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MEMCAD Capacitance Calculations for Mechanically Deformed Square Diaphragm and Beam Microstructures

Brian P. Johnson, Songmin Kim, Stephen D. Senturia, Jacob White

Microsystems Technology Laboratory and the Research Laboratory of Electronics
Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

High fabrication costs and increasing microsensor complexity are making computer simulation necessary, both to investigate design alternatives and to perform verification before fabrication. At MIT, we are developing a Micro-ElectroMechanical Computer-Aided Design (MEMCAD) system to make it possible for microsensor designers to perform realistic simulations easily and quickly. Carefully selected commercial software packages have been linked with specialized database and numerical programs to allow a designer to enter a three-dimensional microsensor geometry and quickly perform both mechanical and electrical analysis. In this paper we briefly describe the system, and demonstrate its effectiveness by accurately calculating the capacitance versus pressure (or force) curve for both a square diaphragm deformed by a differential pressure, and for a rectangular beam deflected by a centrally applied force.

1 Introduction

The high cost of fabrication and the increasing complexity of microsensors will soon make it necessary to use computer simulation to investigate design alternatives, and to perform verification before fabrication. Researchers in microsensors already investigate mechanical properties of microstructures by computer simulation, typically solving stress-strain and diffusion equations numerically using finite-element methods(FEM). For example, Christel[1] and Pourahmadi[2] have used FEM to model mechanical stresses and thermo-mechanical behavior of silicon microstructures. Also, Mullen[3] has used FEM to predict load-deflection and buckling behavior of beams with step-up boundary conditions. Pan[4] and Maseeh[5] have used FEM to perform quantitative studies of models of diaphragm structures used in an experiment to determine material mechanical properties.

Although researchers have succeeded in analyzing relatively simple microstructures using existing software, the approaches taken in those efforts will not easily extend to simulating realistic microsensors with much more complex geometries. At MIT, we are developing a Micro-ElectroMechanical Computer-Aided Design (MEMCAD) System to make it possible for microsensor designers to perform realistic simulations quickly and easily. The system is based on carefully selected commercial software packages linked with specialized database and numerical programs. The architecture of our MEMCAD system has been previously presented[6, 7] and a schematic block drawing of the MEMCAD system, along with a description of the material property database, can be found in the companion paper to this work [8].

In this paper, we will focus on examples that exploit our recent addition to the MEMCAD system, a specialized program for numerically solving three-dimensional electrostatics problems [9]. Such a capability is essential when analyzing either microsensors based on capacitance measurement[10] or microactuators positioned by electrostatic forces [11]-[15]. In particular, it is now possible for a designer to use the MEMCAD system running on a workstation to: specify and mesh an arbitrary three-dimensional solid model, specify boundary conditions and applied pressures, query a material property database for material property insertion, run a finite-element based mechanical simulation to determine solid model deformation due to specified pressures, and then determine the capacitance of the mechanically deformed structure. The software links and specialized electrostatic solver make it possible for a skilled MEMCAD user to compute an accurate capacitance versus pressure curve for a completely new microstructure geometry in less than a day.

Figure 1 shows the new software links, shown as dotted lines, reported in the present paper. The commercial solid modeler, PATRAN, is used to capture the geometry of the structure and to impose finite-element meshing, boundary conditions and mechanical loads. This structure is represented in the PATRAN Neutral File. A software module has been implemented to access the material property database (see reference [8]), and insert the material properties directly into the Neutral File. For the examples presented in this paper, the specific material properties used are the silicon material elastic constants (i. e. Young's Modulus = 169 GPa and Poisson's Ratio = 0.3.). The FEM solver, ABAQUS, is run to calculate mechanical displacements, and then our electrostatic solver, FASTCAP, is used to calculate the resultant capacitance of the deformed structure. In order to facilitate this transfer between modules, careful attention to data formats and to the detailed meshes appro-

