Modeling and Simulation of MicroElectroMechanical Systems

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1 Introduction

Modeling and simulation of MEMS is of vital importance to develop innovative products and to reduce time-to-market at lower total costs. Advanced design methodologies and a variety of software tools are utilized by the MEMS-Design group in order to analyze complex geometrical structures, to account for interactions among different physical domains and to capture the cooperative play of micro devices and connected electronic circuitry or signal processing units. Computer simulations provide a deep understanding of the device behavior and lead to systems with optimized performance parameters.

Activities of the MEMS-Design group are focused on software development for device and system simulations, on modeling and simulation of user-specific applications and practical Microsystems design for prototypes manufactured at our clean room facilities.

In particular, we make use of Finite Element Techniques for structural, thermal, electromagnetic and fluid analyses of moving silicon-parts for sensor and actuator applications. Individual effects and cross-talk among different physical domains are either covered by direct coupling algorithms or parameter extraction methods referred as Reduced Order Modeling.

Reduced Order Modeling of MEMS allows a tremendous reduction of model size which becomes important for time-domain simulations with several hundreds of steps needed for circuit and control system virtual prototyping. Since Reduced Order Models are based on analytical terms, they can easily transferred from one simulator to others and can be adjusted to experimental data. Automated generation of parametric Reduced Order Models is considered as the ultimate goal for the future.

Our work is based on a close cooperation of the Fraunhofer Institute for Reliability and Microintegration, Department Micro Devices and Equipment and the Chemnitz University of Technology, Department Microsystems and Precision Engineering. In-house design, manufacturing and test allow all-embracing service delivered to our partners and customers.

2 Microsystems Design

2.1 Design Flow for MEMS

Microsystems design exploits various analytical and numerical methods for virtual prototyping of MEMS. The entire design procedure is illustrated in Fig. 1 and consists of the following steps:

- Low level system simulations,
- Process sequence and mask design,
- Process simulation and optimization,
- Component and device analyses and
- Simulation of the system behavior.

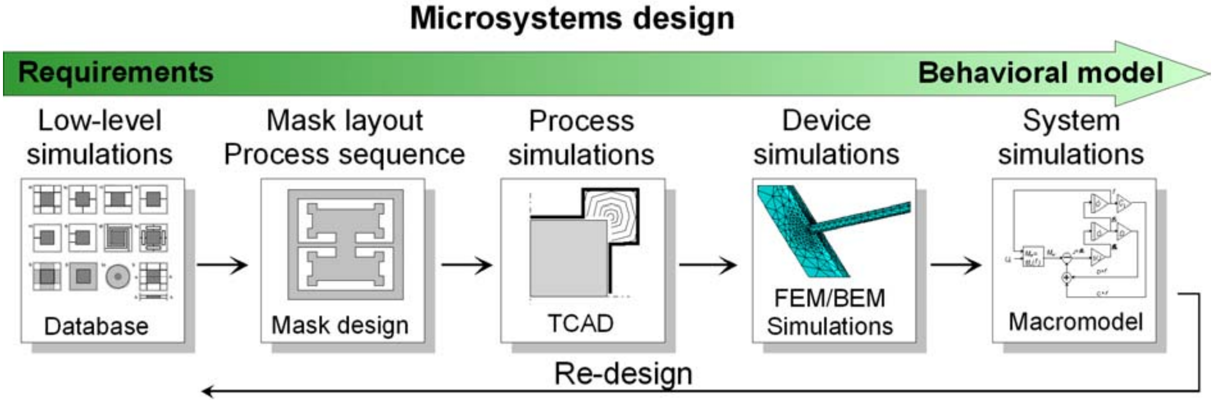

Fig. 1 Microsystems design procedure used for microelectromechanical devices.

2.2 Low level system models

The design process usually starts with low-level system models (block-diagram or lumped parameter models) in order to find a preliminary layout and process sequence. Simplified models are utilized for analyzing the cooperative play of different components and to estimate and optimize the system performance. Results are physical properties such as stiffness data, desired eigenfrequencies or inertial masses, damping ratios and electrostatic coupling terms needed for electrostatic actuation and capacitive detection.

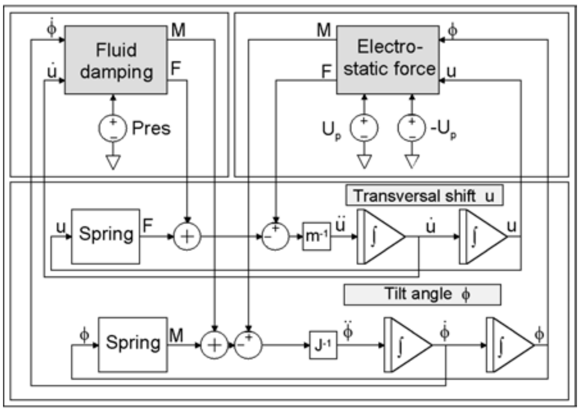

Fig. 2 Low level system model of a Micromirror Cell.

