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An Investigation into the Response of a Micro Electro Mechanical Compound Pivot Mirror Using Finite Element Modeling

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Abstract

This report is a presentation of modeling and simulation work for analyzing three designs of Micro Electro Mechanical (MEM) Compound Pivot Mirrors (CPM). These CPMs were made at Sandia National Laboratories using the SUMMiT^{TM} process. At 75 volts and above, initial experimental analysis of fabricated mirrors showed tilt angles of up to 7.5 degrees for one design, and 5 degrees for the other two. Nevertheless, geometric design models predicted higher tilt angles. Therefore, a detailed study was conducted to explain why lower tilt angles occurred and if design modifications could be made to produce higher tilt angles at lower voltages. This study showed that the spring stiffnesses of the CPMs were too great to allow for desired levels of rotation at lower levels of voltage. To produce these lower stiffnesses, a redesign is needed.

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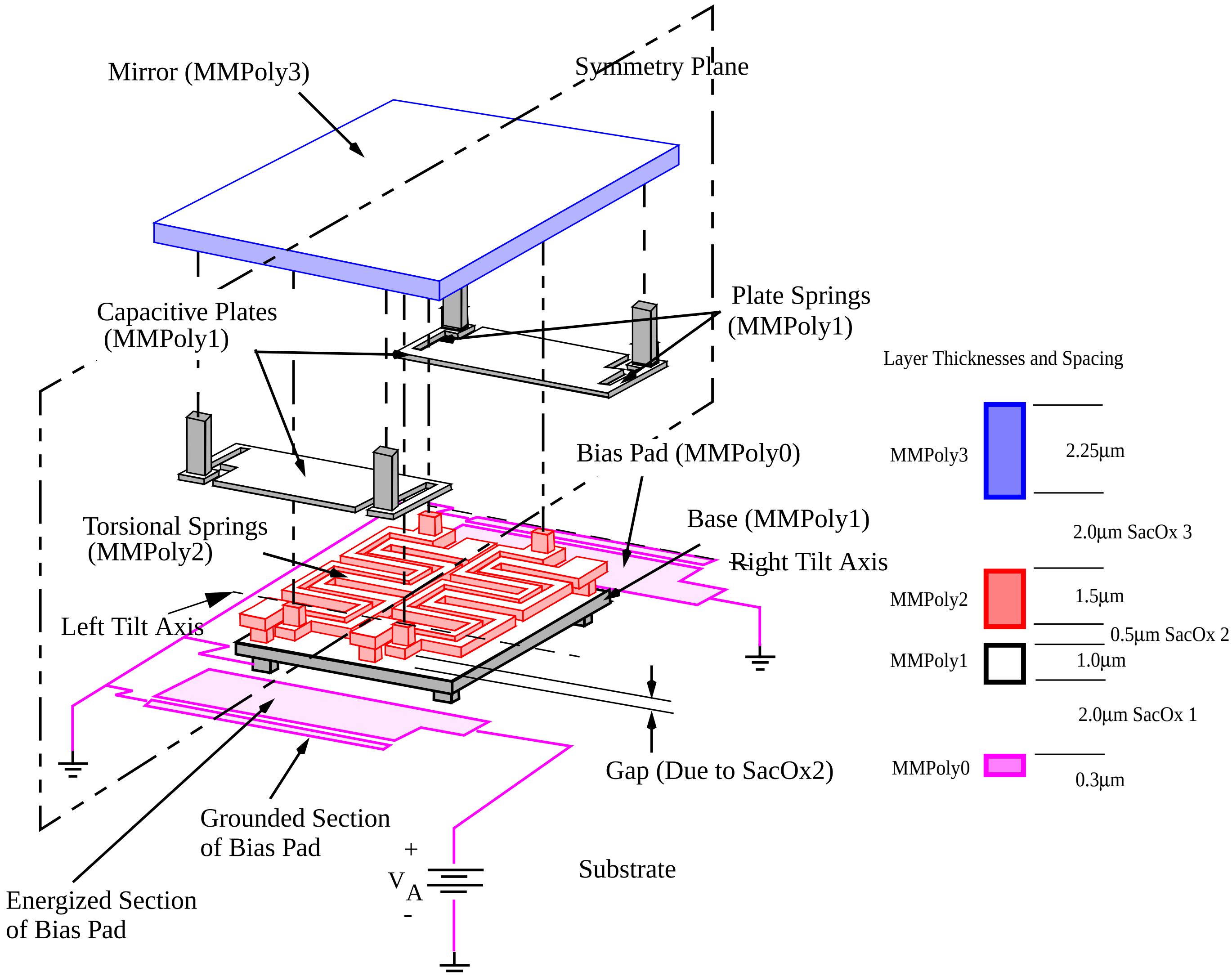

