Subproject A2: "Analysis and simulation MEMS in VHDL-AMS Based on Reduced Order FE-Models"

- ## Prof. Dr. Dietmar Müller
- ## Prof. Dr. Wolfram Dötzel

Authors: Michael Schlegel, Fouad Bennini, Jan Mehner, Göran Herrmann,

1 Introduction

Before constructing a prototype, a simulation of the whole system is necessary to check the functionality of the individual components and their interaction. For MEMS, a design environment is needed which allows simulation of different physical domains including coupling effects. VHDL-AMS is a flexible system description language suited to handle such requirements. Additionally, it allows to describe and simulate the system at different levels of abstraction.

System level modeling and simulation have become state of the art in MEMS design due to the increasing system complexity. But high level models have the disadvantage that they often cause a considerable error in simulation. This error occurs because physical phenomena must be simplified to be expressed in an equation. VHDL-AMS or similar simulation systems can only solve differential algebraic equations and no partial differential equations. If the partial differential equations cannot be solved analytically then an approximated solution must be used which increases the error additionally. But using accurate models from the physical level (e. g. FEM models) is very cumbersome for daily tasks on system level.

Parameter reduction of FEM models (reduced order modeling) is an approach filling this gap in the design flow. Using a shape function method to generate ROM of linear systems becomes state of the art [2], [3]. Expanding these methods for non-linear cases is presented in [1]. For a most effective usage of these methods in system design it is required to export the ROM to VHDL-AMS with an interface matching the system structure.

2 The System Experimental Prototype „Vibration Sensor Array"

Wear state recognition on machine tools during the normal work process is an important fundamental of product quality improvement. Today this is done by measuring the forces on the tool. An alternative method is to control machine and tool vibrations. Approaches to tool vibration measurement have existed for many years. But these approaches are using pieco ceramic wide band sensors which are quite expensive.

The new sensor array which is being developed at Chemnitz University of Technology is fabricated by SCREAM technology [4]. Because of the narrow-band resonance working mode, the signal processing can be simplified due to a better signal to noise ratio and because no FFT is needed. So a low cost sensor system can be built.

The sensor system consists of a sensor array, an analog signal processing unit and a high voltage amplifier. The system is controlled by a micro controller. It also includes a fuzzy pattern classification system.
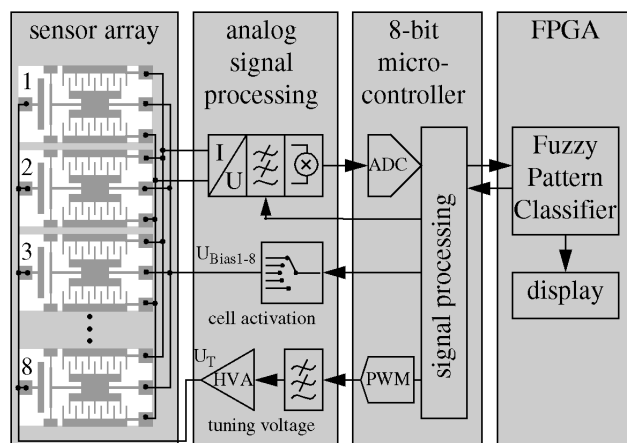

Figure 1: System structure of the measurement system

An environmental model called „virtual machine tool" provides the stimuli for simulation. It reproduces data – measured at a real machine tool – in time or frequency domain or generates fictitious data. The center of the measuring system is the vibration sensor array. This surface micromachined vibration sensor consists of eight laterally moving mass-spring resonators and is intended to work as a frequency selective device at its resonance. Using the stress stiffening effect in the flexures (type A), the resonance frequency is tuned by a voltage (V_{tun}) controlled tensile force, which is electrostatically generated in pairwise arranged lever systems. Vibration detection is effected electrostatically by the symmetrical comb capacitor attached to the proof mass were a DC voltage can be induced. Type B has a similar structure. But in opposition to type A the tuning is performed by an additional curved comb structure at the mass. This structure behaves like a spring with negative coefficient, so the resonance frequency can be tuned directly.
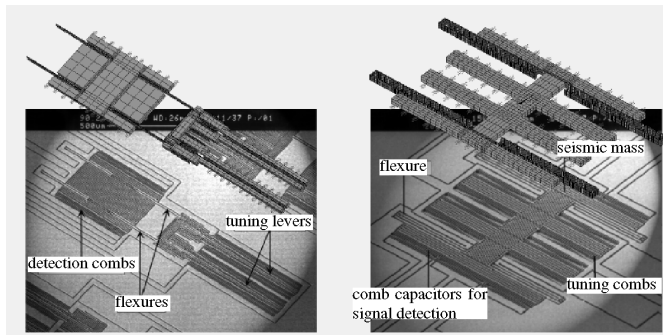
Type A: Frequency tuning using stress-stiffening

