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IMPLEMENTATION OF A MEMCAD SYSTEM FOR ELECTROSTATIC AND MECHANICAL ANALYSIS OF COMPLEX STRUCTURES FROM MASK DESCRIPTIONS

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ABSTRACT

We report the development of a first implementation of the MEMCAD system (version 1.0). The system is composed of three commercial mechanical CAD software packages integrated with our specialize structure generation and electrostatic analysis programs. In this paper we describe the system and demonstrate its capabilities using a comb drive example constructed directly from a CIF description of its mask set. We received the CIF file from U.C.Berkeley[1]. The analysis of the comb drive takes just a few hours, all the way from generating a full 3D model from mask descriptions to calculating comb levitation forces.

INTRODUCTION

MEMS designers are making increasing use of commercially available computer simulation packages as design aids [2,3,4]. Modeling a MEMS device involves three basic tasks: creation of the 3D structure, simulation of some physical behavior of the model device, and visualization and analysis of the results. Commercial tools exist in all these areas; however, the geometric complexity of MEMS structures often makes using such tools cumbersome. An architecture for a MEMCAD (MEM Computer-Aided Design) system has been proposed [5] which would both simplify and accelerate the process of simulating novel MEMS structures.

We have developed a first implementation of the MEMCAD system (version 1.0). The system is composed of three commercial mechanical CAD software packages integrated with our specialized structure generation and electrostatic analysis programs. We describe the system and demonstrate its capabilities by using it to analyze a comb drive example from U.C.Berkeley.

In Figure 1 we sketch the MEMCAD 1.0 system in the context of those three tasks. The shaded boxes represent the commercial CAD tools: Pro/Engineer [6], PATRAN [7], and ABAQUS [8]. They cooperate through their common use of the PATRAN Neutral File (PNF)[7] for interchange of 3D structures. The open boxes represent codes written at MIT. They are STS (or cif2iges)[9] and FASTCAPII+[10]. The three bubbles on the left of Figure 1 represent the basic user inputs to the process of creating a 3D structure.

Figure 1 also summarizes the application of the MEMCAD system to the comb drive example. STS 1.0 converts mask layouts to IGES format. Pro/Engineer, a solid modeling package, is used to read the IGES file, to extrude the mask to build a 3D structure, and to automatically generate coarse analysis meshes. Visualization on geometric structures is done with PATRAN. Mechanical analysis is done with ABAQUS, and electrostatic analysis with FASTCAPII+.

This paper contains three sections corresponding to the tasks above: creation of 3D structure, visualization, and simulation and modeling. In each section we briefly describe the parts of MEMCAD 1.0 in that area, and illustrate them with example of the comb drive. The bulk of our remarks are found in the sections on creation of 3D structure and simulation and modeling, since it is in those areas that we have added both software codes and methods to what is available commercially.

CREATION OF 3D STRUCTURES

Our first task is to create an acceptable 3D model of the device at hand. We do not have the capability to build the 3D model from physical process modelers (i.e. TCAD). Instead, we have implemented an approach to 3D structure creation that we call the "icing" method. This method is based on building 3D structures by extruding each 2D mask layer into a 3D slab and then stacking these slabs correctly in three dimensions. The icing method is particularly well suited to making models of devices fabricated with the techniques of surface micro-machining.

The 2D layout of a MEMS device is usually developed within a mask layout program such as KIC. A common standard format for interchange of mask information is the CIF format.

