An Improved Meshing Technique and its Application in the Analysis of Large and Complex MEMS Systems

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ABSTRACT

This paper presents a new local refining meshing algorithm which is referred to as the Exposed Face Mesh (EFM) algorithm, for three-dimensional coupled electromechanical analysis with multiple dielectrics. This algorithm allows for the independent refinement of the electrostatic mesh and mechanical mesh in a coupled system. This approach is compared to the commonly used volume refining mesh method in which both the electrostatic and mechanical mesh domains are refined concurrently. The new EFM method is shown to have substantial improvement in increasing accuracy of results and reducing computational expense (time and memory) especially for fringe electric field dominated structures. For a typical comb drive structure, the EFM algorithm generates much fewer volume mesh nodes for mechanical analysis (20 times less) and fewer surface mesh panels for electrostatic analysis (10 times less) than the standard volume refining mesh method. At the same time, the EFM method showed an improvement in accuracy from 15% (using the standard mesh) to within 5% for this case. The IntelliCAD™ MEMS modeling software has incorporated this Exposed Face Mesh algorithm and made it a unique software system to handle general device structures accurately.

Keywords: Exposed Face Mesh, Efficient Simulation, Coupled Analysis, Refinement, CAD

1. INTRODUCTION

In the design of MicroElectroMechanical systems (MEMS), the accurate calculation of electrostatic pressure (or force) on the structure surface is essential in determining the structural deformation. Many MEMS devices have specific planes on which the electrostatic pressure is critical for determining the device electromechanical behavior. Examples of such planes include the movable finger tips of Surface Micromachined Accelerometers. These faces will be referred to as Exposed Faces due to their exposure to other electric field sources.

The commonly used method to calculate the electrostatic pressure on these Exposed Faces is to refine the three-dimensional domain locally and/or globally. Unfortunately, the problem size increases rapidly as the volume mesh is refined using this method. The modeling of typical electrostatically activated MEMS using the volume mesh method results in large problem sizes which surpass many of today's workstations' computational capabilities. For many cases the problem size reaches a limit as defined by the required computing expenses (such as 100,000 nodes). Even when the mesh is refined to the computational limit, the electrostatic mesh on the Exposed Faces usually is not fine enough to provide accurate results for coupled electromechanical analyses.

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In this paper, instead of refining the volume mesh [1] [2], we present the Exposed Face Mesh (EFM) method which refines only the electrostatic surface mesh on the chosen Exposed Faces for boundary element based electrostatic analysis, while keeping the original volume mesh topology from finite element or finite difference based mechanical analysis. The advantage of this novel meshing method is that the surface mesh used in the electrostatic analyses is separated from the mechanical volume mesh while assuring full compatibility between the two. The EFM method results in smaller computational models while improving the numerical accuracy in MEMS simulation. With the EFM method, the surface mesh can be customized for electrostatic analysis purposes (such as refining only the Exposed Faces), while the volume mesh can be refined independently to provides correct mechanical results. Considering a simple comb drive structure as an example, this new Exposed Face Mesh algorithm was compared with the standard refining volume mesh method.

2. EXPOSED FACE MESH METHOD

For coupled electromechanical analysis, the governing system of equations for the electromechanical problem can implicitly be expressed as:

$$S = Fm\left[\left(X0(M)\right),\ Fe\left(S + X0, V\right)\right] \tag{1}$$

where X0(M) is a vector representing the released structure, S is the discretized structure surface displacement, M is the multi-material property information, and V is the applied voltage information. From (1) the numerical error of structure surface displacement can be derived. The numerical error can be approximated as:

$$\delta S = \left(\frac{\delta Fm}{\delta X0}\right)\delta X0 + \left(\frac{\delta Fm}{\delta Fe}\right)\delta Fe \tag{2}$$

Assuming that the original structure X0 is correct, the first term on the right of (2) can be ignored. In (2), δFm/δFe is the surface displacement increment due to electrostatic pressure changes, which is inversely proportional to the Young’s modulus. δFe is the numerical error of electric force of total structure, which is proportional to the voltage squared (V^2) and is dominated by the electrostatic pressure discretization error on the Exposed Faces. The numerical error will increase as the structure’s flexibility increases. To reduce δFe and therefore to suppress the numerical error, the Exposed Face Mesh method can be applied, thus significantly reducing the discretization error on Exposed Faces. The more flexible the structure is, the larger the refining factor should be set in the EFM algorithm to keep the numerical error within the given tolerance.

