Modeling and Simulation for Microelectromechanical Systems (MEMS) and Integrated Microsystems

INTRODUCTION

Modeling and simulation (M&S) for microelectromechanical systems (MEMS) and the broader area of integrated microsystems (IMs) is a technology area that is gaining in popularity. As interest in the commercial application of MEMS related technology grows so does the need for the proper M&S tools. These M&S tools are also referred to as computer-aided design (CAD) tools. Two things have become apparent as interested parties explore this M&S arena. First, the groups interested in exploiting MEMS related technology have various ranges of M&S experience. Many interested parties have limited M&S experience and thus do not appreciate the complexity of the task they are pursuing. The successful application of MEMS and IMs require s that the M&S tools be capable of addressing coupled energy domains at the microscale level, which is a formidable task. Second, the interested parties expect the M&S tools to be at the same stage of development as those tools used by the integrated circuits (IC) industry which, at the time this is being written, is not the case. These IC tools are generally referred to as technology computer-aided design (TCAD) or electronic design automation (EDA) tools. In the last couple of years, however, significant progress has been made to close the development gap. The purpose of this portion of the web site is to provide some general guidance in the area of M&S for MEMS and IMs. The contributors to this portion of the web site do not intend for it to be the complete authority in M&S for MEMS and IMs, but rather see it as a launching point for establishing a sound design methodology for MEMS and IMs. The users of the information provided here do so at their own risk. Information presented in this portion of the web site will provide a short overview of M&S for MEMS and IMs, discuss three levels of M&S, introduce a few canonical design problems, point to related web sites and provide references to related articles.

M&S OVERVIEW

M&S for MEMS and IMs has several forms so an overview is required to establish a common level of understanding from which to provide additional information. The design process can be viewed from either a top-down or a bottom-up approach as shown in Figure 1 below.

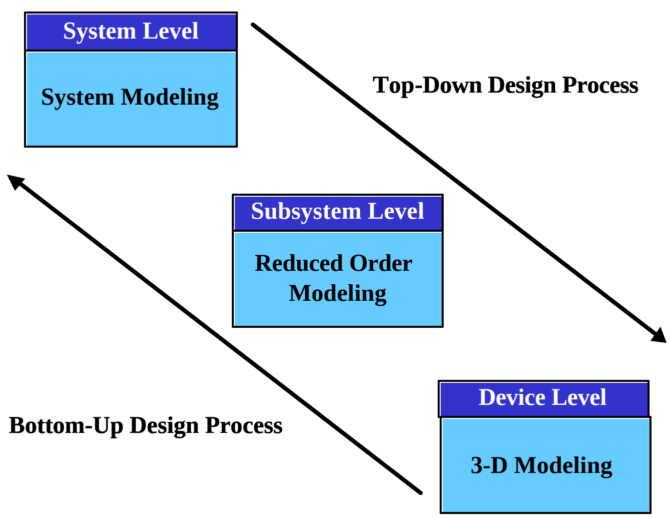


Figure 1. A simple illustration of the design processes with the various levels of design and typical modeling approach used at each level.

In the top-down approach one first explores the system design space to determine critical system parameters. This can be done without the designer having necessarily given much thought to the technology being used or how implementation will take place. Once the critical system parameters have been established, more focus can be placed on examining implementation options and specific technologies through the use of reduced-order models. Techniques associated with reduced-order modeling are essentially the same as macro-modeling. Macro-modeling is familiar to most analog or digital electronic designers. The term reduced-order modeling is used to highlight the fact that the missing ability to address coupled energy domains such as those involving mechanical and microfluidic components now exist. This level of modeling is also referred to as subsystem modeling in some communities. Modeling at this level involving a MEM structure, for instance, would also include the sense and control circuitry. Reduced-order modeling allows the designer to determine what boundary and load conditions will be placed on individual components. The last level of modeling is the more detailed physical modeling more commonly referred to as three-dimensional (3-D) M&S. 3-D M&S allows the designer to examine a structure's response to a particular physical environment in great detail. Computer resources required to conduct 3-D M&S make it an impractical approach for modeling a whole system. Designers use 3-D M&S to examine the characteristics of individual devices. These results are then used to establish the appropriate reduced-order model, which requires a relatively smaller amount of computer resources.

The bottom-up approach naturally refers to the design approach starting at physical modeling and moving up to system level modeling. This is also known as a verification design path. A designer has an idea for new device and conducts the necessary 3-D M&S on the design to establish its characteristics and data necessary to create a reduced-order model of the device. Reduced-order modeling of the device with the necessary sense and control circuitry is then conducted to see how it functions at the subsystem level before moving on to the system level modeling. System level modeling is then conducted to determine the potential impact the device will have on the whole system.

3-D M&S

3-D M&S normally involves numerical methods such as the: Finite Element Method (FEM), Finite Volume Method (FVM), or Boundary Element Method (BEM). As stated above, this level of modeling allows the designer to examine a particular structure's response in great detail. Figure 2 below illustrates one concept for a 3-D M&S process.

