Numerical simulation of micro-assembly of MEMS devices and post assembly electromechanical actuation

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ABSTRACT

This paper presents the latest results on ongoing numerical simulation research of assembly and post-assembly analysis of MEMS devices. Evolving MEMS technologies, including the use of micro-fabricated hinges and gears, have enabled the fabrication of micro-assembled MEMS devices. Examples of these devices include tilting micromirrors, latching mechanisms, and micromotors. A simulation methodology has been developed that allows a MEMS designer to not only model the assembly process, but also to model the effects of various stimuli on the assembled device. Using these capabilities, a MEMS designer can investigate the necessary actuation forces, interfacing mechanisms, and time constraints for micro-assembly, as well as the performance of the device in its assembled state. These simulations rely on multi-stage non-rigid multi-entity contact analysis, dynamic analysis, and large displacement theory. Results are presented for a developed micromirror example. The assembly process for the "pop-up" micromirror mechanism are analyzed. After assembly, the coupled electromechanical actuation behavior will be studied. Changes in structural stress, stiffness, natural frequency, and mirror flatness are calculated and show a marked difference from the unstressed / undeformed shape. The newly developed algorithms allow designers to simulate and look into the details of phenomena often ignored in conventional MEMS design. Recent improvements in simulation methodologies allow micro-assembly analyses and post-assembly analyses of the resulting devices. By enabling micro-assembly and post-assembly analyses, we present the first reported MEMS analysis tool capable of modeling the latching mechanisms and post-latching actuation that frequently control current MEMS devices.

Keywords: contact analysis, micro-assembly, electromechanical actuation, CAD, MEMS, IntelliSuite

1. INTRODUCTION

MEMS design and analysis software products were developed to address the specific needs of MEMS engineers. Fabrication process-based model creation, anisotropic etch simulation, thin film material property characterization, and fully coupled 3-dimensional thermo-electromechanical analysis are examples of capabilities that have been developed to allow modeling of more complex MEMS designs [1]. As MEMS technology progresses, new product realization methods become feasible, and new software capabilities are required to simulate the fabrication and operation of these new devices.

Only recently has the simulation of micro-assembly of MEMS devices become feasible [2]. These complex, multi-step, non-rigid contact problems present several challenging issues, such as numerical convergence at a reasonable computational expense. However, modeling the assembly process itself is only half of the challenge. Once the device has been assembled, it needs to function in some capacity. Therefore, it is necessary to be able to perform post-assembly analyses on these structures; ideally, any analysis that can be performed with an undeformed, unassembled model should be possible to be performed on a micro-assembled device. Figure 1 shows a micro-assembled micro-mirror device, which is ready for post-assembly performance analyses.

