M. VALASEK

ISSN 0543-5846
METABK 49(2) 127-131 (2010)
UDC – UDK 669.14-418:539.37:620.17=111

HIGHLY EFFICIENT MODELS AND SIMULATIONS - THE BASIS OF DESIGN OF MECHATRONIC SYSTEMS

Received – Prispjelo: 2009-02-10
Accepted – Prihvaćeno: 2009-08-14
Review Paper – Pregledni rad

The paper describes the efficient techniques for assembly of multidisciplinary simulation models and then the efficient techniques for their simulation. The current methods of assembly of multidisciplinary simulation models are co-simulation using existing simulation packages for one physical domain and uniform modelling by uniform language. The efficiency of simulation can be achieved besides advanced mathematical methods by parallelization, modification of the problem being solved and surprisingly by solving boundary mapping instead of mapping of variable time behaviour.

Key words: mechatronics, design methodology, modelling, simulation, design by modelling, design by simulation, co-simulation, uniform modeling

Visokoučinski modeli I simulacije – konstrukcijska osnova mehatroničkih sustava. U ovom radu opisane su učinkovite tehnike objedinjavanja multidisciplinarnih simulacijskih modela I njihove simulacije. Trenutno korištene metode objedinjavanja simulacijskih modela su kosimulacija (kooperativna simulacija) na osnovi postojećih simulacijskih paketa za respektivna fizikalna područja, te uniformno modeliranje standardnim jezikom. Osim korištenja naprednih matematičkih metoda, učinkovitost simulacije postiže se paralelnim pristupom, modifikacijom promatranog problema i – iznenađujuće – rješavanjem prikaza graničnog područja umjesto prikaza ponašanja u varijablinom vremenu.

Ključne riječi: mehatronika, metodologija konstruiranja, modeliranje, simulacija, konstruiranje modeliranjem, konstruiranje simulacijom, ko-simulacija, uniformno modeliranje

INTRODUCTION

Mechatronics is the future of mechanical engineering if not of all engineering. Mechatronics is the synergetic combination of mechanical systems with electronics and intelligent computer control [1]. The present most mechatronic product is vehicles that clearly demostrate the combination of components, solutions and technologies from the intersecting circles of mechanical, electrical, control and software engineering. It still does not exist complete design methodology for mechatronic systems, only the experience from successful design solutions [2] and initial generalization into mechatronic design methodology [3]. The key problem is the transition from “dead” uncontrolled state into the “alive” controlled state of the product. This together with the highly innovative nature of mechatronic product as they have no product predecessors and they are completely new products and with the interdisciplinarity of mechatronic product disable to predict the resulting properties of the product just based on experience. Therefore the key part of all existing approaches towards design of mechatronic systems is the modelling and simulation. Therefore the essential problem is the efficient capability to assemble the simulation model of the complete mechatronic product and to pursue the simulations efficiently. This paper is devoted to the overview of approaches towards efficient modelling and simulation of mechatronic systems.

MECHATRONIC DESIGN METHODOLOGY

The design methodology of mechtronic products is still incomplete. The essential part is the creativity and interdisciplinary combination of different technologies and function realization. It is important to create many different concepts of the product. The main stages of the mechatronic design is the market analysis and product specification, conceptual design, detailed multidisciplinary system development and the traditional product development for particular single-domain components (mechanical, electrical, hydraulic, software etc.). The popular mechatronic design methodology is the V-model [4]. The V-model methodology decomposes the design problem into the hierarchical sequence of system decomposition and integration on multiple levels of abstraction of design elements. However, on each level the modelling and simulation is necessary to be done separately for

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M. Valasek, Faculty of Mechanical Engineering Czech Technical University in Prague, Prague, Czech Republic

this level of component abstraction necessary. The empirical experience as well as its initial generalization [3] lead to the conclusion that the essential part of design procedure of mechatronic systems on the stage of detailed multidiscplinary system development is the modelling and simulation of the designed system.