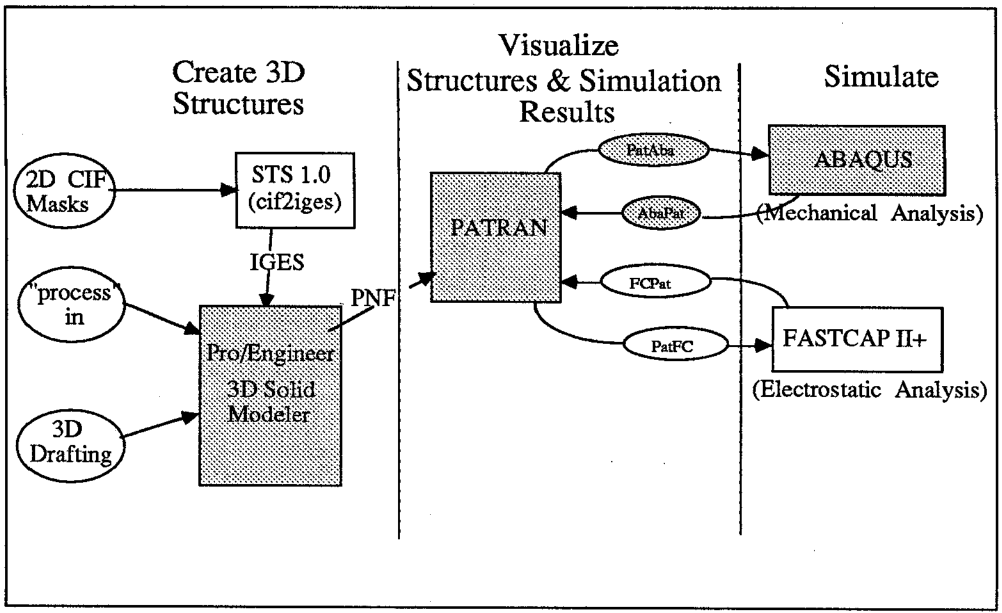

Figure 1 A sketch of MEMCAD 1.0. The outline shows the components that exist in the 1.0 system and the organization by which they work together to analyze the comb drive. The shaded boxes are the commercial parts of the MEMCAD 1.0 system, The open boxes are the parts of the system that were written at MIT.

A. STS 1.0 and cif2iges

Conversion of mask layer descriptions from CIF to IGES is done by a routine called cif2iges. To build this program we used the structure simulator (STS) originally developed to determine mask overlays[9], and we modified it so that the program now generates output files in IGES format. Essentially, cif2iges uses the Mairson-Stolfi[11] intersection algorithm to compute the union of the CIF features in a single mask layer and to extract the outlines of the various masked and unmasked regions of the layer.

In its present version cif2iges works with a subset of the full CIF format, which we call mCIF. The mCIF subset uses only boxes and non-self-intersecting polygons in describing masks. It does not contain self intersecting polygons, wires and circles. Typically the designer should lay out circles as N-sided polygons (we usually use N=50) at the KIC level, and those are perfectly valid constructs in mCIF. This mCIF subset is well matched to the subset of CIF that our pattern generator uses for mask fabrication.

Some of the edges produced with cif2iges are too short to be handled by our solid modeler, particularly when the mask contains non-manhattan features. Cif2iges will delete all edges shorter than a given minimum size. This minimum edge size is adjustable and can be set smaller than the physical resolution of the photolithographic process.

The end result of running cif2iges is an IGES layer for each mask layer in the CIF file.

B. 3D solid modeling--Pro/Engineer

The core solid modeler in the MEMCAD 1.0 system is a commercial mechanical CAD package, Pro/Engineer. Pro/Engineer is used to read the IGES description for each mask layer and to extrude it into a 3D slab. The slabs for successive process layers are then positioned together in a 3D assembly and may also be combined with arbitrary structures drawn directly in Pro/Engineer.

The creation of full 3D structure from a designer's information may be broken down into several procedures. These are illustrated in Figure 2.

Figure 2A shows the IGES description of a comb drive poly layer as imported via cif2iges from a CIF mask. Next, the designer adds one piece of "process" information to the structure by specifying the thickness of the poly deposition. Figure 2B shows the resulting extruded 3D slab. This procedure, which is quite simple to perform, can be repeated one or more times. Each resulting 3D layer can then be correctly positioned in space relative to the other layers.

Figure 2C shows the comb layer positioned 2µm above a ground layer. In a sense the designer is adding more "process" information to set the relative position of the layers (this might correspond to the thickness of a sacrificial layer.).

In Figure 2C we have produced the basic comb drive device. It has four unconnected conductors -- two fixed combs, the central movable comb, and the underlying ground plane.

In order to perform further analysis on the model device, we must perform three further tasks: add material properties, specify appropriate boundary conditions, and mesh the structure. In the MEMCAD 1.0 system all these tasks are done in Pro/Engineer.

VISUALIZATION

Visualization of structures and the results of their analysis is a key part of any CAD system. It is necessary to visualize the responses of a device over its 3D structure. Examples of such responses are deformations, stesses, charge distributions and temperatures, all of which should be visualized as mapped onto the device's actual structure. In MEMCAD 1.0 we use PATRAN as the tool for visualization. Examples of its use are found in Figure 3 (deformations) and Figure 5 (charge distributions).

