# ANSYS Multiphysics Capabilities for MEMS Modeling and Simulation

**Part 3 of 3: Exporting macromodels for circuit and system simulation tools.**

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Today, an abundance of commercial circuit and system simulation tools exist for electronic circuits and control system virtual prototyping. However, MEMS design engineers still long for an efficient link between their FEA tool and their circuit or system simulator. The electro-mechanical component of a MEMS is commonly analyzed in detail using FEA. At the end of this procedure, the question is how to obtain a macromodel from these accurate results that exhibit just input/output interface terminals, which can be directly drawn into the circuit or system schematic by a simple mouse click.

Numerical methods for model conversion are already available. In a future product release, ANSYS, Inc. is working to provide automated generation and export functionality. Concluding this series, we outline the basic procedure, which leads from a detailed FE micro-component model to the desired macromodel for the system level.

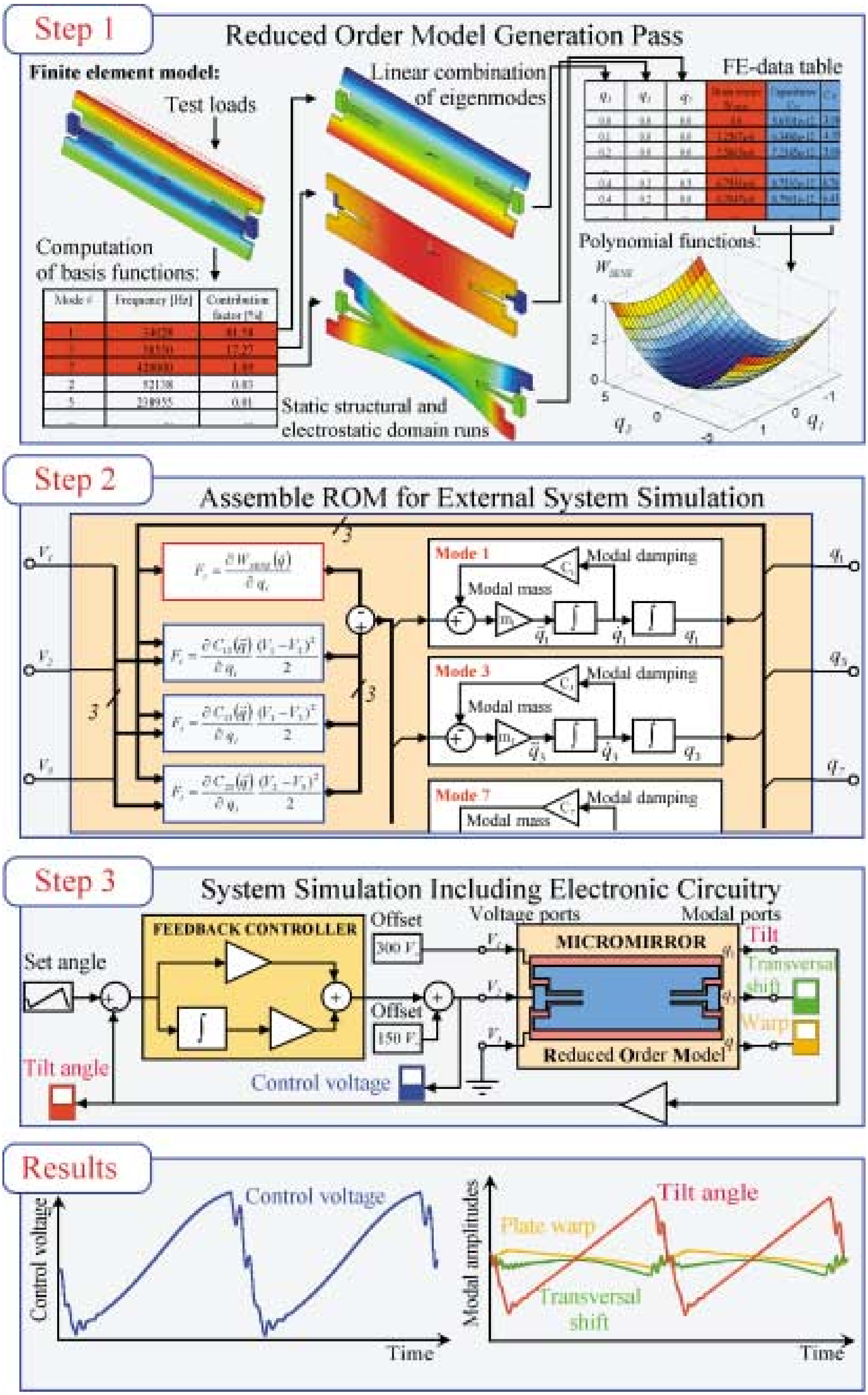
## Reducing Model Size

As in FEA, solution accuracy and speed critically define the performance of a system-level simulation. The requirements for both methods are, however, quite different. A transient dynamic FEA may be set up for several 10-oscillation cycles of a model that typically exceeds several thousand degrees of freedom (DOFs), it is the norm today for model sizes to be in the range of 10,000 to 100,000 DOF. In contrast, on the system level, the signal complexity may include several 1,000 to 100,000 cycles. In order to obtain the result within seconds or minutes, the DOF number in a system schematic is kept in the order of hundreds.