DESIGN THROUGH MODELLING AND SIMULATION

The key problem of the design of mechatronic product is the design of its dynamic functionality. The main tool for that is the modelling and simulation of the designed system because modelling and simulation is the only known method for multidisciplinary system development synthesis, for overcoming many interactions within multidisciplinary system, for the analysis and synthesis of suitable interaction between components and the resulting phenomenon of synergy in mechatronical product. It is the only tool for preparation of stabilizing control and the extensive parameter optimization. The importance of simulation is increasing with the usual nonlinear properties of components of mechatronic systems.

The investigated design methodology is based on modelling and simulation. It is possible to distinguish the design through modelling and the design through simulation [5]. The design through modelling is schematically described on the Figure 1. In this design approach the first step is the assembly of the mathematical model and the formulatation of the performance index of the required mechatronic system behaviour. Then the designer uses this mathematical model and the performance index in the design procedure in order to determine the design parameters. Within this design approach usually the analytical form of the model is used. Examples of the design procedures are the control design by pole-placement, by Riccati equation (LQR), symbolic manipulation for exact I/O linearization, finding the extremity of the performance index, fulfillment of boundary conditions of system behaviour etc.

An important special class of design procedures is the optimisation. Certainly the design procedure does not need to be solved completely analytically, just the analytical form of the mathematical model may be used for the formulation and assembly of equations describing the sufficient condition for determination the design parameters.

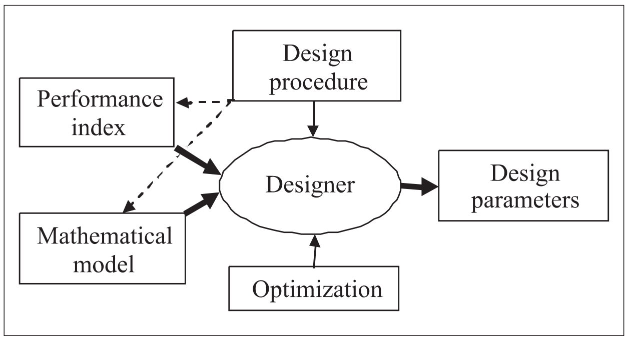

Figure 1. Design through Modelling

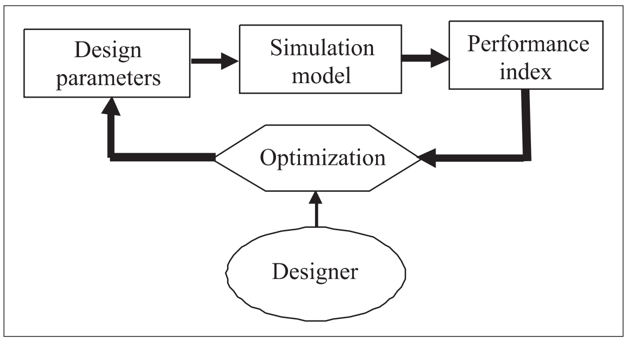

Figure 2. Design through Simulation

The design through simulation is schematically described on the Figure 2. In this approach the first step is the assembly of the simulation model, the formulation of the performance index of the required mechatronic system behaviour and the initial estimation of values of design parameters. Then the designer runs the simulation model with the values of design parameters and evaluates the performance index. Based on the values of performance index the designer controls the change of values of design parameters and repeats the simulation runs with their new values. Here the design procedure for the determination of the design parameters is their iterative modification within simulation loops. This design approach does not use directly the analytical form of the model. Just the capability to simulate the behaviour of the system suffices. Certainly the basic design procedures is the optimisation, but also the adjustment of fulfilment of boundary conditions of system behaviour by design parameter change is an applicable design procedure. The design through simulation based on parameter optimisation can be to great extent automated, for example using the MOPO (multiple objective parameter optimisation) approach [6]. The consequence of these design approaches is the requirement for the capability of efficient assembly of mathematical or simulation models and its efficient simulations.