The EFM algorithm can be described as follows:

1) Generate the global three dimensional (hexahedral, finite element) volume mesh from the model.
2) Extract the global surface (boundary element) mesh from the volume mesh.
3) Locate the Exposed Face surface mesh on the global surface mesh.
4) Refine the Exposed Face surface mesh to $2*N^2$ plane panels as defined in step 1, and remove all non-Exposed Faces. Then generate the surface mesh for electrostatic analysis.

5) Refine the finite element volume mesh if required in other mechanically sensitive regions.
6) Perform electrostatic analysis over the electric surface mesh.
7) Map the electrostatic charge over the Exposed Face to the global surface mesh, then derive the electrostatic pressure over the global surface mesh.
8) Attach the global surface mesh to the three-dimensional volume mesh, and apply electrostatic pressure loads to the analyzed structure.
9) Perform mechanical analysis, update the structure deformation and associated global volume mesh. Then return to step 3 until the increment of the structure deformation is below the given tolerance.

3. CASE EXAMPLE: DEMONSTRATING THE POWER OF EFM

The Exposed Face Method has been implemented in the latest release of the IntelliCAD™ system. To demonstrate the EFM method, a sample problem of a comb-drive is considered as shown in Figure 1. The simple comb drive structure is a typical structure widely used in surface micromachined accelerometers, resonators, and other devices. The comb drive in Figure 1 consists of three fingers. Two of the fingers are fixed, and the other is attached to a folded beam support. The gap between the movable finger and fixed fingers is 1 μm, the thickness of the finger is 20 μm, and the width of the finger is 1.6 μm. A 10V differential is applied between the movable finger and fixed fingers.

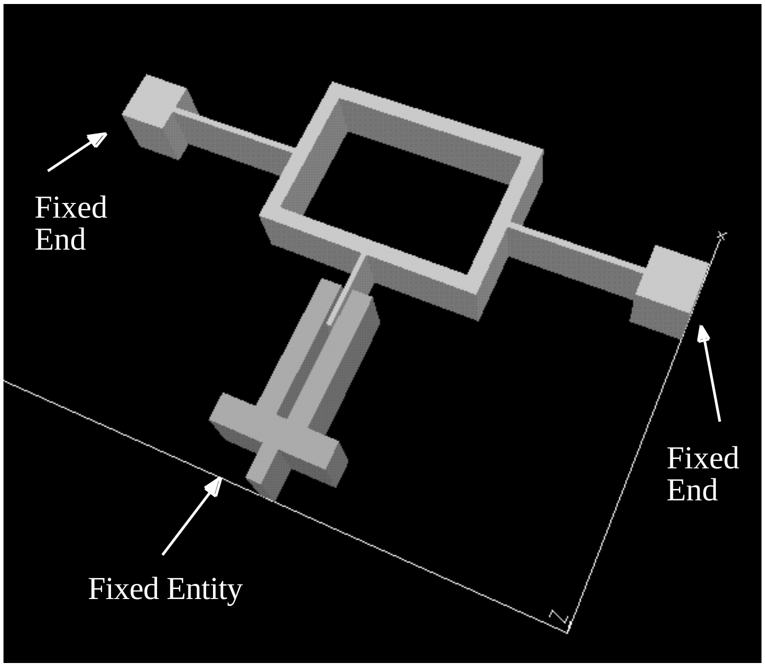

Figure 1: IntelliCAD™ Solid Model of a Three Finger Comb Drive Structure

The electrostatic force acting on the movable finger can be approximated by the following equation:

$$fe = 2\,\frac{\delta\left(\frac{V^2 C}{2}\right)}{\delta x} = \frac{\varepsilon_o W V^2}{g} \qquad (3)$$

where g is the distance of the gap between fingers, W is the width of a finger, ε_o is the permitivity, V is the applied voltage, and the factor of 2 appears because the movable comb finger has 2 sides. By taking into account the comb drive dimensions and the applied voltage, an electric force of $1.771 \cdot 10^{-8}$ Newton can be derived from (3). Using the IntelliCAD™ system, we analyzed the comb drive structures using two approaches, the EFM method and the conventional refining volume mesh method.

Figure 2 shows a close-up view of the electrostatic mesh of the comb-drive structure. The electrostatic mesh was refined only on the Exposed Faces of the comb-drive fingers. In this figure, the refined Exposed Face Mesh consists of 128 panels which corresponds to a refinement factor of 6. The electrostatic mesh on the other non-Exposed Face portions of the comb-drive is omitted from the electrostatic analysis since these areas will not have a significant effect on the electrostatic analysis.