SIMULATION AND MODELING

Once we have finished a structure in Pro/Engineer and exported it to PATRAN, we are essentially ready to analyze it.

A. Mechanical Simulation

We use ABAQUS to predict the modes of excitation of the movable comb structure. Figure 3A shows the fundamental eigenmode in the plane of the poly layer. The ABAQUS analysis predicts the resonant frequency of that mode to be 19.5KHz.

We can also use ABAQUS to predict the deformation of the comb under applied forces. A 200nN load in the z direction was applied to the center of the movable comb in Pro/Engineer. Figure 3B shows the resulting deformation in z. Observing the consequent displacement of the center of the movable comb, we estimate that the movable comb has a spring constant of 370 nN/μm against z displacements.

B. Electrostatic Simulation

MEMCAD 1.0 includes the FASTCAPII+ electrostatic modeler. FASTCAPII+ uses the multipole-accelerated boundary element method to do 3D capacitance computation[10]. With FASTCAPII+ we can calculate the charge on every panel of the meshed comb drive structure for any applied voltage distribution.

Most of the improvements made in FASTCAPII+ aided its integration into the MEMCAD system. These improvements include the ability to determine connected conductors from the mesh description and to use that information to perform rigid relative displacements of each connected conductor. This allows the simple extraction of capacitance $\{C_{i,j}\}$ vs. x, where x is a displacement of any one conductor relative to the others.

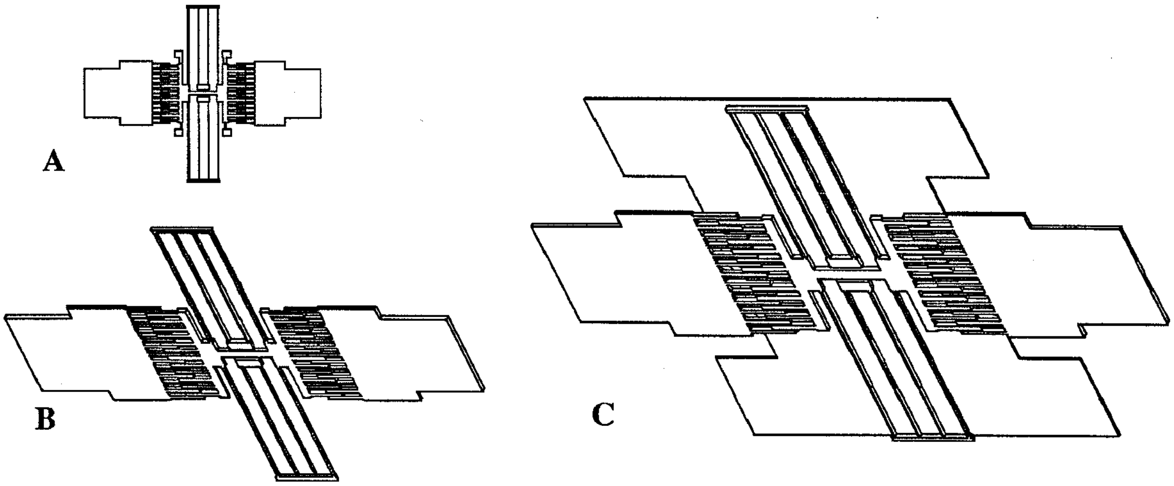

Figure 2 **A** is an IGES 2D description of the comb poly layer. **B** is a 2μm thick extruded slab made from the IGES description in A. **C** is a two slab structure based on the comb poly layer of **B**, positioned over a ground layer.

