A Novel Method of MEMS System-level Modeling via Multi-Domain Virtual Prototyping in SystemC-AMS

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II. SYSTEM-LEVEL MODEL DEFINITION

A. Reduced Order Modeling

Adapting existing 3-D MEMS models to system-level requires to specify their predominant properties and main degrees of freedom. Reduced-Order Modeling (ROM) methods are an efficient way to build a consistent representation. Different ROM methods have been successfully applied on FE Models to extract VHDL-AMS [6], [7] or SystemC-AMS [8] behavioral models. The chosen mathematical process can be applied to linear time-invariant systems with state-space equations [9].

B. Generic Model Export Feature

Inspired by SOAR [10], ROM method with modal truncation has been implemented into MEMS+. The user can choose what control variables to preserve in the reduced model.

Then, the ROM equation system (1) is directly extracted from MEMS+-3D model (Fig. 1). In a second step, the proposed method adapts equation (1) to the standard state-space form (2).

**Fig. 1.** Model export feature in MEMS+:A set of state-space equations is extracted from the 3-D model and exported to a SystemC AMS TDF Module.

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\begin{align*}
A(t) & = X(t) + B(t) \cdot U(t) + R(t) \\
Y(t) & = C(t) \cdot X(t) + D(t)U(t)
\end{align*}
\]
space representation (2) used by SystemC-AMS resulting in a set of matrices \((A, B, C, D)\) for a specific DC operating point.

In the nonlinear case, several DC operating points are generated for a particular configuration in the study range. An interpolation is then done during SystemC-AMS simulation updating the overall system matrices \((A, B, C, D)\) at each time step.

SystemC-AMS supports using state-space representations in modules either in Linear Signal Flow (LSF) or Timed Data Flow (TDF) MoC [1]. The latter has been chosen in order to further extend the initially linear models to nonlinear cases.

In addition, the new Dynamic TDF features of SystemC-AMS 2.0 will allow to change the time-step during the simulation [11] [12]. This feature is currently under evaluation to enhance the convergence of the TDF models for the nonlinear case requiring interpolation and thus control over the size of the time step.

Another approach to deal with non-linearity is to use a dedicated solver, for instance the Non-Linear Network MoC developed by Fraunhofer IIS/EAS in Dresden, Germany [13].

### III. IMPLEMENTATION

#### A. Accelerometer Behavioral Model

As a first example, an accelerometer has been modeled in MEMS+. The export process generates an equivalent reduced-order model in SystemC-AMS, which is then instantiated in a test bench together with other modules.

For this case, the control variables are assumed as linear for the reduced-order modeling. Only one operating point is thus studied in the corresponding state-space equations (Fig. 1).

The simulation is controlled by a user-defined SystemC-AMS test bench, which applies a stimuli on the \(z\)-axis acceleration in form of a impulse step function.

#### B. Results and Perspectives

For this simple linear case, the SystemC AMS model (using the standard \(A, B, C, D\) state space equation form) matches the behavior of the reduced-order Verilog-A models exported by MEMS+ (using the \(E, A', B', RHS\) state space equation form). Nonlinear examples such as gyroscope are currently implemented and tested for this method in order to validate it.

This work helps to evaluate the abilities and limitations of the current SystemC-AMS architecture with the goal to improve parts of its solvers or MoCs in order to make it suitable for mechanical simulation.

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**Fig. 2. Exported model: TDF module with linear or nonlinear configuration**

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### IV. CONCLUSION

Based on ROM, the proposed method aims to integrate MEMS modeling into established HDL design flows using SystemC AMS to enable a tight integration of MEMS with their AMS frontends and controlling digital hardware and software. An automated procedure has been implemented in MEMS+ to obtain a behavioral state-space TDF module for a MEMS design, for instance an accelerometer. In order to assess capabilities of SystemC-AMS with respect to simulating MEMS system-level models, further tests will be performed on nonlinear study cases generated with this presented method.

The tight coupling between mechanical and electrical parts as well as the non-linearity of MEMS models require for the future further enhancements to SystemC-AMS itself in order to better cope with conservative system models and their nonlinear differential equation systems and interpolation tasks.

The goal of this work is also to further enhance the ROM method so that key environment or design parameters of the MEMS can be preserved in the generated reduced-order model. These configurable models are fundamental for virtual prototyping and overall system optimization in early design phases and overall system integration phases.

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**REFERENCES**