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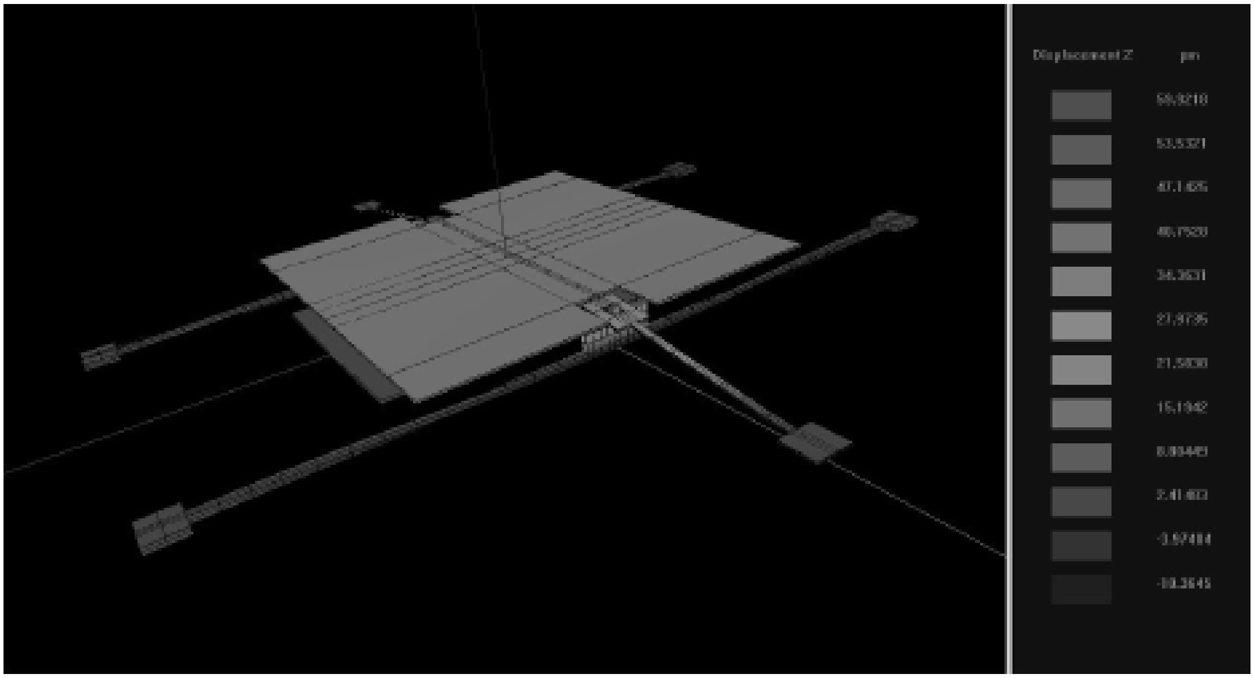

Figure 1: Micro-assembled device model for post-assembly analysis

Computationally, post-assembly analysis can be an extremely challenging task. The assembly process alone is a time-dependent, highly nonlinear, multi-step contact analysis. Model simplifications are necessary to reduce convergence problems and computational expense. However, these modifications must not preclude accurate thermo-electromechanical analyses from being performed on the post-assembly model.

2. IMPLEMENTATION IN INTELLISUITE™

Commercial MEMS software packages have been developed to perform fully coupled 3-dimensional electromechanical dynamics analysis, allowing for analyses including RF switching time and natural frequency shift due to applied voltage bias [3]. In addition, recent advancements have enabled numerical simulation of micro-assembly techniques in MEMS devices [2]. These features require a convergent solution in highly non-linear, time dependent analyses. The use of large displacement theory was vital in achieving the goal of numerical convergence in time dependent analyses at minimal computational expense.

Several advancements were necessary to enable the analyses of these devices. The definition of multiple contact steps, in which contact pairs can be activated and removed from step to step, saves significant computational expense during assembly and post-assembly analyses. Reductions in the device geometry size are employed to reduce the number of required contact pairs while maintaining the accuracy of the model for further analyses. In addition, stabilization algorithms are incorporated into local models to improve the rate of convergence.

Relationships between different parts of the device to be assembled are defined via new algorithms, allowing the program to incorporate local model solutions into the global model. Most importantly, another algorithm separates the mechanical mesh required during the contact (assembly) analysis from the mesh required for further physical analysis, allowing accurate post-assembly analyses to be performed.

The developed software is the first reported CAD software tool for MEMS capable of performing comprehensive three-dimensional assembly and post-assembly analyses. This capability allows for the modeling and analysis of a whole new class of MEMS devices -- micro-assembled products.

3. EXAMPLE: MICRO-ASSEMBLED ELECTROSTATIC MICRO-MIRROR

To illustrate the capabilities of IntelliSuite to simulate micro-assembly and perform post-assembly analyses, a micro-mirror example, shown in Figure 2 will be used. This micro-mirror is assembled using a pop-up latching technique to elevate the mirror surface. The micro-mirror is then electrostatically actuated by applying a voltage to one of two electrodes on the substrate.