Type B: Frequency tuning using electrostatic softening

Figure 2: Photograph of the vibration sensor

Fig. 2 shows both types of sensors.

The high voltage amplifier generates voltages up to 30 V for the natural frequency tuning of the sensor. A micro controller starts or stops the measurement, activates or deactivates resonators and starts self-calibration. It tunes the natural frequency of the resonators and transmits measured data to the classification unit. The classifier decides by a fuzzy pattern classification algorithm whether the data are produced by an sharp or worn out tool. This algorithm is realized in hardware using an FPGA.

3 Application of Reduced Order Models in System design with VHDL-AMS

Reduced order modeling using modal basis functions was originally developed by [3] and has been continuously improved by several authors. In [1] the project A1 „Component Design" of the SFB 379 (collaborative research center) has shown that the approach is able to cover electrostatic structural interactions of arbitrary 2D and 3D structures, allowing for multiple electrodes, geometrical non-linearities and initial pre-stress conditions while supporting static, transient and harmonic analyses. The resulting Reduced Order Models has been used by the project A2 „System Design" of the SFB 379 for the system simulation of this system.

3.1 Problems during VHDL-AMS export

The export of the ROM to VHDL-AMS is performed in two steps. At first, an initialisation file containing all necessary information of the macromodel, such as the fitted polynomial coefficients and orders, is generated. Then, the source code in VHDL-AMS is generated automatically. Thereby a set of differential algebraic equations (DAE) with non-constant, non-linear coefficients emerges. The DAE can be mapped to the *simultaneous statements* of VHDL-AMS where non-conservative nodes (QUANTITY) represent forces, displacements, velocities and accelerations.

The main problem of exporting the ROM in VHDL-AMS is to express the fitted functions of the non-linear strain energy and of the capacities which are part of the coefficients of the DAE (derivatives of the energy *dW* and of the capacities *dCdet*, *dClev*). The algorithm consists of a number of sequential calculations. So this algorithm must be calculated within the VHDL-AMS sequential structures PROCESS/ PROCEDURAL or FUNCTION/PROCEDURE. A PROCESS cannot be used because it is a digital statement. The analog counterpart of a PROCESS is the PROCEDURAL statement. But this statement was not implemented in the VHDL-AMS simulators, which were available at the beginning of this work. So this algorithm must be implemented inside a VHDL-AMS FUNCTION or PROCEDURE. The algorithm returns more than one result, so first an attempt was made to use a PROCEDURE which can return any number of values. But a PROCEDURE can only be called as *sequential statement* within the VHDL-AMS sequential structures described above. The so called *concurrent procedure call* is not really a concurrent call. In this case, a PROCESS is placed around the procedure call. This PROCESS contains a WAIT statement which interrupts the calculation of the PROCESS until a digital event occurs. The parameters of the procedure call are analog QUANTITIES. Therefore, a digital event never occurs and the coefficients are only calculated at simulation start and not during the simulation.