Next step will be to look for shape elements (components) which fulfill the physical properties obtained by low level analyses at reasonable costs and available technology. Databases with frequently used components are helpful to compare different layouts and to optimize geometrical dimensions.

2.2 Process level simulations

Process level simulations are employed to obtain structural solid models from the mask layout and process description. Often, material properties depend on chosen process parameters and must be simulated likewise.

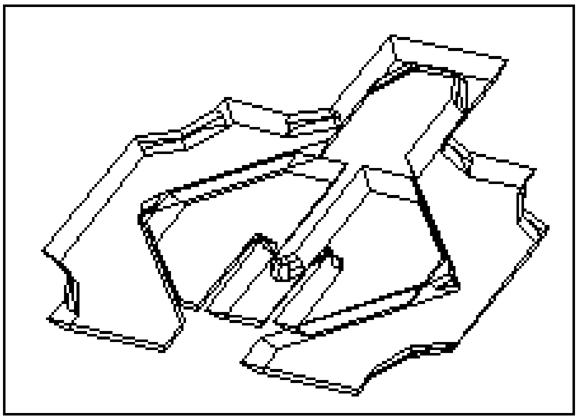

Fig. 3 Simulation of the anisotropic wet etching processes.

2.3 Component and device simulations

The physical behavior of micro components is described by partial differential equations which are typically solved by Finite Element or Boundary Element Methods. Device level simulations are classified in *single domain* and *coupled field* simulations.

Single domain simulations are state of the art and can be realized by a series of commercial software tools. For example, Fig. 4 shows the mechanical response of an accelerometer at external loads in operating direction.

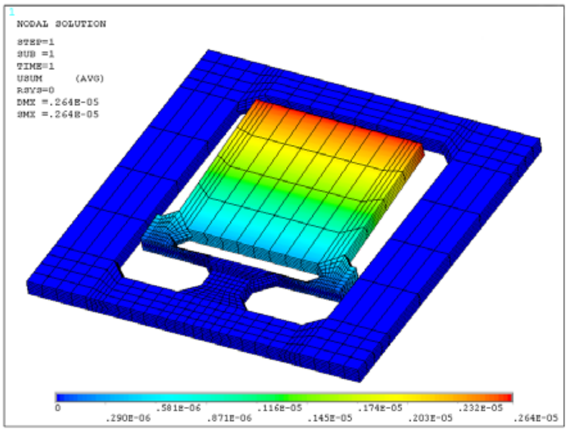

Fig. 4 Displacements at acceleration loads.

Coupled field simulations are vital to capture electrostatic-structural or fluid-structural interactions in sensors and actuators. Usually coupling algorithms must be adapted to special needs in order to account for non-linear effects which are inherent in MEMS devices.

For example, the performance of comb drive actuators is strongly affected by electrostatic fringing fields. This leads to levitation forces which lift the movable component out of the wafer plane. Eventually the forces may cause oscillations which disturb the system functionality.

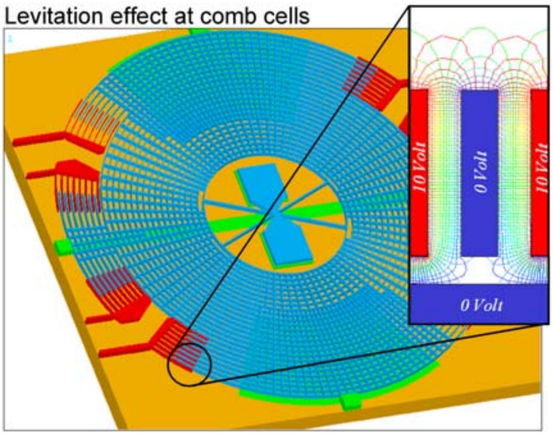

Fig. 5 Electrostatic fields at movable microcomponents.

Fluid-structural simulations are necessary to predict viscose damping of moving microstructures in the surrounding air. Resonant amplitudes and cross-talk of micromirror cells have been analyzed from the dynamic pressure change of air in the small gap between mirror plate and substrate.