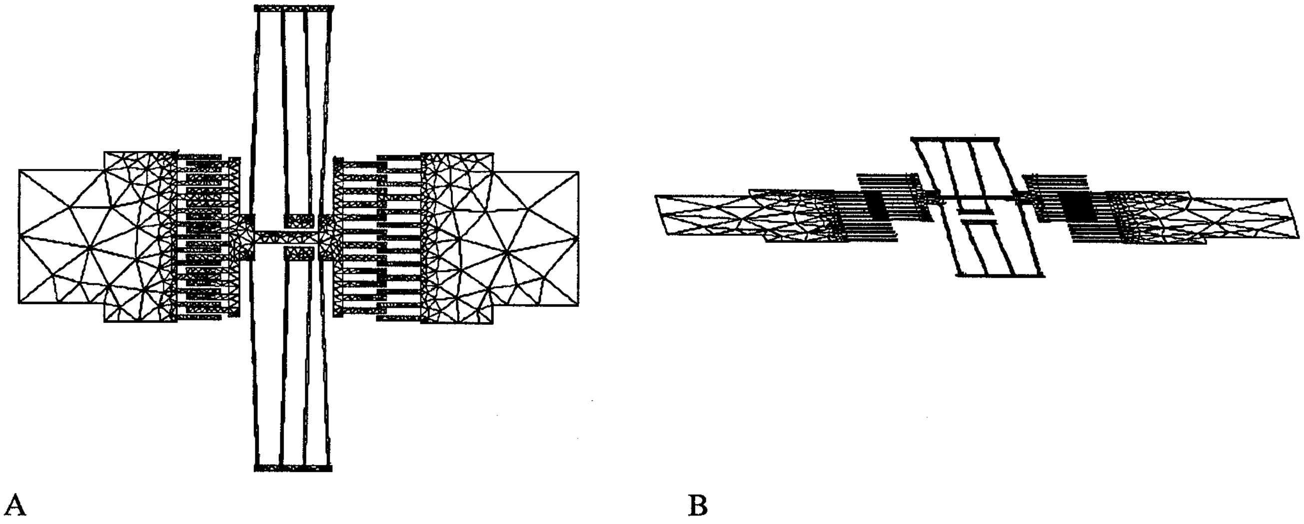

Figure 3 Deformations calculated in ABAQUS. **A** is the fundamental eigenmode for excitation along the x-axis. This mode has resonant frequency of 19.5KHz. **B** is the deformation of the movable comb in the z direction, due to a 200nN point load applied at the center of the movable comb. The point load was set in Pro/Engineer.

Using FASTCAPII+, we can calculate the charge distributions across the comb drive structure. Figure 5A shows the charge distribution over one set of fingers on the comb drive. Figure 5B shows the change in that charge distribution when the movable comb is displaced by 10μm away from the fixed comb. The charges are calculated for 1V on the fixed (left hand) comb, and 0V on the movable comb. We can also calculate the four conductor capacitance matrix $\{C_{i,j}\}$ with FASTCAPII+. This matrix is shown in Figure 4 for the comb drive of Figure 2, coarsely meshed at 10K panels. Running FASTCAPII+ on this structure takes about 20 minutes on a DECstation 5000/240.

The triangular mesh is too coarse, particularly near the comb finger edges, to provide more than a rough estimate of the capacitance matrix. For example, the undisplaced comb drive has reflection symmetry, and therefore C_{31} should equal C_{32}, but the computed matrix entries differ by more than 5%. Memory limitations of our workstations prohibited recomputing the capacitance matrix using a finer mesh, though certainly such a convergence study must be completed before results should be accepted with confidence.

C. Electromechanical Analysis

In Figure 4 we showed the capacitance matrix of the comb layer plus ground plane which has four separate conductors. FASTCAPII+ can also do a rigid offset of any of the conductors, relative to the others, and calculate the resulting $\{C'_{i,j}\}$. This last ability has allowed us to estimate the electrostatic energy W vs. z displacement of the comb structure. From this we can deduce the electrostatic levitation force induced on the movable comb.

This calculation requires the approximation that the movable comb is rigid under the applied electrostatic force. For devices in which this "rigid part" approximation is appropriate, the force due to an applied voltage may be calculated from the change in energy per unit displacement with all conductors held at constant voltage, i.e. equation 1.

$$F_z = \left(\frac{\partial W}{\partial z}\right)_V = \frac{\partial}{\partial z}\left(\frac{1}{2}\sum_{i,j} C_{i,j}V_iV_j\right)_V \qquad (1)$$

$$C_{i,j} = \begin{vmatrix} 122500 & -87 & -7789 & -113600 \\ -87 & 122200 & -7308 & -113800 \\ -7789 & -7308 & 127800 & -111500 \\ -113600 & -113800 & -111500 & 355400 \end{vmatrix}$$

Figure 4 The capacitance matrix for the four conductor comb drive. C is in aF. 1 and 2 are fixed combs, 3 is the movable central comb and 4 is the ground plane.

Figure 6A shows such an estimation of W vs. z (for 1V on each fixed comb and 0V on the movable comb and the ground plane). Using equation (1) and the spring constant found from ABAQUS, we can then estimate the z displacement as a function of applied voltage V. That relationship, describing levitation of the movable comb, is graphed in figure 6B.