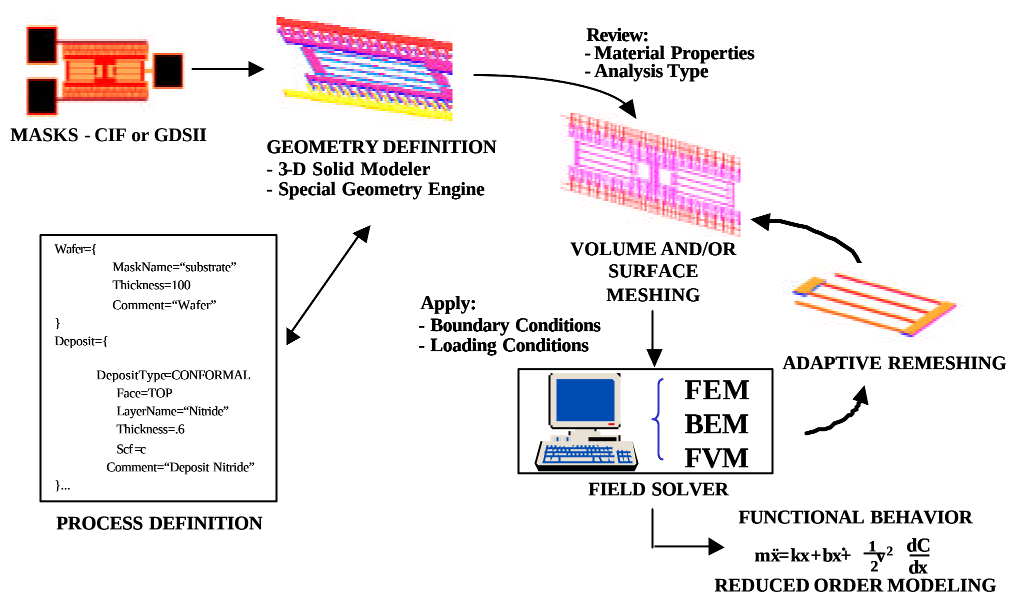


Figure 2. An example of a 3-D M&S process with the major steps shown.

The first step is to create the model that represents the physical shape of the structure one wants to analyze. This can be done by a variety of methods and is highly dependent on the capability of the tool being used. If the mask for the structure already exists in a CIF or GDSII layout file format and the fabrication process known, then certain CAD tools can use this information to create a 3-D model of the structure. Otherwise, the designer will have use a solid modeling tool or a special geometry engine associated with the solver to create the model. Once the model is created the material properties can be provided and the type of analysis (i.e.- nodal, electromechanical, etc.) that one would like to be performed on the structure defined the model is ready to be meshed. Meshing is the process of breaking the complex structure into an arrangement of simple shapes that represent the structure in a manner required by the field solver being used for the particular analysis. The BEM only requires meshing only on the outer surfaces of the model while the other two methods require the whole volume of the model to be meshed. After the mesh has been created the appropriate boundary and load conditions are applied to the model and the analysis run. When the analysis is completed results are examined to determine how well the structure performed for the particular load and boundary conditions. At times it may be required to refine the mesh and rerun the analysis. Some of the tools available can do this automatically in a process that is called adaptive remeshing where the tool automatically adjusts the mesh density so that critical areas have a finer mesh than noncritical areas. Once good results are obtained they can be used several ways depending on the purpose of the analysis. A designer may find out that the structure didn't perform the way it was envisioned and must be redesigned. A process engineer may be using the results to refine the fabrication process to minimize residual stresses during fabrication. A system integrator can use the results to create a reduced order model of the structure required to design the control circuitry for the device or determine its functional behavior in a subsystem or system.

REDUCED ORDER MODELING

Unlike 3-D M &S discussed above, a reduced order model is an abstract notation for a simplified set of equations used to represent the terminal characteristics of a subsystem. Reduced order modeling is used to represent static and dynamic behavior to an acceptable level of fidelity, emphasizing terminal characteristics. This abstracted behavior may contain phenomenon representative of multiple mixed energy domains. Accuracy is measured with respect to the original subsystem behavior. A reduced order model will typically require fewer components or fewer equations than the detailed system model. Since the behavior is largely encapsulated at the terminal characteristics and will not necessarily represent the internal phenomena at the same level of detail as provided by 3-D M&S, faster computation times and smaller storage requirements enable the effective simulation of larger system architectures. In addition to understanding the simplifying rules used in developing the reduced order models, the designer also needs to understand the valid ranges (and processes) for applying the model.

