ANSYS Multiphysics Capabilities for MEMS Modeling and Simulation

Part 1 of 3: Analyzing electrostatic-structural interactions in Micro Electro Mechanical Systems

By Jan Mehner
FEM-ware GmbH
Juergen Wibbeler
CAD-FEM GmbH

Moving from pure microelectronics to microsystems, the silicon technology enters a new age where tiny movable structures with micron dimensions are structured in silicon and joined to electronics either on-chip or in multichip modules. The obtained devices are called Micro Electro Mechanical Systems (MEMS). In two preceding articles by Steve Groothuis and Dale Ostergaard, the importance of multiphysical finite element analysis for MEMS virtual prototyping and the related new features of ANSYS/Multiphysics 5.6 were discussed. With this article, we begin a three-part series continuing the subject with emphasis on the dynamic transfer functions of micromechanical devices. We will stress the two most crucial coupling effects for the device dynamics, electrostatic-structural and fluidic-structural interaction, within this first and the following part, and show a method for obtaining exportable reduced-order models by modal decomposition in the final part.

Energy Domain Coupling

Since the upcoming of SPICE electronic circuit simulators, it has become a usual service by semiconductor enterprises to provide their customers with not only a voluminous choice of different discrete or integrated devices, but also with appropriate macromodel libraries for efficient circuit virtual prototyping. As transistors and ICs, the macromodels are like black boxes for the user relating all terminal voltages and currents, as well as their derivatives with respect to time to each other. Whenever a micromechanical component, or any kind of transducer, is part of the circuitry, a macromodel is required relating electrical and nonelectrical quantities.

Finding a dynamic model for devices with movable parts is heavily complicated by the fact that the geometrical boundaries of each energy domain are not constant. Specifically, MEMS with capacitive function rely on electrode gaps with micron extent that open and close during operation. Several model domains (Figure 1) have to be updated for each deflection state. The strongest impact is found on electrostatic and fluidic pressure forces reacting nonlinearly unto the structural domain. Many system design engineers help themselves using simplified lumped-parameter models based on rigid-body approximations. A core step in the progress of electronic design automation (EDA) will be to acquire accurate behavioral data of the micromechanical component by finite and/or boundary element models (solving a partial differential equation system) and to feed the circuit or system simulator with these data (solving an ordinary differential equation system).

There are several ways to set up energy domain coupling in FEA. ANSYS/Multiphysics provides tools and algorithms for load vector and matrix coupling. Load vector coupling switches between separate single domain models in each load step. Matrix coupling requires coupled-field elements leading to a simultaneous solution for all domains in each load step. A powerful new element concept for directly coupled MEMS models was introduced with TRANS126.

In modeling for dynamic analyses, it is essential to know the basic coupling techniques and to distinguish between load vector coupling (also known as relaxation technique) and matrix coupling. Load vector coupling only transfers the updated electrostatic forces to the structural domain and the structural displacements in the reverse direction once within each iteration cycle. Instead, matrix coupling includes interdomain coupling coefficients within the system matrix which is only possible (but not always practiced; see your Coupled-Field Analysis Guide) by the direct method. As a consequence, load vector coupling is applicable in a transient analysis, but results of a small signal modal or harmonic analysis may be false. For example, the electrostatic stiffness dF(V,u)/du is a typical coupling coefficient causing a voltage-dependent resonance and sensitivity shift that is revealed by the latter analysis types exclusively when set up with fully matrix-coupled elements.

Transient Analysis

A transient analysis gives insight into the true nonlinear vibration behavior of the device, doesn't require coupled-field elements, and allows for interaction with a circuit simulator by simple repeated data exchange in each time step. An ANSYS-PSPICE interface has been programmed to study complete transient system behavior of silicon micromirror arrays developed at the Chemnitz University of Technology (Figure 2).

The purpose of such devices is voltage-controlled laser-scanning in imaging applications. Models on a finite element basis are obligatory since the mirror segments bend significantly under electrostatic load, fringing fields are not negligible, and single segments don't work autonomously, but are always affected by the motion of the adjacent segments. Maintaining surface planarity and segment synchronization within tight tolerance levels during motion is crucial for sufficient optical quality. The mirrors operate in a controlled feedback loop where high voltages are applied to the backside electrodes for mirror excitation and the instantaneous gap capacitances are detected for obtaining the actual mirror rotation.