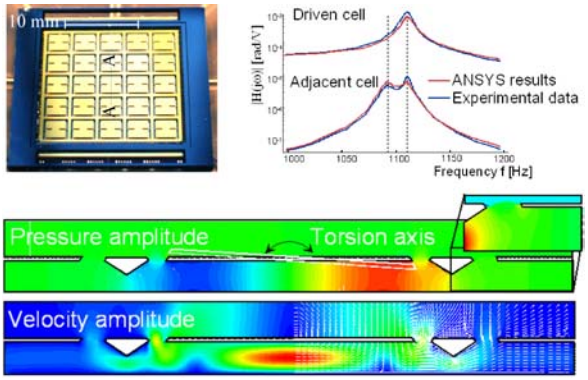

Fig. 6 Fluid-structural interactions in micromirror arrays.

2.4 System simulations of MEMS

Goal of system modeling is to study the cooperative play of microelectromechanical components, the controller unit and the electronic circuitry with the environment. For example, Fig. 7 shows a MATLAB/SIMULINK model which was utilized to predict the image quality of an micro optical laser projection system.

Component models deployed for the mirror cells are directly extracted from finite element models by Reduced Order Modeling techniques. Reduced order black-box models relate essential input signals (e.g. electrode voltage) to output parameter such as tilt angle, plate warp or mirror temperature needed for failure analyses.

Fig. 8 shows the controlled voltage time relationship needed for a saw-tooth like displacement function of image projection systems. In the lower part of Fig. 8, one can observe and evaluate signal distortions of the projected laser light.

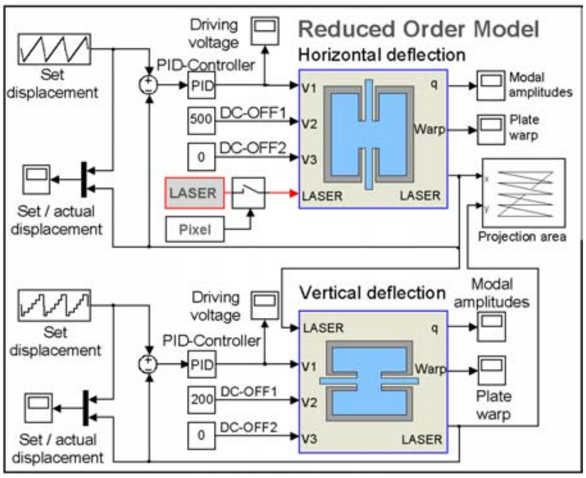

Fig. 7 System model of a micromirror laser display unit.

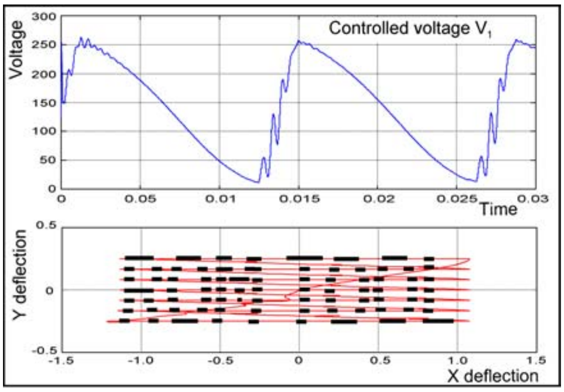

Fig. 8 System simulation results obtained in MATLAB.

3 Development work

Drawback of existing finite element and reduced order modeling techniques is that those algorithms can only analyze a single model configuration with specified dimensions and physical parameters. In practice, designers want to know the influence of parameter variations on the structural response in order to optimize the entire system and to assess the effect of tolerances.

Currently, parametric models of complex devices are extracted by numerical data sampling and subsequent function fit algorithms. Each sample point must be obtained by a separate finite element run whereby the change of geometrical dimensions is realized by mesh morphing or remesh functionality.

Current research work is focused on new "variational" finite element technologies which account for parameter variations in a single finite element run. The key idea of the new approach is to compute not only the governing system matrices of the FE problem but also high order partial derivatives with regard to design parameters by Automatic Differentiation algorithms. Results are Taylor series approximations which characterize the device and system behavior in the vicinity of the initial configuration.

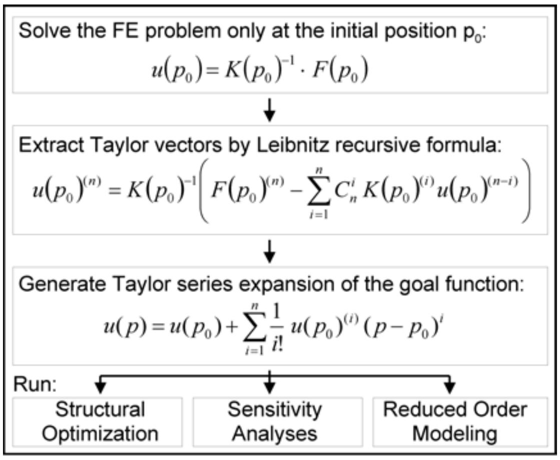

Fig. 9 Parameteric finite element modeling techniques.