A Tool-Box Approach to the Simulation of Multi-Physics Systems

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Abstract
In many cases, modeling and simulation of multi-physics systems cannot be carried out with one simulator or one class of models. Typically, for complex heterogeneous systems a combination of different modeling approaches, sometimes combined with simulator coupling, is the most appropriate method. A tool-box containing different modeling tools and software for simulator coupling is presented which could be applied successfully in the simulation of MEMS.

Keywords:
MEMS, microsystems, modeling, simulation, multi-domain, order reduction, model generation

Micro-electro-mechanical systems (MEMS) and other microsystems are often complex heterogeneous. Multi-domain description, coupled field problems, stiffness, nonlinearities, and an increasing role of electronic signal processing (analog and digital) are characteristic properties of such devices and systems. Therefore, modeling and simulation is a difficult task in the design process. Due to the complexity of MEMS, there is no commonly accepted modeling and simulation approach. We prefer a tool-box oriented approach to cover most of the different requirements: a collection of modeling, simulation, and optimization tools, together with a "canonical" description of the elements as the basis for libraries from which models of complex system may be build-up.

In Fig. 1, the combination of
- modeling by abstraction (from lower to higher modeling levels),
- modeling by equivalence transformation between the different physical domains (e.g. to apply the most suitable system simulator),
- simulator coupling for those problems which can not be modeled for a single simulator is shown. On the component or device level, FEM/FDM/BEM simulation [18], [2] is the most appropriate and widely used analysis method. But for the overall system simulation the underlying models are too complex. Therefore, the generation of more compact models (sometimes called "macromodels") is necessary. In Fig. 2, different approaches to construct compact models for system simulation are summarized [12].

To support the physically-oriented approach, generalized KIRCHHOFFian networks [15], [10], [4] could be applied very successfully. Special attention has to be directed to the multi-port aspect to handle 3-dimensional translational and rotational effects, also in non-inertial systems [9], [14]. The analytical description of the basic elements may be based also on FEM formulas [7]. Geometrically complex or inhomogeneous systems may be composed of an appropriate number of parameterized elements (Fig. 3). It is a main advantage of this approach that also multi-domain problems (as arising e.g. in transducer modeling) can be handled and also some nonlinearities (as usual e.g. in electro-mechanical systems) may be included into the behavioral models. The elements have to model only the "local" behavior, while the "global" behavior is calculated numerically by the system simulator based on the interconnections of the elements and the elements' behavioral models.

Another modeling approach uses the internal models exported from FEM (or FDM) simulators. These models consist of a huge number of ordinary differential equations resulting from the spatial
discretization and describe the component behavior very precisely. But for system simulation, their number has to be reduced drastically. In some simulators, e.g. ANSYS and FEMLAB, order reduction algorithms are implemented. Otherwise, external order reduction has to be carried out. These order reduction may be based on matrix calculus (e.g. [6] or eigenvalue calculation) but may result also from time-domain FEM simulation, followed by an approximation with low-order time-dependent functions (AWE, Prony’s method by exponential functions, ...). The applicability of all these methods is restricted to the linear operation mode.

Sometimes nonlinear effects are essential for the functionality of MEMS and have to be considered in system simulation. Only few general modeling approaches exist for nonlinear dynamic models, e.g. the separation of the describing differential equations into linear dynamic and nonlinear static parts [13], [5]. We focused also on this separation, expressed e.g. by the electro-mechanical equations

\[ M \frac{d^2u}{dt^2} + Ku = f(u, t) \]  

\[ u = \text{displacements}, \quad M = \text{mass matrix}, \quad K = \text{stiffness matrix}, \quad f = \text{displacement-dependent electrostatic forces}. \]

One can generate the different parts of the model by different methods: generate \( M \) and \( K \) automatically by order reduction algorithm and calculate the nonlinearities expressed by \( f(u) \) by separate FEM simulations followed by numerical approximation.

To support these different modeling and simulation approaches a tool-box is under development. It consists of:

- A library of parameterizable micromechanical, microfluidic, and some transducer elements (cantilever, membrane, ...).
- A postprocessor to ANSYS: based on substructuring, it generates system level models. The order of the model and its accuracy is controllable by the number of "master nodes" (in the ANSYS substructuring terminology) of the component. Applying the substructuring approach to modeling with generalized KIRCHHOFFian networks, a further separation of the master nodes into internal nodes and boundary nodes (i.e. the ports of the model) is very efficient (in [1] only the boundary nodes are considered).
- A model generator and simulation environment [8] for electro-thermal interaction in integrated circuit design: TSMG. It is based on an inhomogeneous thermal FDM model and, partially, on extended transistor models.
- A postprocessor to generate linear models based on transient simulations with FEM simulators. The models are described externally by time series and internally by exponential series for recursive convolution [16].
- An approximation tool for static nonlinear functions in many variables using the radial basis function approach which is very insensitive to the dimensions of the approximation problem:

\[ F(x) = \sum_{i=1}^{n} a_i \phi \left( \| x - x_i \| \right) + \sum_{j=1}^{d} b_j x_j + b_0 \]  

- A simulation-based optimization system MOSCITO [11] which combines different optimization algorithms with interfaces to various simulators (ANSYS, Saber, ELDO). It is used for model parameter adjustment and system optimization.
- A set of interface programs for simulator coupling ("simulation backplane") on different levels of the OSI model: TCP/IP, pvm, Java-based, HLA (High Level Architecture). In many cases it is sufficient that the simulators to be coupled have C interfaces for adding new models. In this way e.g. the ANSYS-Saber simulator coupling was realized [3], [17]. Sometimes, simulator coupling is the ultima ratio in simulating multi-physics effects.
It is important to focus on widely used simulators and standardized model description languages. Therefore, the models may be generated in different modeling languages: HDL-A (for the system simulator ELDO), Mast (Saber), VHDL-AMS, and Modelica are at the moment the most applied description languages. The extension to block-oriented Matlab-like descriptions or bond graphs is not a complicated task.

For automated model generation (but also for documentation) a common mathematical structure of the behavioral description is important (Fig. 4): these equations describe the behavior of component and subsystem models with conservative and non-conservative ports as well as analog and digital signals. The internal state variables $s(t)$ may be used to model complicated nonlinearities like hysteresis and jump phenomena. The notation of these five equations in the above mentioned modeling languages is possible without problems. Only the notation of Eq.(5) in Fig. 4, necessary to model digital control or signal processing subsystems, depends strongly on the language: in electronics, VHDL (or similar: VerilogHDL) is mostly used and have to be supported by mixed-signal simulators.

We gained practical experiences in the simulation of electro-mechanical systems like electronically-controlled acceleration sensors [3], [14], valve-less micro-fluidic pumps, electro-thermal systems [17] and electro-magnetic-mechanical relays.

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