For these reasons the calculation of the coefficients (*dW*, *dCdet*, *dClev*) must take place in a FUNCTION. The return values are aggregated in a vector which is the return value of the FUNCTION. The vector is arranged in the following form:

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return_value(0):= function value f(x),
return_value(1):= first derivative df/dx,
return_value(2):= first derivative df/dy,
return_value(3):= first derivative df/dz
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For first testing purposes the free simulator hAMSter from SIMEC/Ansoft was used. But the first version did not support vectors. Former versions of AdvanceMS from Mentor Graphics had similar restrictions. A workaround was using a number of FUNCTIONs each with a scalar return value. But this costs simulation time and makes the VHDL-AMS source code unnecessarily complex. Fortunately, later versions of these simulators supported vectors so this workaround was no longer necessary.

3.2 Using the ROM

Due to manufacturing problems the sensor array using tuning by stress-stiffening effect could not be used. So the sensor with tuning by electrostatic softening was employed. The export of its ROM to VHDL-AMS is described above. The next step is to insert this ROM into the system environment. Because of a lower abstraction level of the ROM compared with the abstract sensor model, it might happen that the abstract sensor model uses an interface other than that of the ROM although the inputs and outputs of the sensor are the same. This will cause a

lot of error prone work to adapt the system interface to the ROM interface. To avoid this, it must be assured that the ROM can use the same interface as the abstract model, wherefore a new methodical approach called „Multi Architecture Modeling" - MAM [5], [6], [7] was created.

The main idea of MAM is to use the interface, which will become necessary at a lower abstraction level (e. g., ROM) already at a high abstraction level (e. g., abstract sensor model). This avoids a lot of work because abstract models of a component can be replaced by detailed models or vice versa without any modification to the interface or the surrounding models.

This approach was applied in the development of the sensor models. This means:

1. to examine which inputs and outputs, including power supply, the sensor will need,
2. which types of interfaces (conservative/non-conservative analog nodes, digital nodes) the ROM will need,
3. which data types/natures these interfaces will need,
4. development of the abstract sensor model with this collected information,
5. checking the functionality of the sensor in the system context,
6. development of the ROM from the sensor's FEM model observing the information collected in steps 1 to 3,
7. to insert the ROM in the system model,
8. simulation of the complete system.

Without MAM, steps 1 to 3 would drop out and step 4 would be easier. But then step 7 would cause more work than needed for steps 1 to 4 because the system model must be adapted. If an error occurs after this adaptation it is not sure whether it was caused by the ROM or the adaptation. If MAM is used and the system model with the ROM is not working although it does with the abstract model then the error must be inside the ROM and the system simulation can be continued with the abstract model until a working ROM is available.

3.3 Simulation of the Sensor ROM

By using the MAM approach, application of the ROM in the system context is very easy. First, the eight models for the individual resonators were tested separately to verify the method of reduced order modeling and the VHDL-AMS export. The results of these tests allowed to improve to the method of reduced order modeling and VHDL-AMS export. At the end of these tests the eight individual models were joined to the sensor ROM. Then the abstract model was replaced by the ROM simply by changing the name of the architecture which is to be instantiated in the VHDL-AMS system model. No further work was necessary. With the macromodel a complete measurement cycle has been simulated.

4 Results

The following simulation has been done on a SUN ULTRA60 workstation with UltraSPARC-II 296 MHz CPU. An AC-simulation with a tuning voltage of 35 V and a stimulation magnitude of 0,6 mm led to the following results:

Table 1. Results of AC Simulation

	abstract, analytical model	ROM	Measured
natural frequency	1,8 kHz	1,7 kHz	1,7 kHz
output voltage	0,6 V	0,8 V	0,5 V
simulation time	7 sec.	2 sec.	

It was a surprise that the more accurate ROM can be simulated faster than the abstract model. But this can be explained simply: The abstract model contains a set of simple equations. The ROM contains less but more complex equations than the abstract model. Obviously, the smaller numbers of complex equations can be simulated faster than larger numbers of simple equations.

The results seem to show that the abstract model is more accurate than the ROM. But this effect occurs due to manufacturing tolerances of the real sensor. If the ROM is compared to the FEM Model the error will be less than 1 %. The simulation results of a transient simulation for 50 ms of the sensor and analog signal processing are shown in Table 2.

Table 2. Results of Transient Simulation

	abstract model	ROM
tuning voltage for a tuned natural frequency of cell 1 at 1 kHz	36,7 V	36,0 V
output voltage	1,2 V	1,1 V
simulation time	15 min.	7 min.

