RECENT ADVANCES IN AUTOMATED SYSTEM MODEL EXTRACTION (SME)

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Abstract. In this paper we present two different techniques for automated extraction of system models from FEA models. We discuss two different algorithms: for (i) automated N-DOF SME for electrostatically actuated MEMS and (ii) automated N-DOF SME for MEMS inertial sensors. We will present case studies for the two different algorithms presented.

1. Introduction

Accurate modeling of electrostatic MEMS devices such as micromirrors and inertial devices needs to properly capture far field electrostatic effects (such as actuating one micro-mirror on other micro-mirrors in an array), full capture of all relevant high order modes (for instance, energy contained in higher order modes in a gyro can severely effect performance), and the fluidic damping of the devices. While hierarchical models such as NODAS, SUGAR or SYNPLE are useful for quick exploration of the design space, complete FEA models are needed to fully capture the entire second order effects.

However, hierarchical models have an advantage over FEA models; they can be easily incorporated into system simulators. Previous attempts in creating system models have been limited to creation of 6DOF macromodels. While 6DOF models are useful for providing an insight into the system, they do not capture higher order modal behavior. MEMS devices are often made out of thin films, where the 6DOF models are not sufficient, accurate N-DOF models are needed to describe the behavior of these devices.

Energy based techniques based on modal superposition have previously been reported to capture the system energy and transformation into Lagrangian models. However, such techniques are useful for only linear problems. We present a new method to automatically capture the total energy in the system at multiple operating points i.e. the total strain and electrostatic energy of each of the important modes is captured. A novel lookup table based approach is used to create the system model. The system models have been implemented in various HDLs.

We present SME for two typical cases (i) a torsional micro-mirror model and (ii) an inertial device and compare the system modeling results with FEA. In each of the cases, we show that SME based models can accurately capture (within 1-5%) the transient behavior of the devices at a fraction of the computational cost (15-30 seconds versus 3-5 hours).
2. Implementation of System Model Extraction in IntelliSuite

This new SME mechanism has been designed in an effort to allow for quick and easy simulation of a complex finite element model within a system level tool while maintaining the accuracy of the simulation. It allows for dynamic simulations that are faster by orders of magnitude when compared to a full dynamic analysis with the whole FEA model. Another important application of the system model is that this model can be fully simulated with a control structure when incorporated into the system level tool. Not only is device simulation much faster, but the entire system (not just the MEMS device) can be fully optimized quickly and easily.

The method for the system model extraction within IntelliSuite is to determine the modes of the device, the strain energy stored within the device, and to determine the electrostatic energy stored in the device. The first step in the process is to analyze the mode shapes and their contributions to the overall deformation of the device. Then the modes are separated, and the stored strain energy is calculated at incremental steps within the mode shape for each mode. Finally, the capacitance matrix is determined at the same incremental steps for each mode [1]. Once these analyses have been completed, the information is stored in a look up table that can be used in a system level simulator. Within the system level simulator, different loading conditions can be applied to the system model to analyze how it will react, allowing optimization of the device and its control structure.

The SME capability that has been incorporated into IntelliSuite is designed to allow a user to determine which modes are the most important. Our SME implementation allows a user to decide which modes to examine for the energy computation. For each device and for each method of actuation, there are important modes and relatively insignificant modes. Examining all of the modes would keep track of all of the energy in the system. However, in most cases there will be one or two, sometimes three, important modes that contain greater than 95% of the energy stored in the system.

Once the modes and mode shapes are determined, the mechanical energy stored in the system must be analyzed. This is done separately for each mode. The mode shape is actuated within a user defined range and the stored strain energy is calculated at steps within the range. This data is stored in a file that, once complete, will be able to be referenced as a look-up table from within the system level simulation tool.

Finally, the electrostatic energy stored in the system must be calculated. This is done by determining the capacitance matrices and saving them in the look-up table. The capacitance matrices are determined at the same steps that were used in the strain energy analysis.

Once all of the necessary data is collected, the user must select a set of important nodes within the FEA model that will be used to apply forces and produce displacement outputs in the system level tool.

3. Using the System Model in SYNPLE

Once you have a system model of your MEMS device, you can import it to your system level simulator. This allows you to run dynamic simulations of your MEMS device in a matter of seconds instead of hours or days. A multi-domain system level simulator like SYNPLE will allow you to co-simulate your CMOS with your MEMS device.