Figure 1: Compound Pivot Mirror (CPM) Assembly

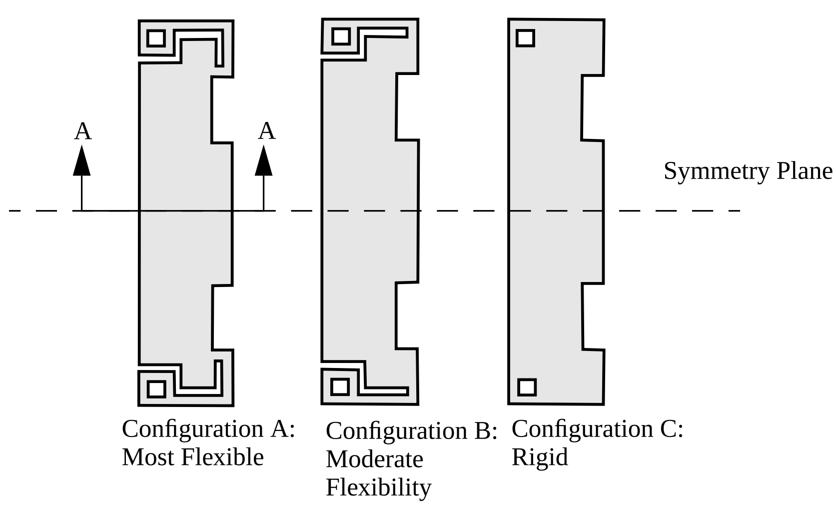

Figure 2: Left Capacitive Plate Geometries

INTRODUCTION

Optical Micro Electro Mechanical Systems (MOEMS) technology has the potential to revolutionize the telecommunications industry by enabling low cost methods of interconnecting mass amounts of communication data [1]. One aspect of achieving this revolution is through the use of low cost arrays of pivoting micromirrors. In this paper a study focusing on one such mirror, the Compound Pivot Mirror (CPM) [2] is discussed.

The Compound Pivot Mirror is a complex design. The structure includes a 50 micron square mirror atop torsional springs, left and right capacitive plates attached to the mirror base, and bias pads. The torsional springs provide a restoring force to the mirror after a left or right tilt has occurred, the capacitive plates offer the electrostatic surface which is pulled to the bias pad underneath them. The mirror tilts in three orientations: Flat, to the left, and to the right.

The CPM discussed in this paper is of particular interest considering that initial testing of a set of CPMs failed to perform as expected. These CPMs were designed using geometrical relationships that should have yielded tilt angles of approximately 10 degrees; however, initial testing showed that tilt angles were only up to 7.5 degrees.

A study as to why CPM tilt angles were below design values was initiated.

The objective was to:

- determine what physics lead to trends seen within the experimental data
- determine design parameters important to enhancing tilt angles to 10 degrees for excitations below 28V.

DESIGN DESCRIPTION

Figure 1 illustrates the construction of a CPM using SUMMiT IV™ surface micro-machining technology. This process technology contains four structural Polysilicon layers, MMPoly0, MMPoly1, MMPoly2, and MMPoly3, each successively situated above the other. The spacing between and thickness of each layer are shown in Figure 1.

As shown, the CPM mirror, a 50 x $50 \mu m^2$ MMPoly3 plate, was attached to a set of MMPoly2 torsional springs that were mechanically anchored through MMPoly1 to the substrate. Another set of springs connected a set of MMPoly1 capacitive plates to each end of the mirror. Below these plates were MMPoly0 bias pads [3]. By applying a bias potential to the pads, an electrostatic load was produced which rotated the mirror about pivot points marked on Figure 1. Resistance to this rotation was through the torsional springs.