Again it can be seen that the simulation with the macromodel is faster than the simulation with the abstract model. The ROM is also more accurate.

By simulation of these system parts some side effects were determined, e. g., a „snapping" of the resonators at high tuning voltages which was taken into account when assembling the prototype.

At last a simulation of the whole system was performed to select stimuli patterns for the fuzzy pattern classifier. This simulation was done on a SUN Blade2 with 900 MHz CPU and 4 GByte RAM. It took about 1 hour and 30 minutes. A simulation plot can be seen in Figure 3.
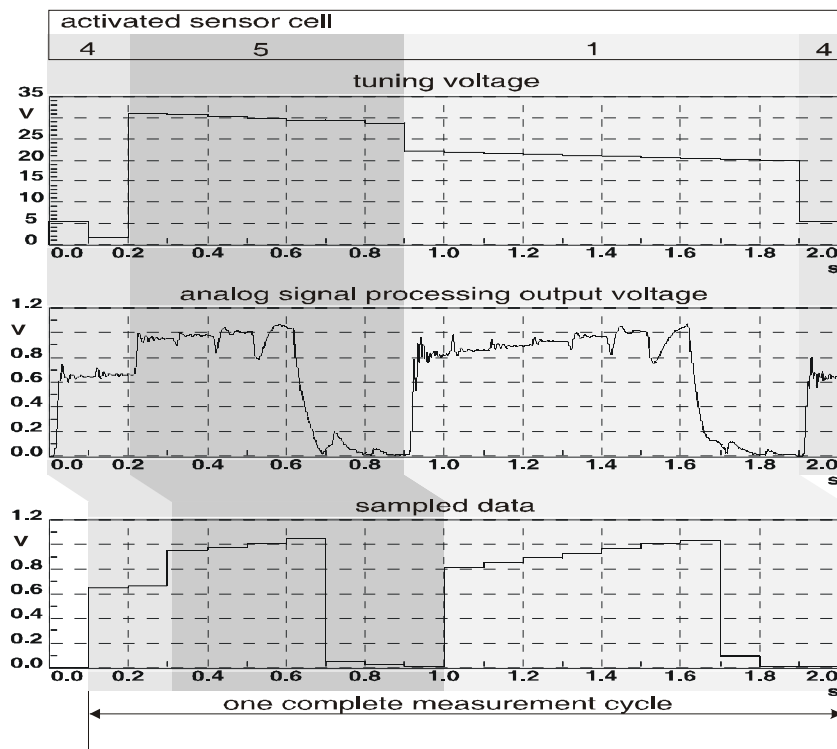
Figure 3: Plot of system simulation using sensor ROM

The first two curves in this Figure display the applied tuning voltage and the output signal of the analog signal processing during a complete measurement cycle.

The last curve shows the data sampled by the microcontroller which are transferred to the fuzzy pattern classifier. The differently grey backgrounds of the curves on the right show which sensor cell of the array is activated.

In comparison to the manufactured system the simulation shows an error of approximately 3 % in frequency measurement and 40 % in amplitude measurement. These errors are due to manufacturing tolerances. Regarding the high amplitude measurement error, it must be noted that the sensor works in a resonant mode, so even small manufacturing tolerances may cause big measurement errors. These errors cannot be predicted, neither by VHDL-AMS nor by FEM simulation. With the results of the system simulation it has been possible to select significant patterns for digital signal processing using the fuzzy pattern algorithm.

5 Conclusion

Within this work it was shown that the application of reduced order modelling in system design is a powerful approach to higher accuracy and simulation speed. By using the reduced order model instead of the abstract model [8] the simulation error has been reduced from 20 % to below 1 % and the simulation speed has been doubled.

The application of the Multi Architecture Modelling approach within this context assures an easy, fast and safe exchange of abstract and reduced order models.

The approach of ROM including VHDL-AMS export is supported by a self developed EDA-Tool in combination with a commercial FEM simulator. In the future, this approach will be able to avoid a good deal of human work for developing abstract, less accurate models.

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