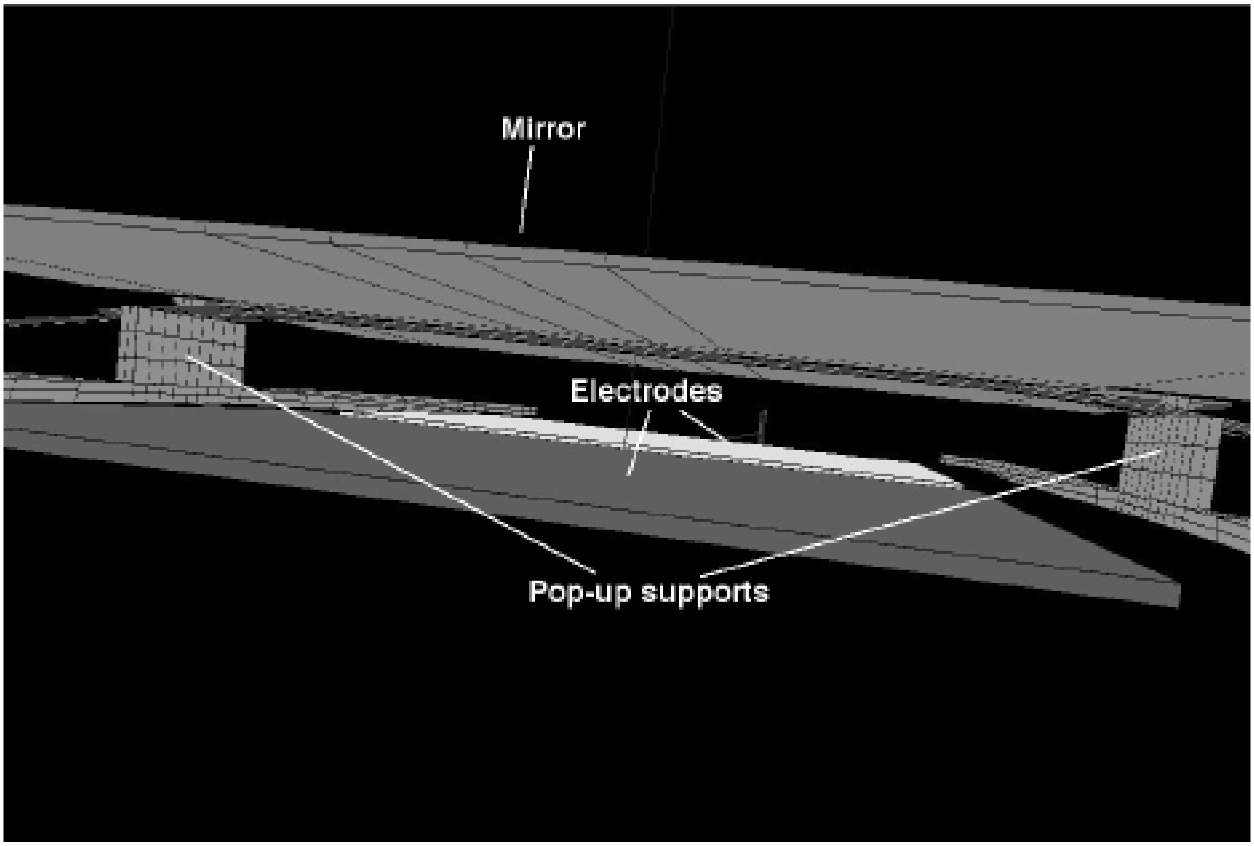

Figure 2: Micro-assembled, electrostatically actuated micro-mirror

In the micro-assembly analysis section, the creation of the model and the simulation of the latching technique will be demonstrated. In the post-assembly analysis section, the assembled device will be analyzed to determine the relationship between applied voltage and rotation angle.

3.1. Micro-assembly analysis

The bottom view of the micro-mirror device, presented in Figure 3, shows the various components of the MEMS device. The entire device consists of two actuating electrodes, two pop-up supports for the mirror, the supporting beams for the mirror, and the mirror itself. Created via surface micromachining, the device is fabricated mainly of polysilicon with metallic electrodes.