As with many MEMS devices, design variations were produced to enhance the probability of success. In these devices, the plate springs were modified such that the stiffness between the plate and the mirror varied. As shown in Figure 2, three variations were manufactured.

The micromirrors in question are 50 μm square and 2.25 μm thick. Attached to either side of a mirror base is a

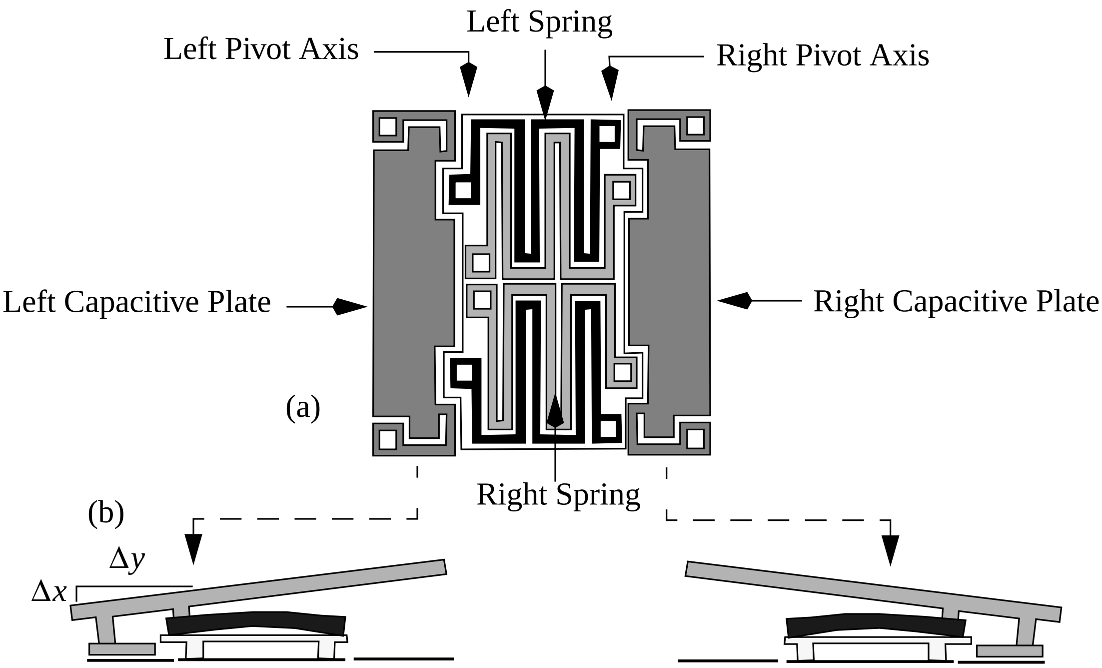

Figure 3. Least-Stiff Compound Pivot Mirror Design

capacitive plate, which is electrostatically pulled to an energized MMPoly0 bias pad.

In Figure 3a, a top view of the device without the mirror is shown. The left and right pivot axes are indicated by the arrows in Figure 3b. When voltage is applied to a bias pad, the associated capacitive plate deflects downwards pulling the mirror with it until the plate hits a mechanical stop, the grounded section of the bias pad. The torsional springs flex to allow tilting motion and to provide a restoring force.

As shown in Figure 3b, these mirrors are compound pivoting mirrors, tilting about two different axes depending upon which bias pad is energized. The mirrors are geometrically designed to tilt to approximately 10 degrees. This angle is obtained from the inverse tangent of the vertical travel distance (Δx) over the pivot arm length (Δy) [3].

MODEL DEVELOPMENT

Figure 4 is a picture of the Finite Element (FE) model used to model CPM response. This model was developed using the commercial preprocessing code PATRAN^{TM} and the processing code ABAQUS^{TM}.