EFFICIENT MODELLING

The efficient modelling of multidisciplinary systems is not an easy task. The natural basis of simulation models of mechatronical systems are the multibody models (MBS) [7, 8] that are feedback controlled. Traditionally the mathematical models and corresponding simulation models are being developed for systems from one physical domain. The similarity of physical principles, laws and resulting model assembly procedures are well known and described (e.g. [9]). However, the complete smooth practical connection and unification of model assembly from several physical domains is still not common. Therefore two approches for multidisciplinary modelling have been developed, i.e. for assembling mathematical and simulation models of systems with components con-

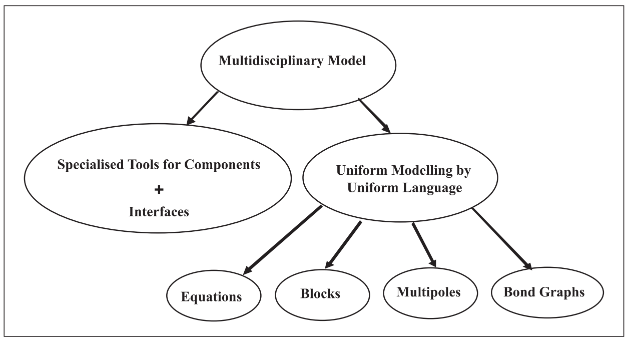

Figure 3. Different approaches to multidisciplinary modelling

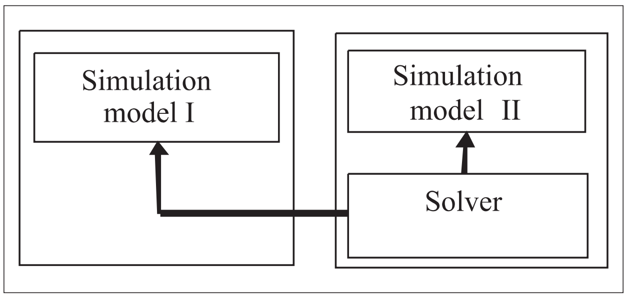

Figure 4. Variants of tight co-simulation

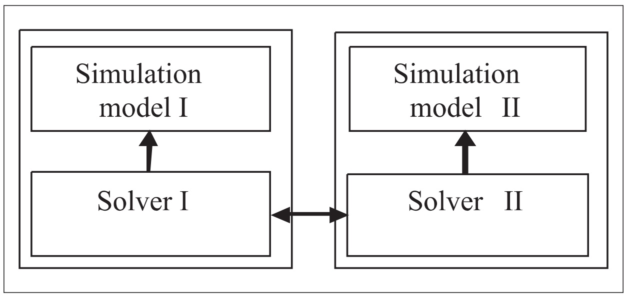

Figure 5. Variants of weak co-simulation

sisting from several physical domains (Figure 3). The first approach is based on the interfacing of the resulted models in different physical domains and the second is based on the uniform modelling of the whole multidisciplinary system within one uniform language.

The first approach is the usage of tools for specialized (component) modelling in one particular physical domains and then interfacing the resulting models. This is very promissing approach because the methodologies and corresponding software tools for modelling and simulation the systems from one physical domain are very well established, immediately available and very well tested. The long-term effort invested in the development of these specialized packages is not lost. The disadvantage of this approach is that it is to great extent limited to the design by simulation. Recently great progress has been achieved in methodologies for interfacing of particular software tools. There are many possible methods for interfacing of software tools for mechatronic system simulation. Their classification uses the general consideration of coupling CAE software tools.

The distinction is between the descriptive and operational models [10]. The descriptive model just describes the structure and content of the plant model. The operational model can be interpreted and generates new data about the plant (e.g. time sequence of the plant behaviour, the value of the performance index). Examples of descriptive models are CAD models, symbolic equations of motion, programme source. Examples of operational models are running simulation models, running computer codes. The next distinction is between simulation model coupling as the coupling of time sequence of values of system behaviour from different simulation models and the single value coupling as the coupling of single values produced by different models (e.g. exchange of values of performance index within optimisation). The simulation models can be coupled on the level of descriptive models (e.g. coupling of symbolic equations or symbolic source code) or on the level of operational models when the values generated during the simulation are exchanged.

The next distinction is the number of independent integrators which are communicating. One integrator (Figure 4) is ’tight coupling’ method (function-call [6]) of the systems and two/more integrators (Figure 5) is ’weak coupling’ method (co-simulation [11, 12]).

All coupling variants can be implemented on one or more processes. The second approach tries to describe the complete multi-disciplinary system by uniform language. As the uniform language the four different formalisms can be used: equations (differential and algebraic), dynamic blocks, multipoles and bond graphs.