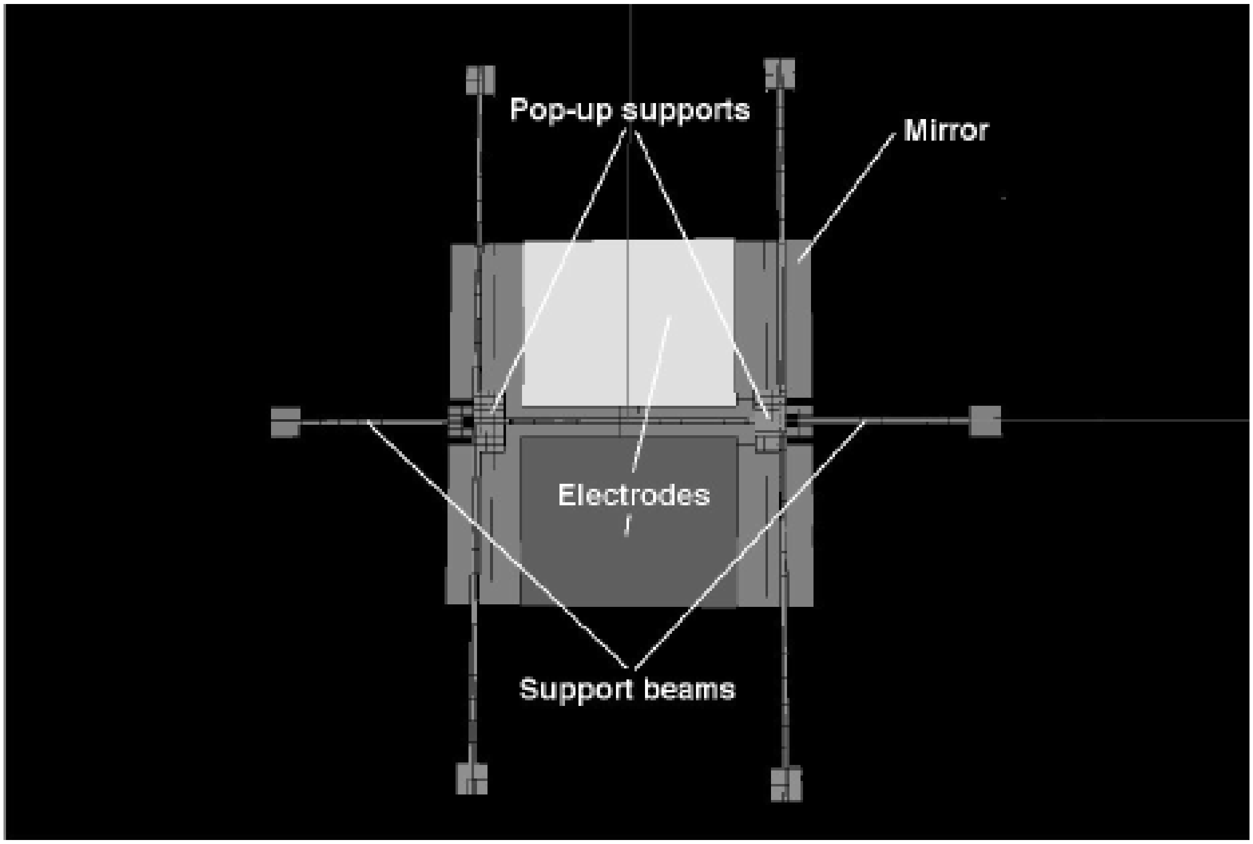

Figure 3: Bottom view of the micro-mirror device

The pop-up beams have a 10 μm x 10 μm cross section, with a length of 400 μm. Each pop-up mechanism consists of two beams connected to a 100 μm x 40 μm support, with a 10 μm x 10 μm latch at the end. The mirror itself is 600 μm x 600 μm, with cutouts to allow for the latching assembly to occur. The mirror is supported by a 900 μm long beam, with a width of 10 μm and a thickness of 3 μm. The support beam has two holes that are positioned to allow the latching of the pop-up mechanisms.

In the pre-assembled state, an air gap of 1 μm separates the elevation mechanism from the support beams of the micro-mirror. As shown in Figure 4, pressure is applied to one side of the pop-up support, causing it to rotate upwards. The rotating support in turn pushes up on the mirror support beams. When the support has been rotated to its fully vertical position, the mirror is elevated 50 μm from the electrodes, as shown. This elevation allows for a much greater rotation with a large mirror.