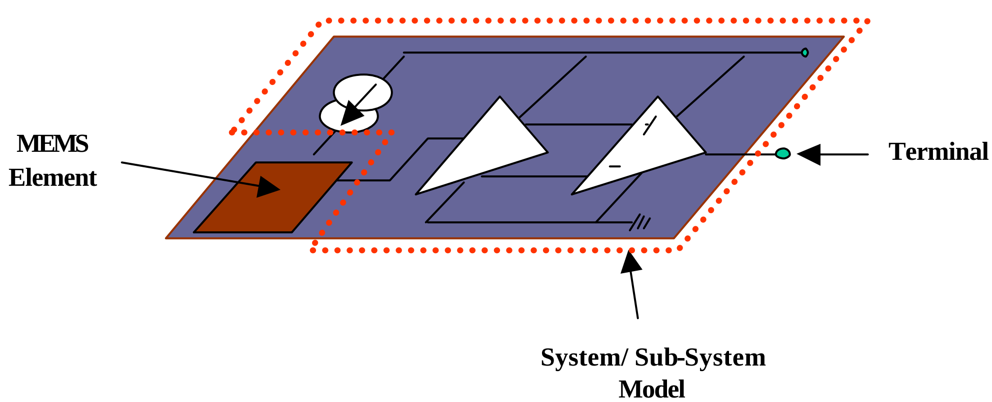


Figure 3. MEMS element with control circuitry that can be represented with a reduced order model.

One additional benefit mentioned by those familiar with reduced order modeling is that it may also provide a means of providing some protection to intellectual property. Providing only an abstracted view could protect the individual component design. Designers would have access to an abstract component behavior that would be sufficient for design integration by incorporation of the component model into the integrated system model.

SYSTEMS LEVEL MODELING

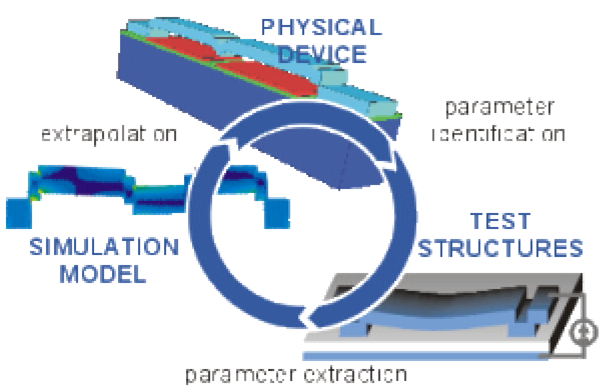
The highest level of modeling, and most abstract level of modeling, as presented in this portion of the web site is system level modeling. System designers conduct functional simulation of a design concept. The models they use will examine the behavioral and performance characteristics of the concept to determine how well it meets the desired system specifications. The tools system designers use to evaluate a particular design concept may incorporate techniques used in reduced order modeling, but will not approach the resolution of 3-D M&S. The system is generally represented by an arrangement of block diagrams that represent its major components, or subsystems.

CANONICAL DESIGN PROBLEMS

Effort has been expended by several groups to establish some canonical design problems to explore the adequacy of coupled energy domain simulations and reduced order modeling approaches. The canonical design problem was defined to be a well-characterized MEMS device level analysis problem supported by a body of accurate design, fabrication, and as built device performance information. Below are a couple examples of canonical design problems. More will be added in the future.

RF Switch (http://www-tcad.stanford.edu/~chan/mems/canonical/index.htm)

This particular canonical design problem is a simple, but practical, pull-down switch which is of great interest to the RF community. CIF and GDSII files are provided along with the process specification, analytical results and experimental results.



High Q Filter (http://www.ece.cmu.edu/~mems/memsyn/canonical_resonator/index.html)

This canonical design problem is one of the better known MEMS structures, an electrostatic comb drive specifically designed to perform as a resonator. The figure below is the result of one of several 3-D finite element analyses conducted on various configurations of this resonator design concept. CIF layout files, comparison of the results of various analytical approaches and experimental data are provided.

RELATED WEBSITES

3-D M&S

ANSYS (http://www.ansys.com/products/multiphysics.shtml)
CFD Research Corporation (http://www.cfdrc.com/datab/Applications/MEMS/mems.html)
Coyote Systems (http://www.coyotesystems.com/applications/applications.html)
IntelliSense Corporation (http://www.intellisense.com/software.html)
Microcosm Technologies, Inc. (http://www.memcad.com/products.html)
Stanford University (http://www-tcad.stanford.edu/tcad.html)
University of Illinois (http://galaxy.ccsm.uiuc.edu/mems_research.htm)

Reduced Order Modeling

Analogy (http://www.analogy.com/Mixed/default.htm)
Duke University (http://www.ee.duke.edu/Research/IMPACT/)
Massachusetts Institute of Technology (http://rle-vlsi.mit.edu/research)
Microcosm Technologies, Inc. (http://www.memcad.com/products.html)

System Level Modeling

Carnegie Mellon University (http://www.ece.cmu.edu/~mems/projects/memsyn/index.shtml)

University of California – Berkeley (http://ptolemy.eecs.berkeley.edu/)

Tool Suites

MEMSCAP (http://www.memscap.com/)

Other

University of California – Berkeley (http://www-bsac.eecs.berkeley.edu/~cfm/)

RELATED ARTICLES

The following articles are listed as a means to provide a starting point from which the reader can obtain more detailed information on the M&S for MEMS and IMs. The articles below represent only a sample of the articles that are available in open publication. Several universities and companies around the world are working in or have a documented interest in, this technology area.

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