The equations are very natural common language for all mathematical and thus simulation models. Recently, the equations are the basis of the powerfull modelling language within VHDL-AMS language and standard [13]. The disadvantage of this approach is that either a symbolic equation generator based on another uniform modelling approach or the specific symbolic equation generators for each physical domain with prepared multidomain interfaces are needed. The dynamic blocks as the uniform language have been used since the first simulation languages. Their disadvantage is that first the symbolic equations of the multidisciplinary model must be generated and second these equations must be sorted and modified into a causal sequence, both outside the formalism of dynamic blocks.

The other two approaches for uniform modelling languages (multipoles [14, 15] and bond graphs [9, 16, 17]) belong to the network approaches. Both these network approaches are based on the recognition that any physical interaction in or between any physical domain requires an exchange of energy. This means that parts of a physical system can be thought to interact via ports that allow energy to be exchanged, the so-called power-port. Secondly, it is recognized that any dynamic interaction can be described by two dynamically conjugated variables (’bilateral exchange of information’). Usually the product of these variables expresses the power or energy flow.

It is possible to derive both analytically [15] and empirically that the through and across variables can be introduced and have direct interpretation in each physical domain and thus naturally enable uniformly to describe the multidomain physical systems.

Example of connection of two models in multiple modelling [15] is in Figure 6. The models are connected in the pole P where the through variables t_1, t_2 and the across variables a_1, a_2 must fulfilled

$$\begin{aligned} t_1 + t_2 &= 0, \\ a_1 &= a_2 \end{aligned} \qquad (1)$$

The examples of the interpretation of the through and across variables for different physical domains are in the Table 1.

Table 1. **Interpretation of variable in multipole modelling**

Physical Domain	Through Variable	Across Variable
Mechanics	Force	Displacement
Electronics	Current	Voltage
Fluid-Power	Flow	Pressure

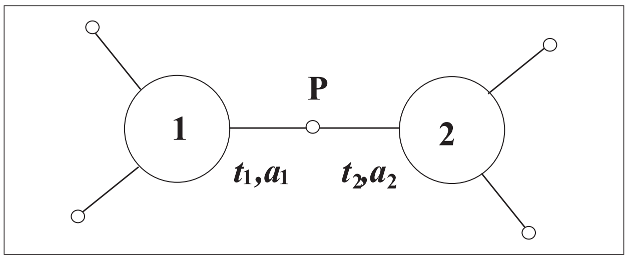

Figure 6. Connection of multipole models

The general advantage of network approaches is the natural multidomain capability of modelling which has been for long time almost the only possibility for multidisciplinary modelling.

The general disadvantage is that there have been already devoted too much effort and accumulated too much experience for modelling systems of particular specific physical domain and that the users in these specific domains use their specific language and schemes which are for them better and more naturally understandable than rather neutral and abstract network description. These disadvantages have lead to the development of interface methodologies for component modelling software tools which now posseses the full capability of multidomain modelling. The other disadvantage of network approaches is that specific solving algorithms for particular physical domain are sometimes difficult to be expressed in general network approach, e.g. recursive formalisms for multibody systems.

EFFICIENT SIMULATIONS

The next problem having the assembled simulation model is to efficiently run its simulation. First it is the effort of numerical mathematics (e.g. [18]) to develop efficient solvers (solution and integration procedures). Second it is the usage of multiplied computational power, i.e. the usage of parallel computer processors. Third it is the effort of the specialist assembling the simulation models for its simplification. The simplified simulation models can be then solved more rapidly than the models before simplification. The fourth approach is surprisingly based on the solution of mapping the boundaries of accessible values of variables instead of mapping of time behaviour of these variables. The time solution of differential equations can be often transformed just into the solution of nonlinear transcendental equations.