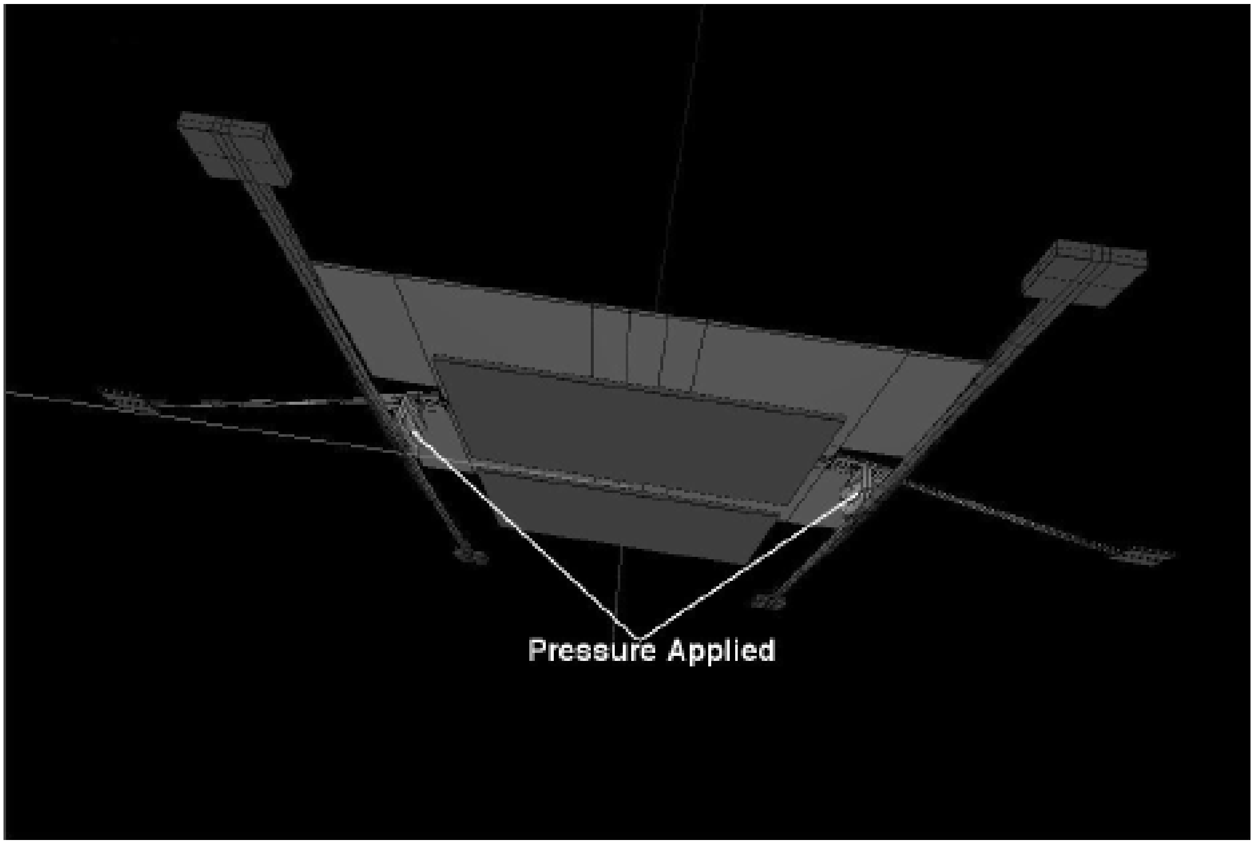

Figure 4: Pressure is applied to pop-up supports to elevate mirror structure.

For the second stage of the analysis, the active contact pairs are switched, so that the software can direct computational power away from the sliding of the pop-up assembler along the beam and focus on the latching of the assembler tab into the hole in the beam. When the tab on the pop-up micro-assembly support reaches the hole in the micro-mirror support beam, the device latches together. This latching action is displayed in Figure 5. This latching allows the rotated supports to maintain the elevation of the micro-mirror without the need for any external loading.