Experimental measurements on a similar comb drive with 19 drive fingers have been made at UC Berkeley [12]. They report an observation of

A B

Figure 5 Charge distributions from FASTCAPII+. **A** is the charge distribution in the comb fingers, at their equilibrium position. **B** is the charge distribution on the fingers with the movable comb displaced by 10μm. Both calculations were done only on the regions shown, meshed with about 5K surface panels. This is a denser mesh than that of used for the calculations of Figures 4 and 6, however it is still not known to be convergent. The charge distributions are also interpolated by PATRAN for display. The gray scale represents surface charge density and goes from black at -0.741 $fC/\mu m^2$ to white at 0.741 $fC/\mu m^2$.

47pN/V^2 per drive finger. This is reasonably close to our estimated 80pN/V^2per drive finger.

We believe that for a large class of MEMS devices this kind of "rigid part" approximation may be useful. However, we are working to extend MEMCAD to cover a fully self-consistent electromechanical analysis of deformed structures as well as rigidly displaced ones.

CONCLUSION

The MEMCAD 1.0 system as reported here can handle only a modest subset of all possible MEMS structures. The structures must be well described by one or more extruded single mask layers, and layers generated directly from mask data may have only vertical side walls. In the present version, we can only perform separate electrostatic and mechanical simulations; i.e. their results may only be mixed through use of some coupling approximation, such as the rigid part assumption and equation (1).

The significant victory in the MEMCAD 1.0 system is the establishment of the full pathway for the user/designer to bring real devices all the way through from CIF mask and simple "process" information through to analysis of spring constants, resonant frequencies and electrostatic forces. All further developments of MEMCAD can now fit into the existing system, allowing improvements in each area to improve the analysis of all devices that go through MEMCAD.

ACKNOWLEDGMENTS

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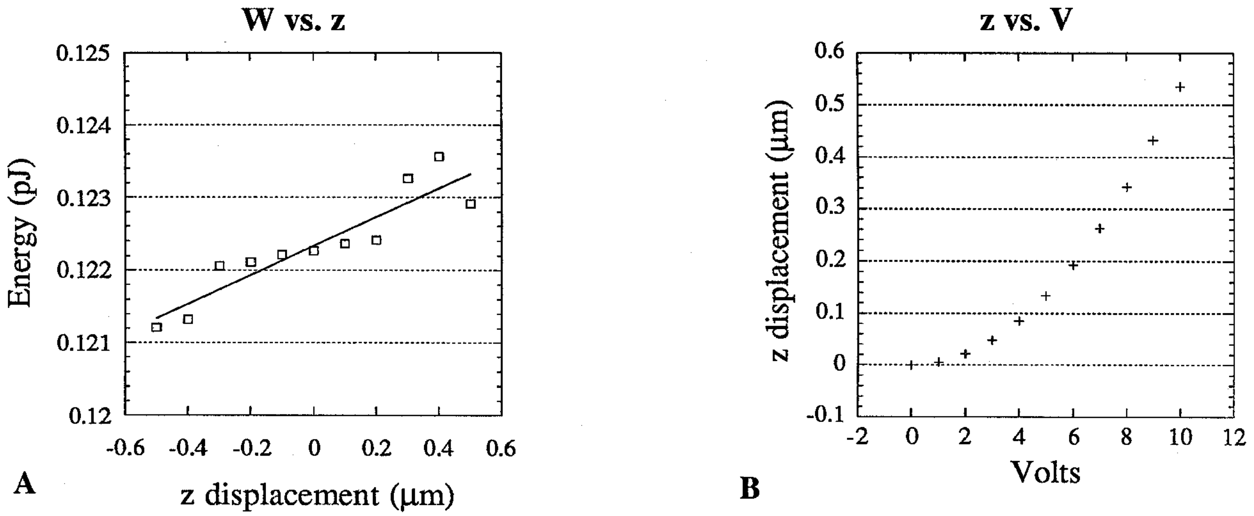

Figure 6 Levitation in the rigid part approximation. **A** is the electrostatic potential energy W vs. displacement z of the central comb with 1V on each of the fixed combs and 0V on the central comb and the ground plane. Each point represents one run of FASTCAPII+ and takes about 20 minutes on a DECstation 5000/240. In the region from -0.5μm to 0.5μm we find a reasonable fit of F_z=2nN. In **B,** we estimate z vs. V using the spring constant of 370nN/μm found with ABAQUS for motion of the moveable comb in z.

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