As shown in Figure 1, the CPM was symmetric about a center plane. Therefore, only half of the CPM needed to be modeled. Also, since the mirror was pulled down by only one capacitive plate at any time, only one plate and pad needed to be modeled. This reduced the total number of degrees of freedom in the model by over half. Lastly, since the MMPoly1 base was considerably more rigid than the structure above it, it was treated as rigid. The total number of

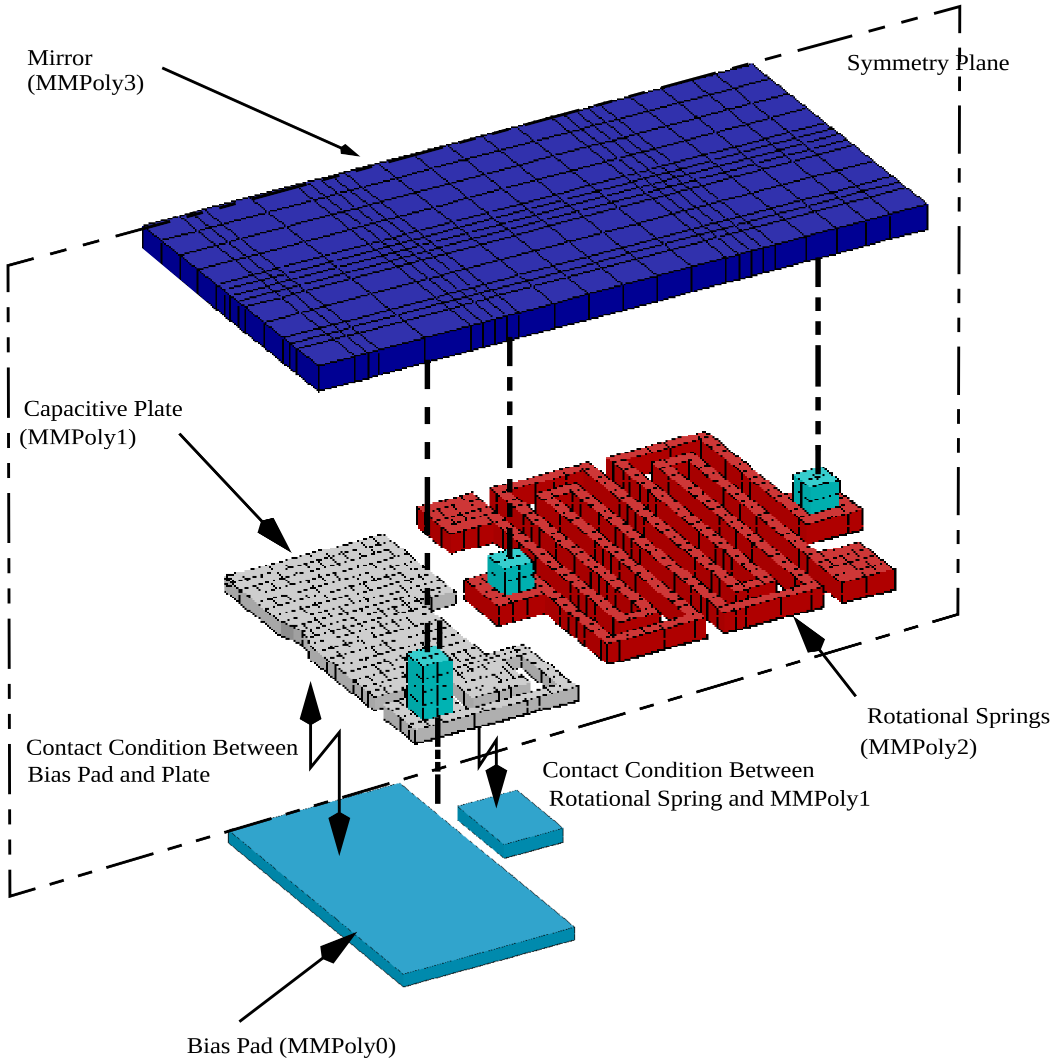

Figure 4: Finite Element Model of Compound Pivot Mirror (CPM)

degrees of freedom in the model were less than 7000. Young’s modulus for Polysilicon was set to 155 GPa and Poisson’s ratio was 0.23 [4].

Manufacturing effects were either included or not included depending on their significance to modeled mirror response. Considering that displacements, not stresses were important, rounded corners and indentations that could have caused large stress concentrations were neglected. Nevertheless, variations in line width were included. Modeled mirror response is very sensitive to the line width. Both sets of springs were designed to widths of 1um. However, variations due to lateral etching in the fabrication process reduced that width to about 0.8μm [5]. This significantly affected the stiffnesses of springs and the rotation of the mirror.