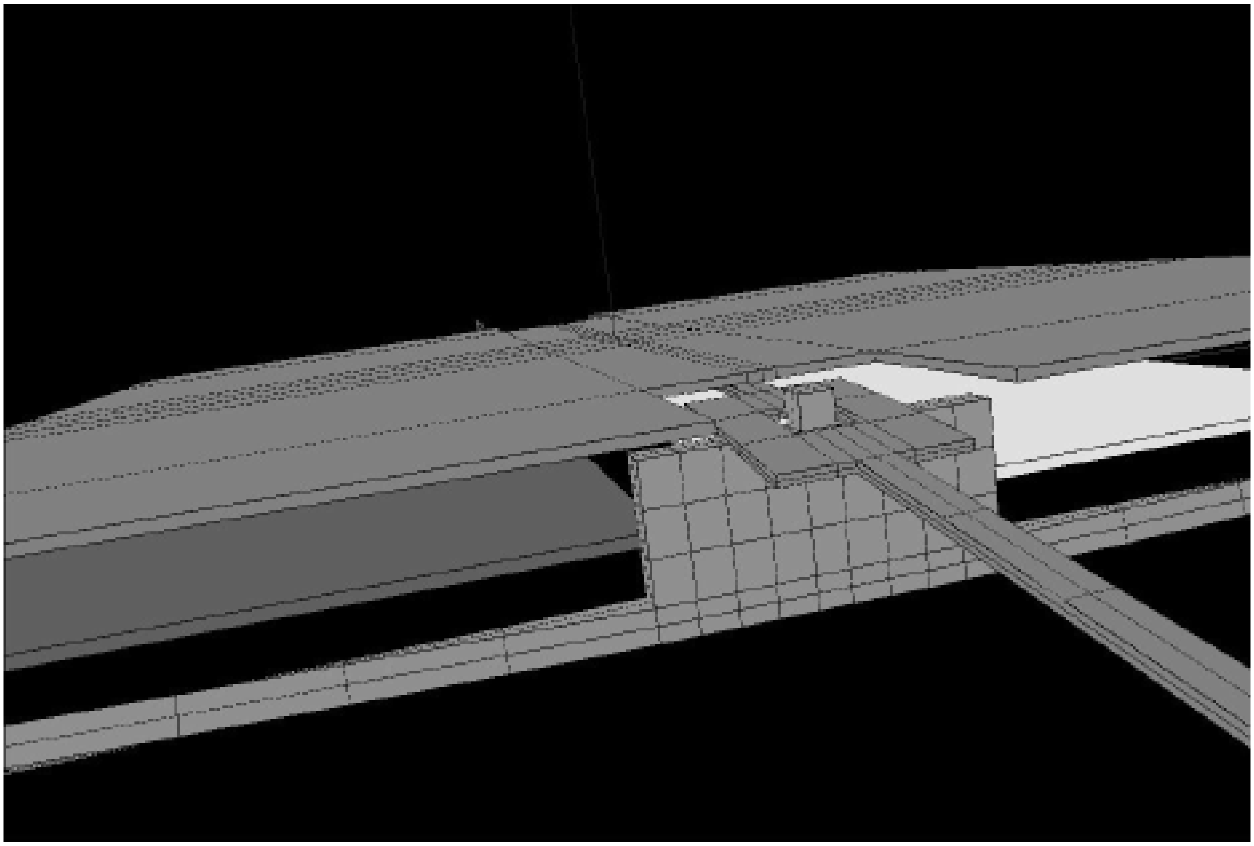

Figure 5: Tabs fit into holes on micro-mirror support beams, completing the micro-assembly process

At this point, the micro-mirror has been elevated 50 μm above the actuating electrodes, which will allow a rotation of over 9 degrees in each direction. This improved rotational freedom is vital in the performance of many MEMS micro-mirrors. The effects of electrostatic actuation on this micro-assembled device can now be investigated.