Within the iteration cycle, ANSYS is responsible for reading the instantaneous output voltage given by PSPICE, calculating a self-consistent solution for this time step and returning the capacitance value into PSPICE. The circuit simulator for this part reads the capacitance value, calculates the electronic circuit response within the current time step, and writes the new driving voltage for the following time step. Data exchange and time step synchronization of both software products are managed by generating ASCII data files. For calculating the self-consistent solution, ANSYS performs the actual sequential coupling in an iterative procedure that needs only few APDL commands. This procedure is identical if no system simulation is desired, and ANSYS works stand alone, except the user must now define a transient input voltage.

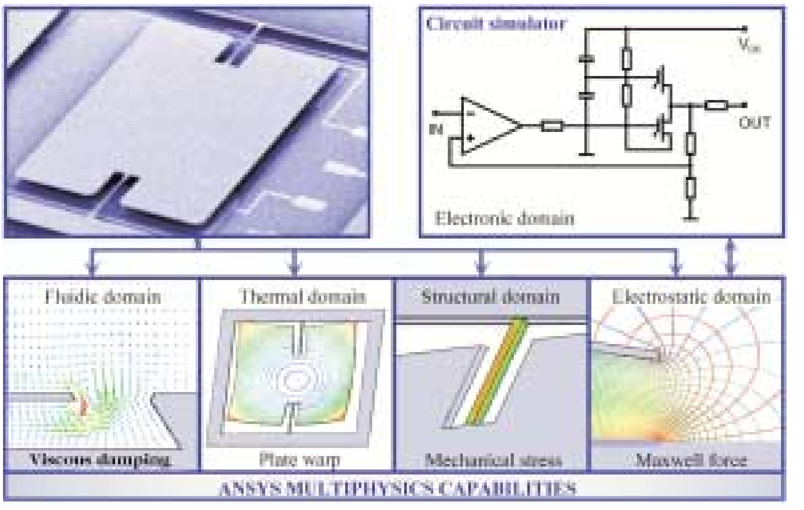

Figure 1: Modeling MEMS devices involves multiple interacting domains.

Small Signal Analysis

Though a MEMS component is usually governed by nonlinear laws, the majority of its dynamical parameters are covered in their small signal characteristics, for example, eigenfrequencies, eigenvectors, and frequency response curves taken at different operating points. The data are a prerequisite for generating reduced-order macromodels and exporting them into circuit simulators, a method we see as the ultimate future of feeding a circuit or system simulation with FEA results. We will comment on this subject in detail in the final article of the series.

The capacitive transducer element, TRANS126 (available with ANSYS/Multiphysics 5.6), provides fully coupled matrices and enables prestressed modal and harmonic analyses of electrostatic-structural problems. Because it uses electrical current instead of charge as through-variable, it is compatible with conductive do-

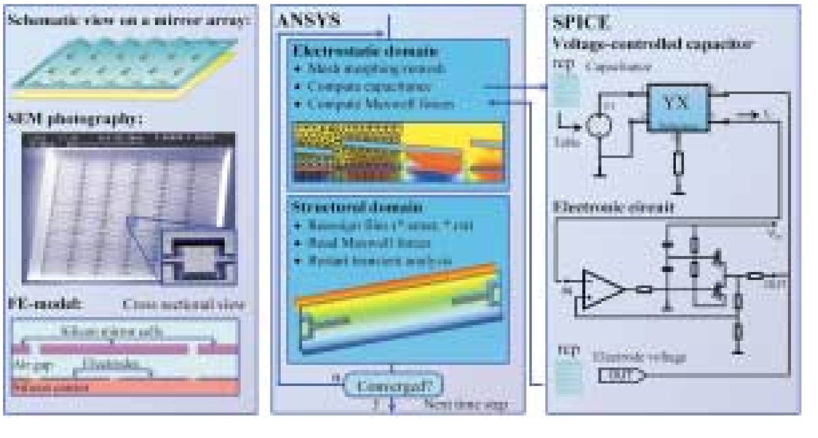

Figure 2: An ANSYS-PSPICE interface allows studying complete transient system behavior of silicon micromirror arrays.