Even though the model contained a small number of degrees of freedom, computational time was not minute due to two contact constraints. In general, when contact is present, numerical simulations slow due to a reduction in

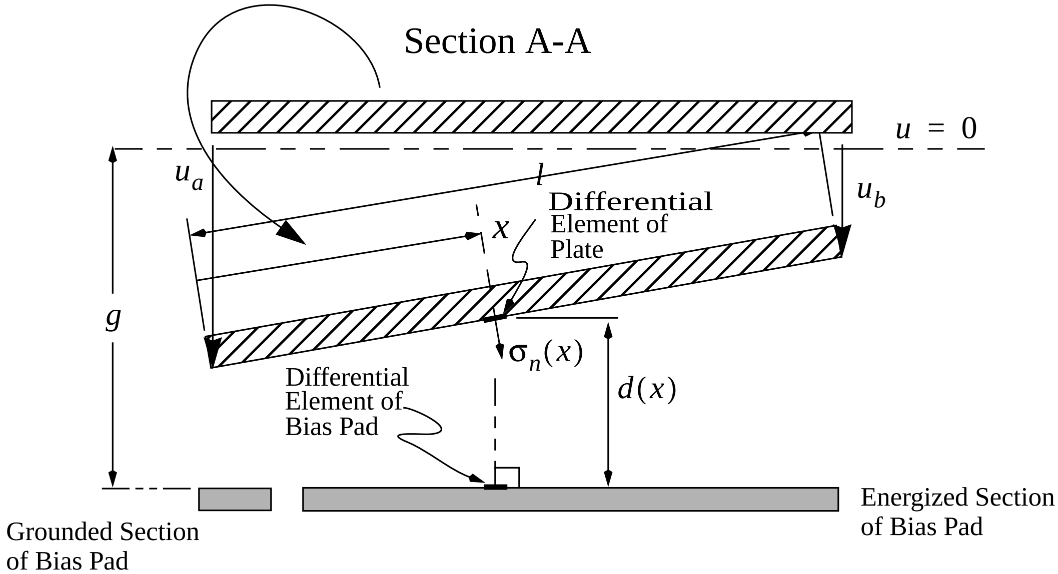

Figure 5: Left Capacitive Plate Tilt From Figure 2 Section A-A

time step. Contact occurred first between the torsional springs and the base MMPoly1 plate, and then between the edge of the capacitive plate and the bias pad.

ABAQUS™ does not have the ability to model electrostatics; therefore, an approximation to the electrostatic loading had to be made. Figure 5 shows the Figure 2 A-A cross section of a left capacitive plate. A coordinate system was defined across the plate such that normal stress could be specified as a function of location. It was assumed, and later verified, that the plate flexed little across the A-A section and therefore, deflection was assumed to vary linearly across its width. Assuming a parallel plate approximation and neglecting large rotations, the loading on the plate could be approximated by

$$\sigma_n(x) \cong \varepsilon \frac{V^2}{2d(x)^2} \qquad (1)$$

where $\sigma_n(x)$ is the outward normal stress on the lower surface of the plate, ε is the permittivity of air, V is the voltage difference between the plate and the bias pad, and $d(x)$ is the distance between a point on the bottom of the plate and a corresponding point on the top of the bias pad [6]. Relative to the above assumptions,

$$d(x) = g - \left\{ \frac{(l-x)}{l} u_a + \frac{x}{l} u_b \right\} \qquad (2)$$

where g is the gap between the plate and bias pad when $V = 0\text{V}$, l is the width of the plate and u_a and u_b are the downward displacements at $x = 0$ and $x = l$.

In general, fringe effects and the rotation of bodies relative to each other would need to be accounted for in this analysis. However, the plate and bias pad are essentially a set of closely spaced parallel plates, and therefore equation (1) was appropriate so long as plate contact did not occur. When the gap between the plate and the bias pad became very small, normal stress approached infinity. Therefore, the distance between the plate and pad was constrained to always be greater than 0.05µm. This value was obtained by matching analytical and experimental data. In the future, to avoid this approximation, an electrostatic capability that accounts for complex geometry and fringe effects is needed.