3.2. Post-assembly analysis

Through the use of IntelliSuite's non-rigid contact analysis algorithms, an accurate model of the micro-assembled mirror has been generated. In the previous section, external pressures were applied to the initial, undeformed geometry that allowed the simulation of the latching process used to elevate the micro-mirror from the lower electrodes.

However, the creation of the 3-dimensional coupled finite element/boundary element model is only the beginning of the analysis process. For this model to be truly valuable in the product design and development process, it must be able to be used in post-assembly performance analyses. An engineer can then perform the same thorough design analysis and optimization procedures employed for non-assembled devices.

In this case, the micro-assembled device is a micro-mirror. This mirror is actuated by applying a voltage to one of the lower electrodes; the resultant electric field causes one side of the mirror to be pulled toward the electrode, resulting in a rotation of the mirror itself.

A parametric electro-mechanical performance analysis was run in the software. The mirror and one of the lower electrodes were held at 0 V. The voltage other electrode was varied from 0 to 150 V, in increments of 25 V. Figure 6 shows a graph of the rotation (in degrees) of the micro-mirror as a function of voltage.

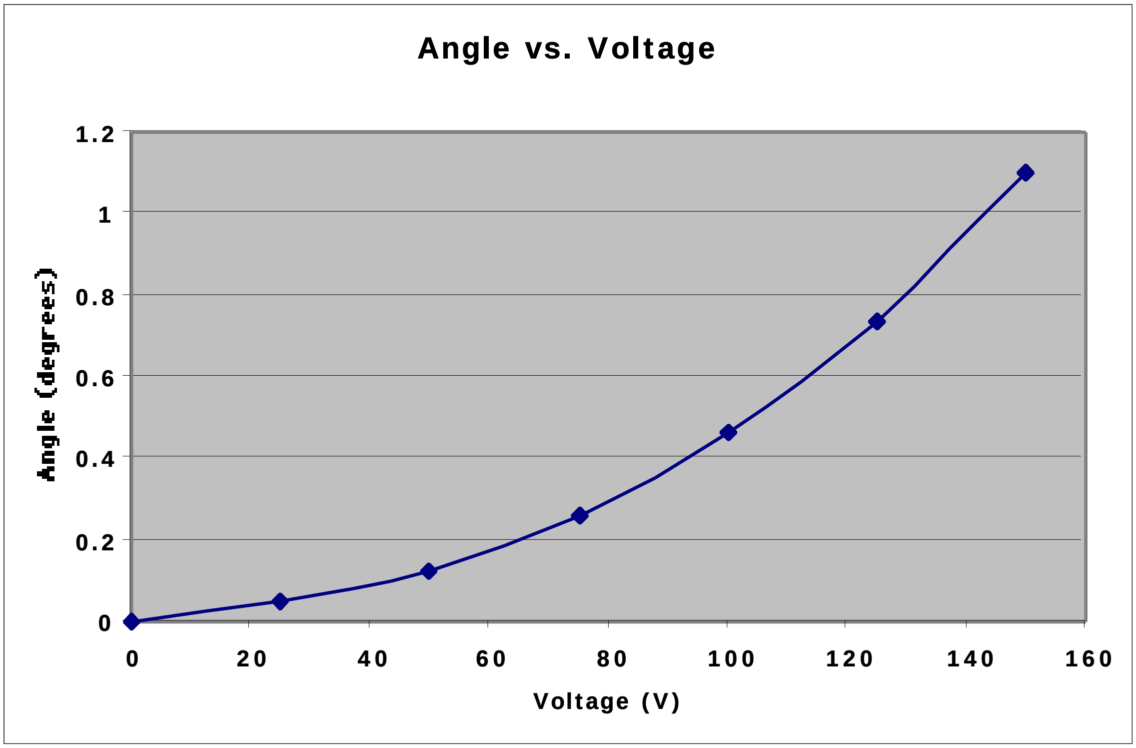

Figure 6: Rotation of the micro-mirror as a function of electrode voltage

Figure 7 shows a the post-assembly, electrostatically actuated micro-mirror. In this view, a voltage of 150 V has been applied to one of the lower electrodes. The resulting displacement in the z-direction is shown.