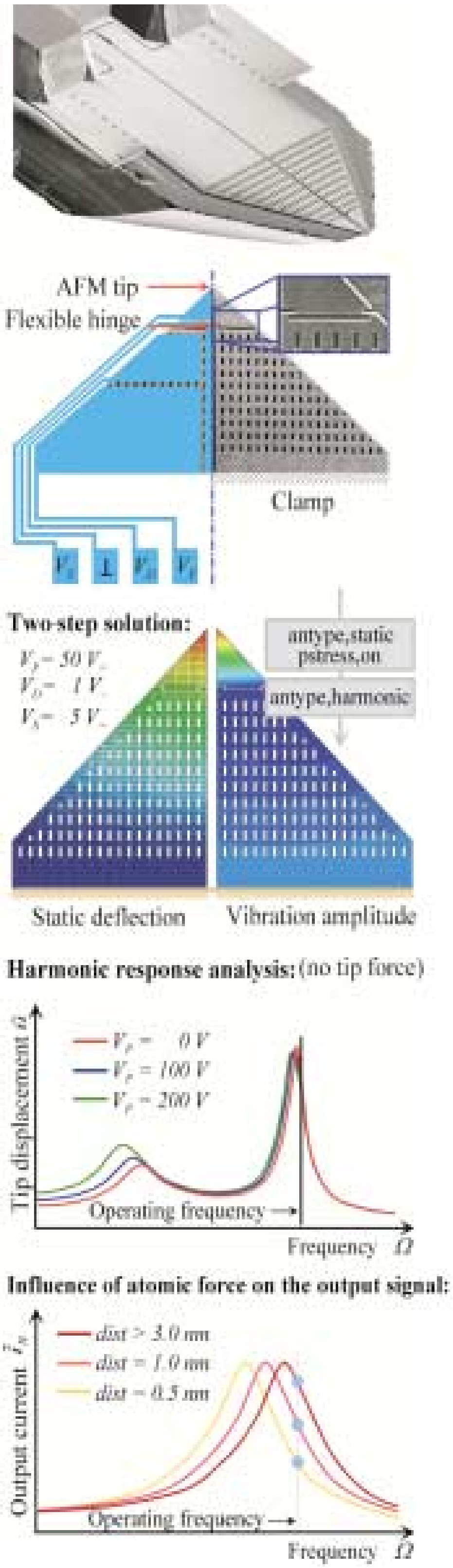

Figure 3: This capacitive AFM-device is a wide playground for electrostatic-structural harmonic analyses.

main elements like PLANE67, SHELL157, or CIRCU124. A matrix-coupled MEMS model may be stimulated by an electrical or nonelectrical harmonic load at any location and the harmonic solution of any quantity acquired at the same or another location.

An analysis of a micromechanical atomic force microscope (AFM) demonstrates the power of matrix coupling. Atomic force microscopy relies on extremely compliant microcantilevers with tips of nanometer-scale radius, the resonance frequency of which is sensitive even against atomic forces acting in a tip-specimen distance of 1 nm and less. Physicists use this technique to analyze the atomic surface structure of materials.

The capacitive AFM-device shown in Figure 3 is a wide playground for electrostatic-structural harmonic analyses. A set of three electrodes is located below each of the two delta-shaped cantilevers in a gap distance of 10 µm. The proximity between AFM-tip and specimen surface is controlled by the positioning voltage VP. A harmonic voltage VD stimulates the tip at the operating frequency with vibration amplitude of picometer range. The mechanical vibration amplitude is finally sensed via the capacitive current IS on VS. If the stimulation frequency is close to but not coincident with one of the resonance points, the response amplitude becomes extremely sensitive against a resonance shift caused by the atomic tip forces. The detection current IS becomes a measure for the tip force gradient.

Not visible in the model top view of Figure 3, a single layer of TRANS126 elements connects the backside structural nodes with their facing counterelectrodes. The nonlinear atomic tip force is represented by a single TRANS126 element containing the given force-distance law as a polynomial. A static analysis for a certain positioning voltage VP is followed by a harmonic analysis with excitation VD. The PSTRES,ON option in both analysis steps keeps the electrostatic spring softening effective. The frequency response plots show the effects of electrostatic spring softening and atomic tip force on the modal resonances, as well as on the detection signal.

Conclusion

The electrostatic-structural interaction severely impacts the dynamics of a MEMS component on one hand and makes up the signal link to the electronic circuit on the other hand. With the introduction of elements with full matrix coupling not only transient, but also prestressed, modal and harmonic analyses are now capable of capturing the coupled dynamic behavior. FEA now allows a comprehensive component level design of MEMS. A worldwide speed-up of software developments in this field has already begun, and the design engineer will be provided with further numerical methods and tools especially for interfacing with the system level simulation.

For more information on MEMS simulation, read "Analyzing Microminiature Devices" by Steve Groothuis in the Spring 1999 issue of ANSYS Solutions, *and "Tooling Up for MEMS" by Dale Ostergaard in the Winter 2000 issue.*