To couple the normal stress defined in equations (1) and (2) to mechanics, the method of successive approximations was used. The values of u_a and u_b were set to zero and stress was calculated from equation (1) and integrated into the ABAQUS^{TM} code through PATRAN^{TM}. ABAQUS^{TM} was then used to calculate new values of u_a and u_b that could be used to calculate a new normal stress. This was repeated in a successive fashion until convergence occurred [7].

RESULTS

In general, the model agreed very well with experimental data. Therefore, it was believed that the model represented reality and could be used to explain mirror response.

Figures 6, 7, and 8 show experimental and model data for plate configurations A, B, and C respectively. As shown in Figure 6, model and experimental data agreed very well up to 75V. Above this voltage the model slightly underestimated the response. This was due to assumptions in modeling the electrostatic force when the plate was in proximity to the bias pad, as explained in the discussion section.

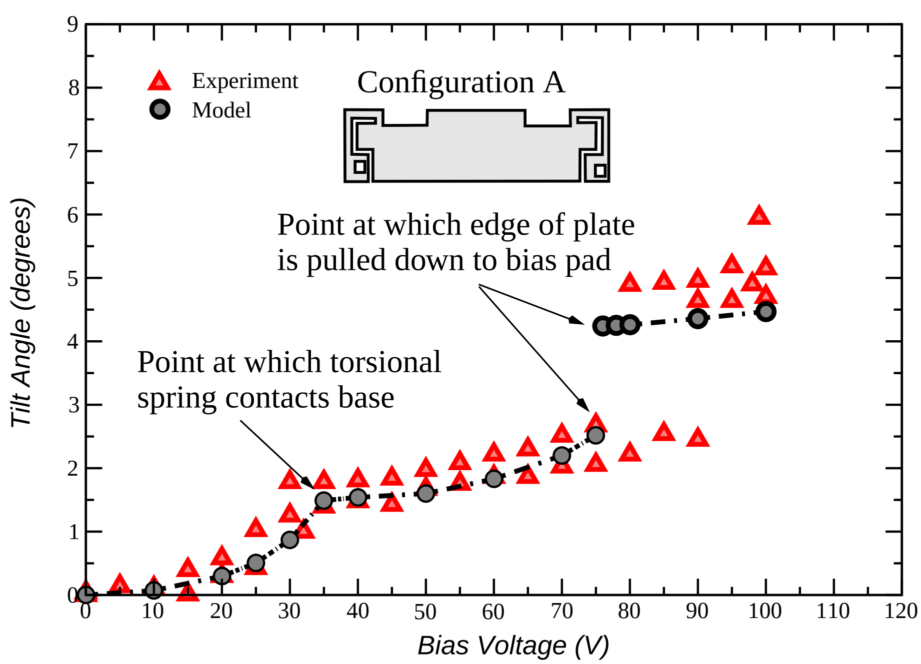

Figure 6: Case A Results, Flexible Plate

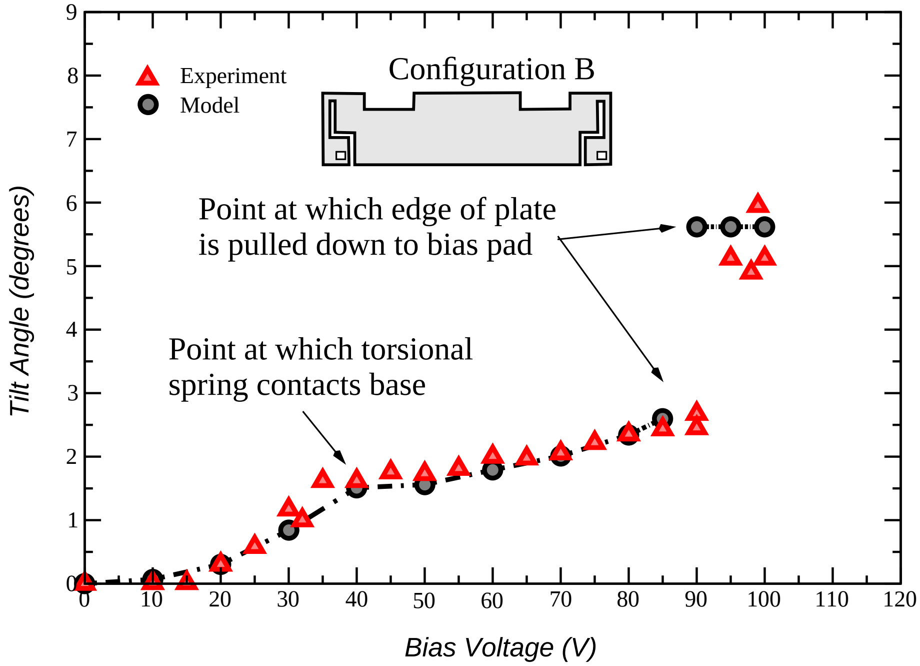

Figure 7: Case B Results, Mid-stiffness Plate

There are two discontinuities in this data. The first occurs at 35V where there is a discontinuity in the slope of the function. This is due to contact between the torsional spring and the MMPoly1 base. Up to this point the mirror pivoted about its center. Then, at contact, it began to pivot about this new location. Contact also altered the stiffness of the system. Therefore, the slope of the curve changed.