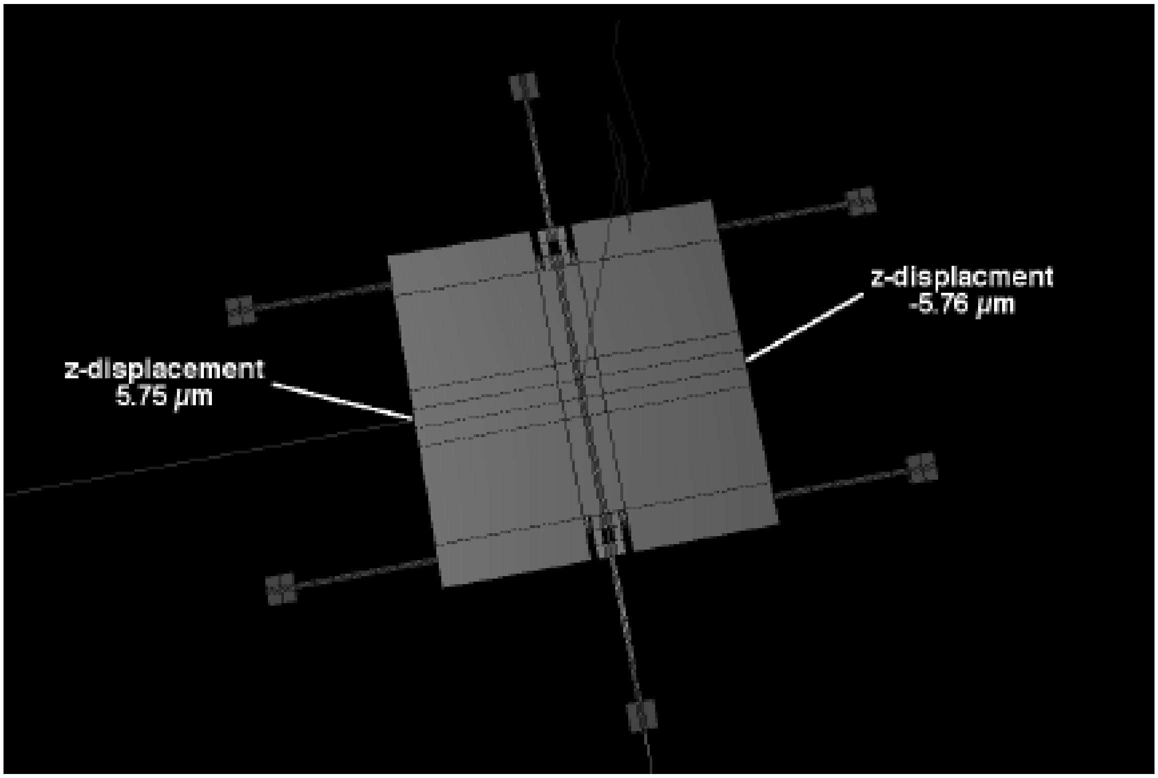

Figure 7: Z-displacement caused by application of 150 V to one of the lower electrodes

4. CONCLUSIONS

A micro-assembled, electrostatically actuated micro-mirror was used as an example, as optical MEMS have become more and more common recently. Starting from the initial, undeformed geometry, the structure was assembled using a latching mechanism. After the assembly process itself was complete, post-assembly coupled electromechanical analyses were performed to investigate the rotation of the mirror as a function of applied voltage.

As the variety and complexity of MEMS devices continues to expand, more and more analysis capabilities become necessary. With fabrication process-based model creation, fully coupled 3-dimensional thermo-electromechanical analysis, multi-dielectric contact analysis, and squeezed-film damping analysis, IntelliSuite has met each of these new demands with improved simulation capabilities. Most recently, the simulation of micro-assembly of MEMS devices has become feasible.

Now, with the ability to perform post-assembly analyses, another new family of MEMS devices can be modeled and simulated in a finite element environment. Using advanced modeling approaches and large-displacement theory, mirco-assembled models have been generated which allow analyses to be performed in the same manner as they are for non-assembled devices.

5. REFERENCES

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