In the simplest case, lowest-order macromodels of electro-mechanical parts are manually designed apart from FEA by rigid-body approximations using lumped-parameter methods. The parameters of movable components—stiffness, damping, inertial mass and electrostatic coupling—are replaced by equivalent circuit elements such as inductors, resistors, capacitors and controlled nonlinear sources or by system blocks, respectively.

The problem with rigid-body models is that they do not represent the flexible nature of silicon components as accurately captured by FE models. On the other hand, directly linking an FE-model into a transient system simulation—as presented in our first series contribution—considerably slows the system solution process. The most efficient way is to compress the FE model size by several orders of magnitude, to write a macromodel from the reduced data in a language which is compatible with the available circuit or system simulator and to proceed within the latter one only.

Through substructuring and modal superposition, reduced-order techniques have been available in ANSYS for a long time, and in 1999, through transducer elements TRANS126. As a novel requirement, the generation of reduced-order macromodels must link




**System simulation with FEA accuracy. The basic procedure to obtain a macromodel based on FE model data explained at a scanning micromirror example.**

together the structural, electrostatic and fluidic domains, not to mention nonlinear characteristics.

## Shape Function Methods

The deformation state and dynamics of mechanical systems are accurately described by weighted combination of mode shape functions or modal superposition. In fact, shape function methods can also be applied to nonlinear systems. Geometric nonlinearities, for instance, stress stiffening, can be regarded if the modal stiffness is computed from the first derivative of the strain energy function with respect to the modal amplitudes. Capacitance-stroke functions provide nonlinear coupling between each eigenmode and the electrical quantities, such as electrostatic modal forces, electrical current, if stroke is understood as modal amplitude. Damping parameters are assigned to each eigenmode, as described in our second series contribution.

Modal representations of MEMS are very efficient since just one equation per mode and one equation per involved conductor are necessary to describe the coupled system entirely. The approach will be demonstrated subsequently as the example of our already known electrostatic scanning micromirror.

## Step 1: Reduction Procedure

The first step of the ROM generation is to determine which modes are significant and to estimate a proper amplitude range for each mode. Several criteria can be applied, for instance the lowest eigenmodes of a modal analysis, modes in operating direction or modes that contribute to the deflection state at a typical test load. Applying a unit voltage as test load at one electrode of the micromirror reveals that its motion is dominated by the rotational (1), transversal (3), and warp (7) eigenmodes.

Next, the dependencies of the strain energy $W_{SENE}$ and of all mutual capacities $C_{ij}$ from the modal amplitudes are described by polynomial function fits. The necessary data points are obtained by imposing each eigenmode with varying amplitude to the mechanical model for strain energy and to an electrostatic space model for capacitance. Modal damping parameters are obtained at a fluidic model (shown at left).

## Step 2: Export Macromodel

In the concept of modal superposition, each eigenmode represents a single independent resonator with modal mass $m_i$ and modal damping $c_i$. The system schematic replaces the resonator's equation-of-motion by a simple arrangement of summation, gain and integrator blocks. Polynomials for nonlinear modal excitation forces and stress-stiffness forces are written into analytical-function blocks.

The structure of this schematic remains constant for all types of system simulators, and therefore, needs to be exported into a model file using the appropriate macro language. In the example, the model was generated for MATLAB/SIMULINK and has three voltage input ports $V_i$ and three mechanical output ports carrying the elongations of eigenmodes 1, 3 and 7. A similar structure is available for network simulators where the electrical ports carry bidirectional signals, according to the Kirchhoffian network theory (VHDL-AMS language).

## Step 3: System Simulation

Combined with a feedback controller unit, the micromirror's rotation shall realize a smooth saw-tooth-like function for scanning image projection. The system simulation using MATLAB/SIMULINK traces the mirror motion in the three implemented modes. In practice, the transversal mode disturbs the electrostatic forces, which are meant to drive only the rotational mode. The control loop must provide compensation for those and other disturbances, which is now the objective of circuit prototyping. Based on the information about the warp mode, we are able to conclude on the reflection quality of the mirror.

A rigid-body-based macromodel would only include the rotational mode, perhaps, with a strong degree of approximation, the transversal mode, also. Instead, the reduction of FE data guarantees an accuracy level typical for FEA at a system analysis speed typical for system and circuit simulators.

While our previous two articles discussed coupled-field methods that are already available within ANSYS/Multiphysics, this final article casts a view onto the near future of MEMS virtual prototyping. It requires far more than one single numerical method. The developments in most organizations and engineering companies are based on various commercial tools for CAD, FEA, simulation of electronic circuits, control systems, multibody systems and also the microfabrication processes. Although we are on the forefront of this progress, many of these tools will be linked together by appropriate interfaces.

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*For further information on reduced order modeling techniques, read J. Mehner, L. Gabbay and S.D.Senturia:* Computer-aided Generation of Nonlinear Reducer-Order Dynamic Macromodels, *J. Microelectromech. Syst., Vol. 9, June 2000, pp. 262-278; and F. Bennini, J. Mehner, W. Dötzel:* Computational Methods for Reduced-Order Modeling of Coupled Domain Simulations, *11th Int. Conf. On Solid-State Sensors and Actuators, Germany 2001, pp. 260-263.*