At 75V, another discontinuity occurs. Due to the non-linear nature of the electrostatic force ($F \sim 1/d^2$), at higher voltages, the force on the plate overwhelms any mechanical resistance ($F \sim kd$). Therefore, the edge of the plate is suddenly pulled down to the bias pad. This occurs as a jump discontinuity from 2.5 to 4.5 degrees.

Figures 7 and 8 show similar results. Again, two discontinuities exist in these plots for the same reason as those explained for Figure 6.

DISCUSSION

The trends in the experimental data can be explained through the model. As voltage is applied to the CPM, it pivots about its center up to the point of first contact. The tilt angle versus voltage curve is not linear because of the non-linearity of the electrostatics and of the mirror design.

When the torsional spring makes contact with the MMPoly1 plate, the mirror begins to rotate about this new location (marked as left and right pivots in Figure 1). Also, at contact, rotational stiffness of the mirror increases; therefore, causing a discontinuity in the slope.

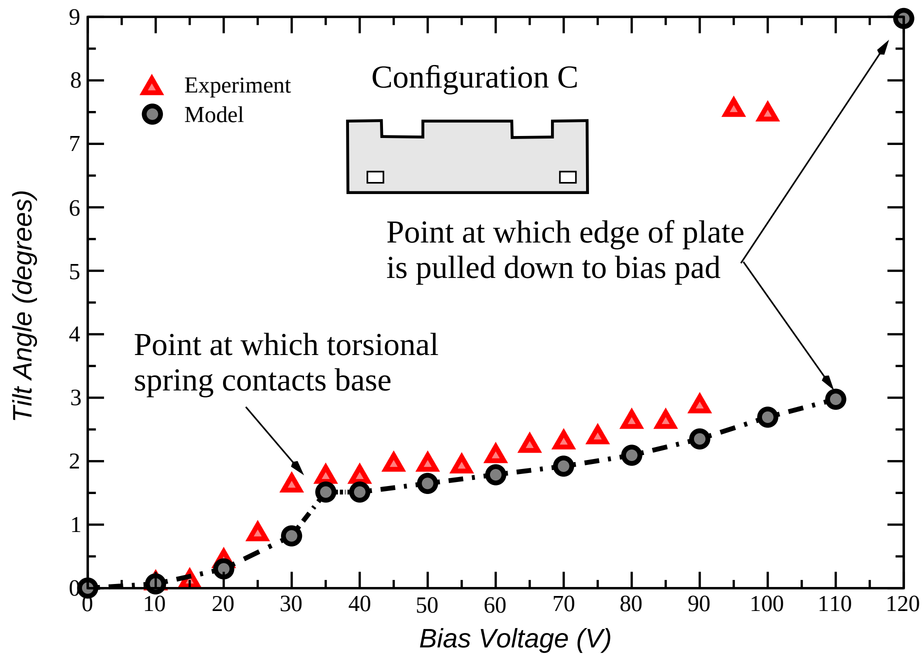

Figure 8: Case C Results, Rigid Plate

When the force becomes large enough, a second discontinuity occurs as a jump in the data. The edge of the capacitive plate is violently pulled down to the bias pad. This jump discontinuity is a strong function of the capacitive plate spring stiffness. As stiffness of the springs is reduced, the voltage at which this jump occurs is lowered.