4. Results and Discussion

4.1.1. Micromirror case study. The extraction of a macromodel from an FEA model and the comparison of results from an FEA analysis and a hierarchical model analysis of an array of torsional micro-mirrors are presented in this section. An array of micromirrors was modelled in IntelliSuite’s Thermo-electro-mechanical (TEM) simulator and the system model was extracted for implementation in the SYNPLE system modelling tool. Figure 1 shows an array of three micro-mirrors as simulated in
the TEM module with a pitch of 80µm. The array of micro-mirrors is actuated by electrostatic effects. A single mirror is actuated to actuate multiple mirrors in the array.

The macromodel (Hierarchical model) was derived for the array of micro-mirrors and implemented in SYNPLE. The macromodel contains the important modes of the device, the strain energy stored in each frequency mode and the capacitance matrix for each mode. This derived macromodel is implemented in the system modeler for further simulation at a fraction of the computational cost. Figure 2 shows a comparison of the voltage vs. deflection results for the TEM and SYNPLE models. Comparing the TEM and the SYNPLE results, we notice that the results are accurate to within 2%.

Figure 1: An array of 3 torsional micro-mirrors simulated in IntelliSuite’s TEM module

Figure 2: Deflection vs. voltage results from the TEM (FEA) model and SYNPLE (hierarchical) model.

4.1.2. Inertial device case study. The extraction of a macromodel from an FEA model and the comparison of results from an FEA analysis and a hierarchical model analysis of an inertial device are discussed in this section. The FEA modelling of the inertial device was performed in IntelliSuite’s Thermo-electro-mechanical (TEM) simulator and the system model was extracted for implementation in the SYNPLE system modelling tool. Figure 3 shows MEMS inertial sensor as simulated in
IntelliSuite’s TEM module. The inertial sensor is a µg accelerometer with capacitive sensing. It is used to measure the acceleration and the acceleration response is measured in terms of change of capacitance between the electrodes. Figure 3 shows the X-displacement of the accelerometer in microns for a 1g acceleration load. The two rectangular blue structures in the middle are the electrodes. The capacitance change between the inertial mass and the electrodes is recorded to sense the acceleration. The macromodel was extracted using IntelliSuite’s System Model Extraction (SME) module and the system model is simulated in SYNPLE.

Figure 3: MEMS Inertial sensor modeled in IntelliSuite’s Thermo-Electro-Mechanical module

Figure 4 shows the x-displacement of the accelerometer for various voltage loads for the Macromodel and the TEM. The graphs overlap and again show the high accuracy (< 2%) between the FEA model and the Macromodel. The electrostatic response of the accelerometer was compared initially followed

![Graph showing x-displacement vs voltage]

Figure 4: The x-displacement of the Inertial Mass vs. voltage applied for the Macromodel and the FEM model where TEM is the results form Thermo-Electro-Mechanical finite element analysis.
by the comparison of the acceleration vs. displacement response as shown in Figure 5. The acceleration responses of the FEA model and the Macromodel overlap, showing the accuracy of the system model.

Figure 5: The x-displacement of the Inertial Mass vs. applied acceleration for the Macromodel and the FEA model

One of the main advantages of a Macromodel simulation is faster dynamic analyses. Fully dynamic analyses can be performed at the same accuracy and fraction of the time with the Macromodel. Figure 6 shows a comparison of the dynamic responses from the TEM model and the Macromodel for a 1msec 1g acceleration pulse. Figure 7 shows the implementation of the MEMS Macromodel in SYNPLE.

Figure 6: The dynamic response of the accelerometer from the Macromodel and the FEA model for a 1g acceleration pulse.
5. Conclusion

The successful system model extraction of the MEMS Electrostatic device and a MEMS inertial sensor was discussed in this paper and the comparison of the results show that the Macromodel and the FEA model match within 2%. Equivalent system models of MEMS devices can be used to perform fully dynamic simulations in a fraction of the time required for a fully dynamic FEA model simulation. MEMS macromodel can effectively be used to interface the MEMS devices with the electronic controls.

References
[1] IntelliSuite Technical Reference, Copyright IntelliSense Software Corporation 2006.