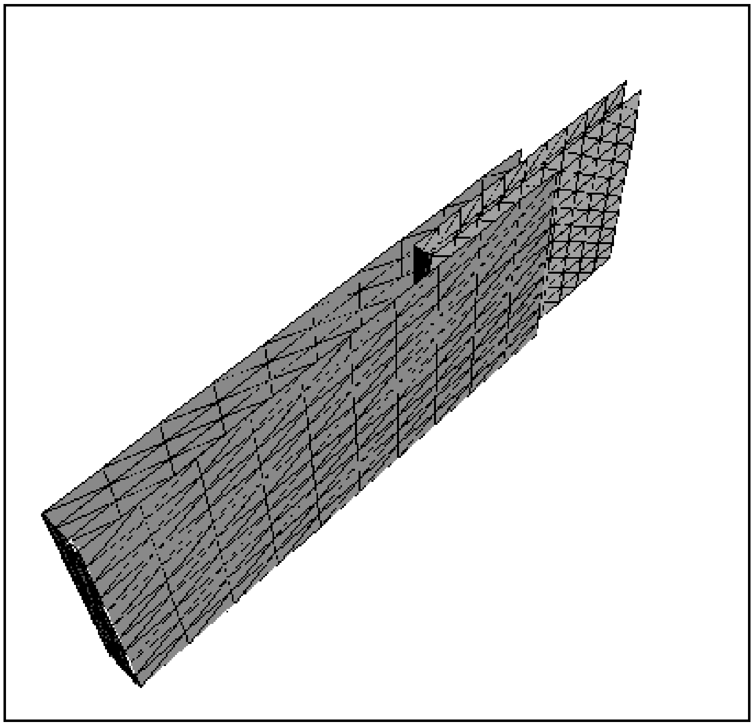

Figure 2: Close-up View of Comb Drive Finger Showing the Refined Exposed Face Mesh (EFM)

The resulting electrostatic problem size is smaller than if the entire volume and surface mesh was refined while an accurate analysis is insured. Additionally, the refinement of the boundary element electrostatic mesh does not have an effect on the mechanical finite element mesh. Figure 3 shows the mechanical mesh for the same comb-drive structure unaffected by the electrostatic mesh manipulations.

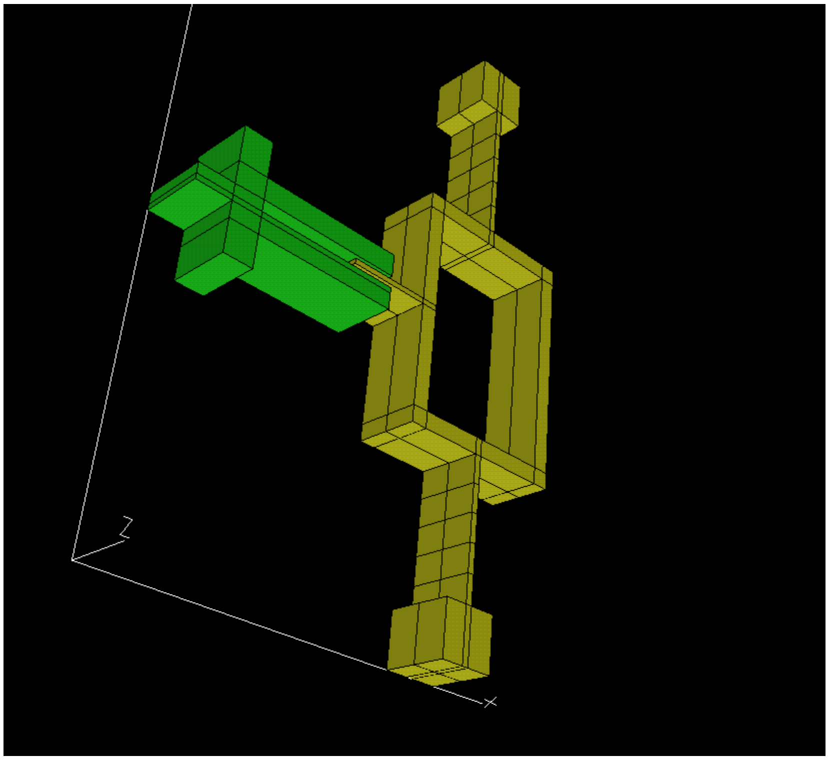

Figure 3: Comb-drive Shown with Mechanical Finite Element Mesh

Coupled electromechanical simulations were performed with IntelliCAD^{TM} varying the level of mesh refinement. Figure 4 shows the electrostatic force versus the number of total surface panels in the electrostatic mesh. Results are given for three different methods: the EFM refinement method, the refining volume mesh method, and the analytical model.