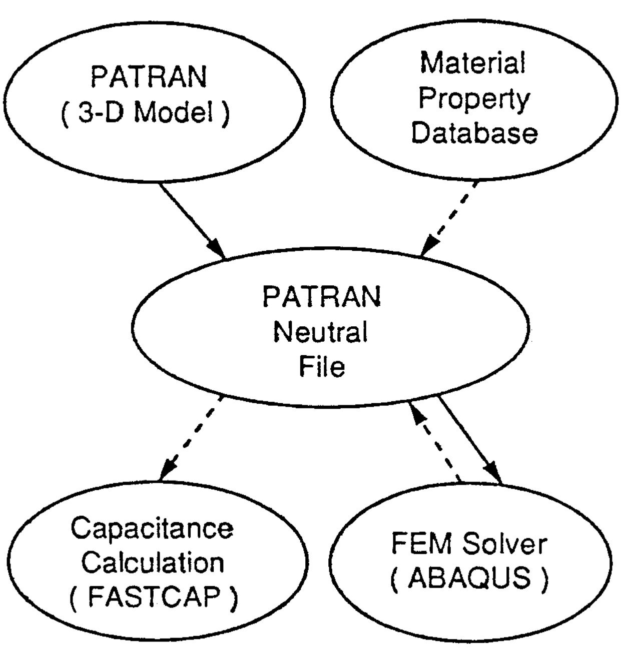

Figure 1: Conceptual Diagram of Reported Software Links.

priate to the separate mechanical and electrical analyses were required. These issues are explained with the aid of the examples in the following sections.

2 Square Diaphragm Capacitance

The first example involves a square diaphragm that is deflected by a differential pressure. Deflections due to various pressures can be measured as capacitance changes between the diaphragm and a ground plane [10]. The square diaphragm presents a severe test for the capacitance calculation of the MEMCAD system because the deformation due to pressure can be made sufficiently large to force the capacitor plates to touch. In our example, the initial separation between the diaphragm and ground electrode is 1 μm with a diaphragm edge length of 1000 μm^2 and a diaphragm thickness of 5 μm. At a pressure of 1.5 KPa, the diaphragm separation reduces to 0.02 μm in the center of the diaphragm geometry. With the gap reduced to 2% of its original value, we are still able to obtain adequate precision in both mechanical and electrical behavior, provided appropriate meshing is used. This particular diaphragm touches down at a load of 1.53 KPa.

Due to symmetry properties of FEM, only a quarter of the diaphragm geometry is meshed. ABAQUS is run to find the diaphragm deformation due to the pressure loads imposed. The FEM output and 3-D solid model of the diaphragm are then passed to FASTCAP to find the resultant capacitance in the presence of the applied pressure. FASTCAP requires the entire geometry of the diaphragm and ground plane to be meshed, but this can be done efficiently within PATRAN. Four-node shell elements were used for both the modeling of the mechanical deformation and the modeling of the capacitance calculation to simplify the analysis. This is not a fundamental limitation of the MEMCAD system, but the data compatibility between FASTCAP and ABAQUS is more complex when solid elements are used for the FEM analysis.

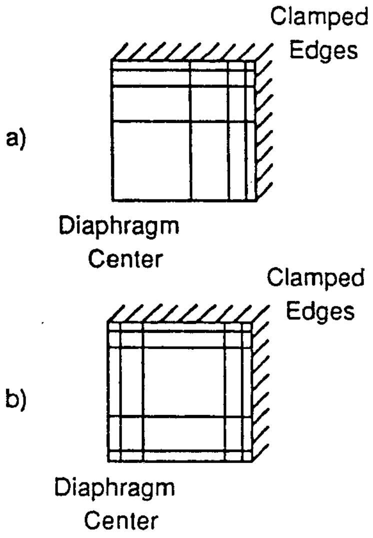

Figure 2: Schematic Drawings of a) Ratioed Elements and b) Double Ratioed Elements over a Quarter of the Square Diaphragm Geometry.

A variety of elements and mesh sizes were used to study convergence for the diaphragm geometry. Lin performed an element and mesh analysis on the square diaphragm and reported a mesh of 256 ratioed shell 4-node elements was sufficient to calculate mechanical deformations [16]. The ratioed elements, see Figure 2, are meshed so that there are a larger number of elements at the edge of the diaphragm as compared to the number of elements in the center of the diaphragm. We found that these ratioed elements do not model accurately the capacitance calculation of the square diaphragm structure when the deflection is large, as shown in Table 1. The 256 ratioed mesh calculates a capacitance value that is smaller by 11% then the value calculated by smaller mesh sizes. The reason is that when the deflection is large, the capacitance is dominated by the diaphragm center, which has relatively few elements. The last two row entries in Table 1 show calculations based on a double-ratioed mesh (see Figure 2). This mesh allows a larger number of elements to be placed both in the center of the diaphragm which dominates the capacitance calculation, and at the edge of the diaphragm, to account for mechanical deformation.

