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Automated behavioral modeling and analytical model-order reduction by application of symbolic circuit analysis for multi-physical systems

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ABSTRACT

The aim of symbolic analysis that has its origin in the design of analog circuits is the extraction of dominant system behavior by automated derivation of approximated symbolic formulas. Since exact symbolic analysis will yield exceptionally complex expressions even for rather small systems a class of symbolic approximation techniques have been developed that allow a reduction of the complexity of symbolic equations and their later solution by means of mixed symbolic and numerical strategies. Hence, it becomes possible to reduce the underlying nonlinear differential-algebraic systems of equations (DAE systems) of component-based networks and systems to a behavioral description of a predefined accuracy. It is a major advantage of the approach that the model simplification is performed by an automatic error control and that the simplified model is physically interpretable again. The contribution will give an overview of the symbolic tool *Analog Insydes* algorithms for extraction of dominant behavior of linear systems, e.g. formulas for poles and zeros as well as algorithms for generating behavioral models from nonlinear DAEs. Moreover, the underlying methodology has been extended to the application of analysis and modeling of gas-pipeline nets and mixed electrical and mechanical systems. For the latter a library was developed in cooperation with the Fraunhofer IIS/EAS for symbolic models of micro-mechanical elements that can be connected to networks, even together with electrical components.

1. General

The paper will give an application oriented introduction into symbolic analysis of analog electronic circuits and multi-physical systems using the electronic design automation (EDA) tool *Analog Insydes* [3]. Starting with a brief review of the problems in current industrial analog circuit design an overview of the state of the art concerning the functionality of symbolic analysis methods will be given. A modeling methodology will be introduced where the netlist-based modeling language has been extended for handling of multi-domain and vector-type through and across variables. With this approach, an automated setup of symbolic model equations in terms of a differential-algebraic system of equations starting from a netlist description is possible. This allows application of DAE solvers for numerical simulation as well as application of symbolic model reduction methods of multi-physical systems. Special attention will be devoted to the subject of symbolic approximation strategies in general but particularly to the approximation of linear and nonlinear equations resulting from electrical and multi-physical systems. The strategies have been successfully applied to analyze industrial analog circuits, e.g.

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extracting symbolic formulas for their dominant and critical poles and zeros as well as for the automatic generation of behavioral models from nonlinear dynamic equations of multi-physical systems.

2. Introduction

With the decreasing structural size going along with expanding complexity of technical systems there is an emerging demand for new design methods and modeling support. This becomes even more important because of the increasing heterogeneity of technical systems. In particular, for the design of mechatronic systems this leads to the following problem: There are established tools for the design of the mechanical or electrical parts like FEM, multi-body, or circuit simulators, but those are usually specialized on their physical domain. Therefore, consideration of interactions between mechanical and electrical components is extraordinarily laborious. These interactions often have to be taken into account because the assembly of independently optimized sub-components usually does not lead to an optimal system. On the other side, considering coupling effects results in new challenges in many aspects, which lead from the need of designers competence in multiple disciplines (electrical and electronic as well as mechanical engineering, physics and mathematics) up to the high complexity of mathematical models which demand the employment of adapted simulation tools.

Such software has to be capable of dealing with the multi-physical aspects of such systems. There are several suitable modeling languages like VHDL-AMS [1] or Modelica [6] and corresponding simulators like AdvanceMS^{TM} or Dymola^{TM} available. They allow for a modularized modeling of the complete system or parts of it with arbitrary accuracy. But the modeling process of heterogeneous systems is very time consuming and, moreover, the resulting mathematical models become very complex even for comparatively small systems, posing numerical problems with respect to robustness, efficiency, and stability.

Today the simulation of industrial-sized systems lies beyond the limits of this approach. In order to reduce the numerical effort, model reduction techniques become more important. In this paper, we present a modeling approach which is based on symbolic methods and can be adapted to multi-physical systems due to its general mathematical principle. This includes an automatic generation of behavioral models as well as model reduction for electrical as well as for mechatronic components and a combination of both. Such generated models allow an interactive processing and a more efficient simulation of the overall system, due to their reduced complexity. This may even enable application of optimization and control methods.

The basic principles of this modeling approach, i.e. the idea of model reduction, and the tool which has been used, are described in Sections 3 and 4. Sections 5 and 6 give examples from the domains of hydraulics and mechatronics, respectively. Finally, in Section 7, a summary is given.

3. Symbolic modeling approach

3.1. Symbolic analysis

The symbolic modeling principle originates from the field of analog circuit design where the motivation has been to gain a deeper circuit understanding by interpretation of analytic formulas. In this context dedicated techniques for linear as well as for nonlinear applications have been developed [8]. Starting from a netlist description – the topological representation of an analog circuit, which includes information about the connecting graph of the circuit's components and corresponding device models and parameters – it is possible to formulate a mathematical equation system that, in general, is a nonlinear differential-algebraic equation system (DAE system). The equations consist of Kirchhoff's current and voltage laws as well as the circuit element characteristics given by the corresponding current–voltage relations. The equation system can be set up automatically using standard formulation techniques, e.g. modified nodal analysis (MNA) or sparse tableau analysis (STA). The decisive property of such an equation system is that it can be analytically parameterized in the system parameters, e.g. using the resistor value R_1 instead of the numerical value 10 Ω, which motivates the term "symbolic". Due to the symbolic formulation, the equation system is valid not only for one dedicated parameter set, but for a complete class of models with arbitrary parameter values. Using computer-algebra methods it is possible to analytically investigate the behavior of the corresponding system.

The above described symbolic methods are integrated in the software package *Analog Insydes*, which is an add-on to the computer-algebra system Mathematica [27]. The tool includes functionality for analysis, modeling, and optimization of linear and nonlinear circuits of industrial size. *Analog Insydes* is based on a hierarchical netlist description language that allows to automatically set up symbolic circuit equations. Besides standard electrical engineering analysis like AC, DC, and transient analysis as well as visualization methods, dedicated model reduction methods are available within *Analog Insydes* that will be explained in more detail in the next sections. Moreover, the tool has been integrated into industrial design environments and frameworks and, thus, includes interface functionality for exchanging data with commercial circuit simulators like Eldo^{TM}, PSpice^{TM}, Saber^{TM}, or Spectre^{TM}.