A reduction in the spring stiffness also lowers the maximum tilt angle since, at lower stiffness, there is more displacement across the plate spring. As shown in Figure 9, a plate spring with no stiffness (infinitely compliant) would not tilt the mirror for any displacement of the capacitive plate, because upon application of a bias, the spring would

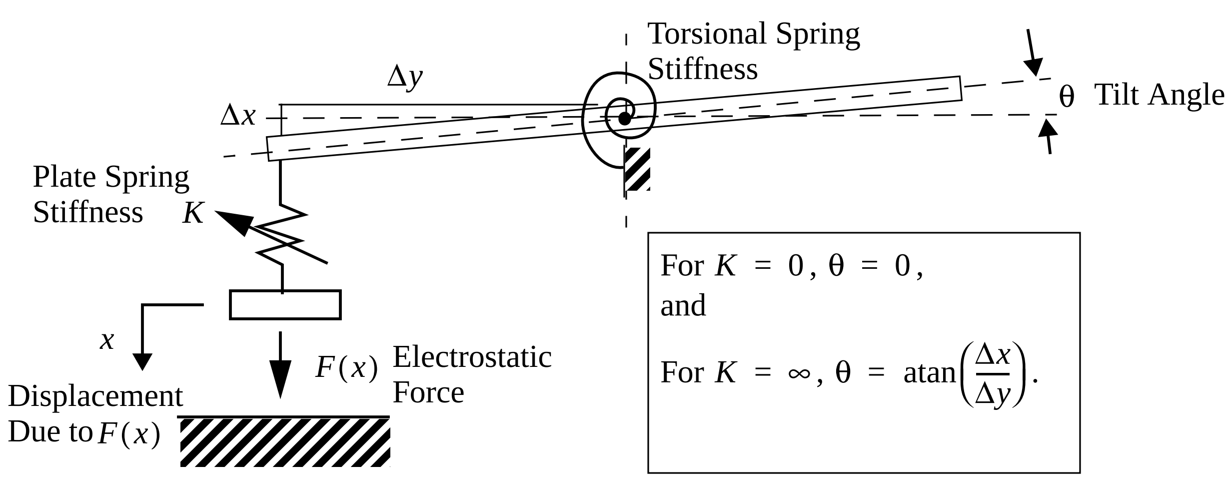

Figure 9: Minimum and Maximum Tilt Angle Rotation

just stretch and not pull on the mirror surface. However, a completely rigid plate spring would produce maximum tilt of the mirror, assuming the capacitive plate is not allowed to touch the energized section of the bias pad, and thus, electrically short out.

To enhance tilt angles to 10 degrees at 28V, torsional and plate springs need to be redesigned to some intermediate stiffness. The torsional springs, in particular, provide a restoring force, and by making them longer (less stiff), the required force applied is lower, and thus a lower voltage is needed to tilt the mirror.

CONCLUSIONS

The objective of this work was to:

- determine what physics lead to trends seen within the experimental data
- determine design parameters important to enhancing tilt angles to 10 degrees for excitations below 28V.

In conclusion, three different capacitive plates were modeled for a Compound Pivot Mirror using the Finite Element Method. The model data matches the experimental data almost perfectly and the trends in the experimental data can be explained through the model also. A clearer understanding of the mirror behavior is now known and a redesign will be more straightforward.

FUTURE WORK

Possible redesigns will be explored for this micromirror. To obtain higher tilt angles at lower actuation voltages, the torsional springs should be reduced in stiffness.

The capacitive plates should also be redesigned so that little force is required to pull them to the bias pad. The capacitive plates need to be stiff across their length and width, but must be able to rotate with little force required. If the capacitive plates are redesigned to rotate with little force, i.e. a hinge structure, the mirror will be able to tilt to its maximum displacement at a lower voltage.

These mirrors are also able to tilt to several discrete angles at specific voltage ranges. The non-linear nature of the mirrors could be used as an advantage. The mirrors can be designed such that the angles allow for optical switching applications. Currently, the design allows for three distinct angles on each side of the mirror, and this number of angles could possibly be increased.

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