Based on the meshing study, 900 4-node shell elements were used to calculate the capacitance-pressure curve of Figure 3. Computer times for ABAQUS and FASTCAP on a Sun4 platform were 6.0 min. and 18.6

Number of Elements for ABAQUS	Center Displacement (μm)	C (pF)
256 Ratioed	0.980	19.40
625	0.980	21.56
900	0.980	21.91
1225	0.980	21.88
400 D. Ratioed	0.980	21.85
900 D. Ratioed	0.980	21.92

Table 1: Mesh study for the Square Diaphragm at an applied pressure of 1.5 KPa, for which the gap is reduced from 1.0 μm to 0.02 μm.

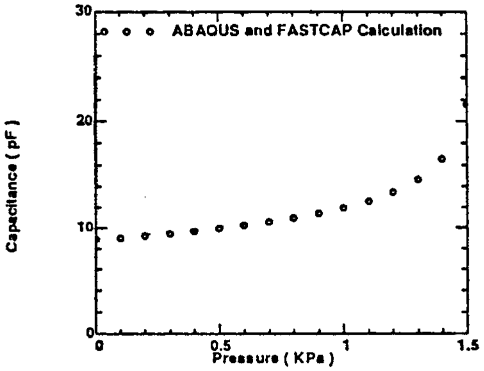

Figure 3: Capacitance versus Pressure of a Square Diaphragm.

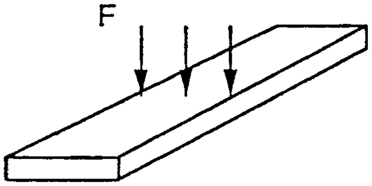

Figure 4: Beam Structure showing Applied Force for Capacitance Calculation.

min. for this example, respectively, at the 1.5 KPa data point. A comparison of the diaphragm deflections calculated from ABAQUS to a Fourier series representation of the deflections agree to within 1.0% of each other for pressures which deflect the beam to 98% of the gap [17].

3 Beam Microstructure Capacitance

The second example consists of a beam that is clamped on both ends. A force is applied at the center of the beam across the width perpendicular to the beam's length (see Figure 4). The doubly-clamped beam structure has been used to measure material properties of thin films [12]. Four-node shell elements were used for mechanical and electrical simulations with mesh sizes of 400 elements. Capacitance per unit beam width is calculated for changes in applied force per unit beam width, and is shown in Figure 5. The beam widths are scaled so that the effects of fringing electric fields become important as the beam width decreases, hence the increase in capacitance per unit width for small applied forces. There is a 81% increase in capacitance per unit width at small loads between beam widths of 10 μm and 1 μm. Because FASTCAP is fast, analysis of this type, where fringing fields become important, can now be done routinely as part of a design.

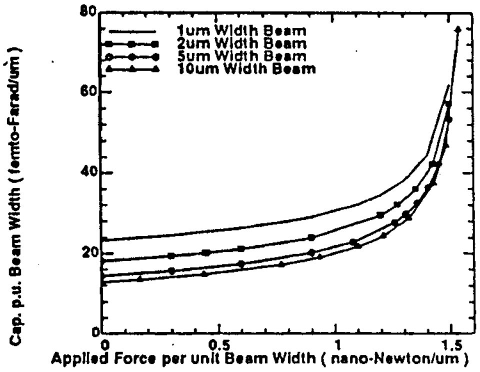

Figure 5: Capacitance per unit width versus Applied Force per unit width for Rectangular Beams. Length = 1200 μm, Thickness = 1.0 μm, Electrode Gap = 1.0 μm.

4 Conclusion

The MEMCAD system has successfully implemented the following: querying a material property database for material property insertion, combining a 3-D solid model with displacement information from FEM, and interfacing the 3D solid model format with a capacitance extraction program. The meshing of a 3D solid model requires careful attention to not only the mechanical deformation calculation but also to the details of the capacitance calculation. The capacitances of a square diaphragm deflected by a differential pressure and a rectangular beam deflected in the center by an applied force are calculated to verify the software links. The rectangular beam example demonstrates the usefulness of the MEMCAD system in the combined presence of significant fringing electric fields and large mechanical deformation.

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