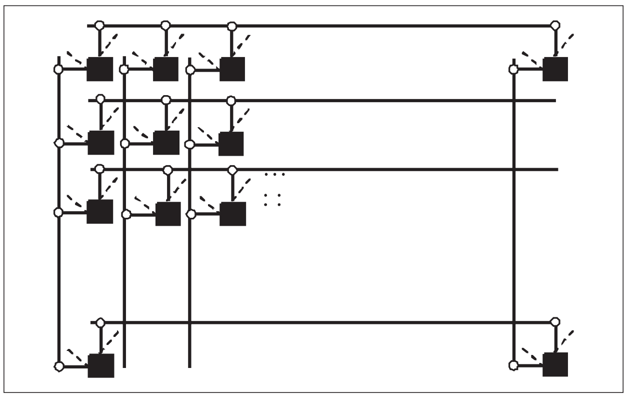

Figure 7. Grid of parallel processors

The parallelization of the solution of problems from computational mechanics is being developed. The efficient solution for FEM models on clusters of computers is described in [19]. The massive parallelization of MBS models on the grid of processors [20] is in Figure 7.

The suitable formulation of mathematical model of MBS is using natural coordinates and modified state space with stabilization [21].

$$\begin{aligned} &\dot{p}^* = F(q,\dot{q}) + \dot{A}^T\mu \\ &\begin{bmatrix} M & A^T \\ A & 0 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \mu \end{bmatrix} = \begin{bmatrix} p^* \\ -\alpha f \end{bmatrix}, \end{aligned} \qquad (2)$$

where **q** are natural coordinates, **p*** are modified momenta, **A** is Jacobian matrix of kinematical constraints **f** among natural coordinates **q**, **M** is the mass matrix, **F** is the vector of applied forces, μ are the modified Lagrange multipliers and α is the modified Baumgarte stabilization factor. These equation can be through the particular matrices (Figure 8) mapped into the grid of processors (Figure 7).

The traditional problems of mechanics that can be generalized into problems of any differential equations are the direct and inverse problem. The direct problem is the determination of the system response (time behavior of output variable) based on the knowledge of time behavior of input variables. The inverse problem is the determination of the time behavior of input variables based on the knowledge of the system response (time behavior of output variable). Besides these two traditional problems (Figure 9) a new one, so called global problem has

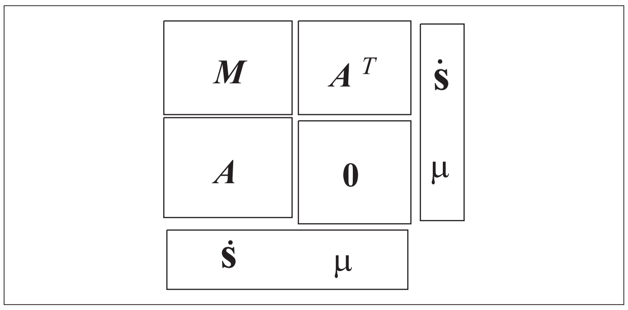

Figure 8. Mapping of matrices into parallel processors

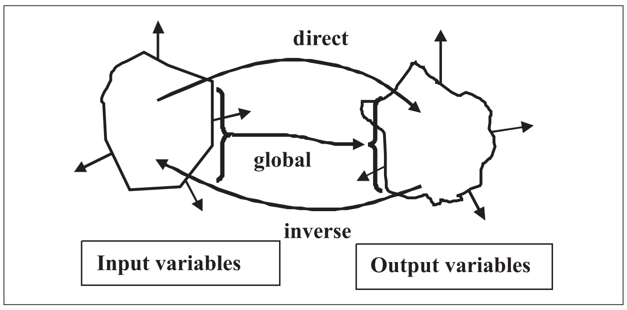

Figure 9. Direct, inverse and global problems

been defined [22]. It determines the area of accessible values of output variables based on the knowledge of the area of values of input variables. Suprosingly it can be shown that in many cases this problem leads to the determination of algebraic boundary curves instead of tedious time solution of differential equations. This approach can be generalized into global computation for the determination of other relationships between the design variables (e.g. [23]). Then this approach is a very efficient design tool for any but especially mechatronic products.

CONCLUSIONS

The paper provides an overview of current techniques for efficient modelling and simulation of mechatronical systems that represent the basis of important part of design of mechatronical products.

Acknowledgement:

This work has been supported by the project "Development of methods and tools of computational simulation and its application in engineering" MSM 6860770003.

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Note: The responsible translator for English language is prof. Ing. Michael Valasek, DrSc.