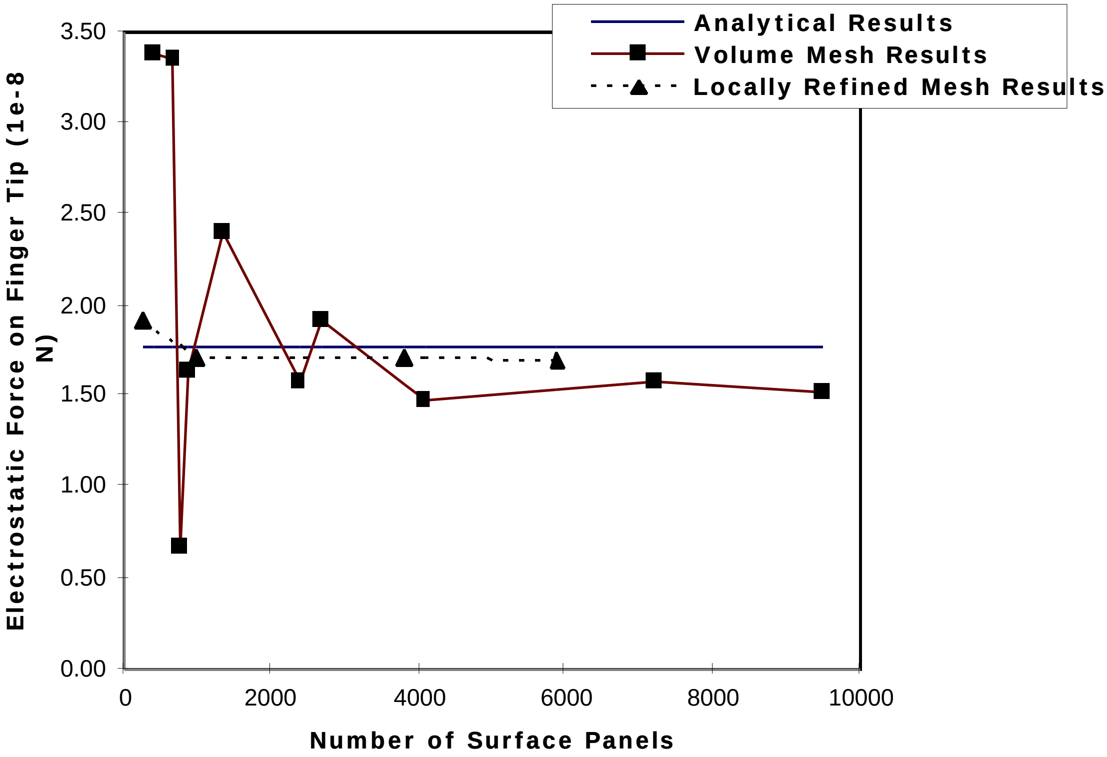

Figure 4: Results of Electrostatic Analysis of the Comb Drive Structure Using Three Analysis methods.

Figure 4 shows that the new Exposed Face Method exhibits a faster rate of convergence than the volume refining method. A nominal accuracy of 5% is achieved with approximately 1000 surface panels using the EFM method. This result must be compared with the refined volume method requirements of over 10,000 surface panels for a 15% accuracy. Results from other examples show that the EFM algorithm can generate 20 times fewer volume mesh nodes for mechanical analysis than the refined volume mesh method.

4. CONCLUSION

The EFM method significantly improves the numerical analysis accuracy for coupled electromechanical analysis while insuring manageable problem sizes for today's state-of-the-art workstations. With this novel EFM method, the current IntelliCAD^{TM} system can analyze fringe field dominated structure accurately, and to within 5% for the discussed comb-drive example.

ACKNOWLEDGMENTS

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REFERENCES

[1] X. Cai, P. Osterberg, H. Yie, J. Gilbert, S. Senturia, J. White, “Self Consistent Electromechanical Analysis of Complex 3-D Microelectromechanical Structures Using Relaxation / Multipole-Accelerated Method,” Sensors & Materials, Vol. 2, No. 2, 1994.

[2] S. Akkaraju, Y. He, R. Harris, G. Napadensky, F. Maseeh, “Completely Integrated Thermo-electro-mechanical Analysis of MEMS Devices,” Late News Digest for Solid State Sensors and Actuators Workshop, Hilton Head, SC, June 5, 1996.