristic of $K_f$ and $C_f$ are measured by frequency response experiments using the same HDM with no fluid; the volume elasticity of $K_{up}$ and $K_{low}$ are estimated by the finite element analysis of static fluid-rubber interactions; the piston area of $A_p$ is estimated on the basis of the finite element analysis of static fluid-rubber interactions; the fluid inertia of $I_f$ is estimated according to the original 3-dimensional geometry of the fluid track, and the fluid resistance $R_f$ is dynamically estimated according to the fluid flow state in the inertia track. More details about these parameter identifications are in Refs. (35) – (37).

The predictions of static elasticity and the vertical stiffness of 155.36 N/mm, as shown in Fig. 5, fits well with the experimental result, which verifies the effectiveness of the proposed functional model for the static characteristic simulation of HDM. The predictions of dynamic characteristics are investigated by the simulation of the dynamic working process of HDM under harmonic loading upon the top surface of the upper connector. The predicted reaction forces of the upper connector under various excitation frequencies are compared with the experimental results, as shown in Fig. 6 in which the time axle of the simulation reaction force is moved in order to compare respond period and force amplitude with those of measurements. The predicted reaction forces meet well with experimental results, which proves the effectiveness of the proposed functional model for dynamic analysis of HDM.

5. Conclusions

Graphic modeling methods help to establish quickly understandable models. The functional model as a promising graphic modeling method for performance predication and the analysis of a complex system is sys-
tematically studied in this paper. A set of fundamental items and a general modeling procedure are proposed on the basis of comparisons between the functional model and the bond graph. The functional model can be quickly established directly from the physical structure by attaching the element unit to the effort-flow structure with sum-to-zero and distribution connectors. This convenient modeling method helps engineers to build up a unified and hierarchical functional model for a multidisciplinary system in a logical way, and enable more engineers to adopt the functional modeling method in engineering analysis. Applications in electrical, mechanical, and hydraulic systems verify the practicability and effectiveness of the proposed functional model and modeling approach. The presented method can also be conveniently combined with other types of product design methods, such as finite element analysis and experimental analysis methods, to enhance the capability of CAE system technology for complicated engineering problems.

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References


(10) Jean, U.T., Simulation by Bondgraphs — Introduction to a Graphical Method, (1990), Springer-Verlag, Berlin, Germany.


(34) Broenink, J.F., Objected-Oriented Modeling with Bond

