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# Parameterized macromodeling of passive and active dynamical systems

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## Dissertation Summary

The increasing trends of device integration and miniaturization, combined with the ubiquity of high frequency components and low power applications, pose major challenges in robust design of electronic systems. First-pass designs are only possible through extensive and repeated simulation-driven verification at any stage of product development, aimed at validating both the functional and electrical performance of the system at different levels of granularity. Therefore, Electronic Design Automation (EDA) tools have rightly become one of the pillars that sustain semiconductor industries against the pressing challenges imposed by technological and economic requirements.

A direct approach for system-level verification based on numerical simulations of physics-based descriptions is not realistic. Especially in high-frequency and high-speed applications, the interplay between complex electromagnetic interactions and device/transistor-level descriptions may drive complexity to levels that cannot be handled even with powerful computing hardware. Some model simplification or approximation is in order to enable fast numerical simulations.

Behavioral macromodels provide one of the most effective solutions to this problem. Such models are intended to replace highly complex descriptions through simplified reduced-order equivalents, given an acceptable level of approximation. A macromodel is constructed to accurately mimic the input-output response of a given reference system based on a minimal set of descriptive equations, which (desirably) can be cast as an equivalent reduced-order circuit. Beyond accuracy, the equivalents must reflect fundamental structural properties of the reference devices, such as stability and passivity. Numerical simulations based on certified stable and passive macromodels provide a major speedup and are now regarded as the method of choice in practically all commercial EDA tools.

Parameterized macromodels further extend the potential of this approach by explicitly incorporating the dependence of the target structure response on a number of physical or design parameters. This allows the user to explore different device configurations to perform fast optimization, what-if analyses and statistical assessments.

The generation of guaranteed stable and passive parameterized macromodels is still an open research field. This problem has been addressed in the literature in two main directions. One approach imposes a model structure that is inherently stable and passive by construction; alternatively, an initial unconstrained model is constructed and is successively perturbed to correct any stability or passivity violations. Both approaches have pros and cons. The former is extremely robust at the price of reduced accuracy due to the conservativity of the constrained model structure. The latter enables better accuracy but may be unreliable due to lack of convergence in the perturbation process.

The first technical contribution of this dissertation fills the gap between these two competing approaches. A general model structure for linear parameterized passive structures is introduced, based on a rational multivariate Bernstein polynomial expansion. Then, a set of numerically tractable conditions on the model coefficients is derived. These are imposed as convex constraints during model extraction, leading to guaranteed stable and passive models for any combination of the parameters, without need of any post-processing. Further, the particular form of these constraints enables a user-defined trade off between identification time and accuracy, a highly desirable feature for designers.

The above convex formulation is exploited to support a second set of technical contributions, aimed at constructing reduced-order models of nonlinear analog circuit blocks. A first extension involves mildly nonlinear devices designed to operate under small-signal assumptions given a predefined bias level, such as integrated voltage regulators. We show that bias-dependent small-signal models with guaranteed stability can be derived in case of programmable, uncertain, and even time-varying bias conditions. The key enabling factors include an affine linear time-varying model structure for which we are able to prove strong quadratic stability. This implies unconditional asymptotic stability under any possible time-varying bias trajectory. The most notable impact of this results is a dramatic speedup in transient simulations, which can reach up to three orders of magnitude on realistic test cases.

The last contribution of this thesis further extends the macromodeling framework to approximate or identify local dynamics of systems for which data samples are available only via real-time monitoring. The result is always a small-signal bias-dependent reduced-order model, whose identification is performed in time domain using samples that possibly include the contribution of non-vanishing (and unknown) initial conditions. The resulting algorithm that we denote as Real-Time Vector Fitting (RTVF) is demonstrated on two applications belonging to power system modeling and even to haemodynamic modeling of the human cardiovascular system, by exploiting the analogy between electric and fluid dynamics variables.

In summary, this dissertation provides a unifying framework and a set of numerical algorithms for the data-driven reduced-order modeling of some wide classes of dynamical systems. Improvement of the state of the art is demonstrated both under theoretical standpoints thanks to the stability and -if required- passivity conditions, and under the practical standpoint through extension in scope and applicability.