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Structural Analysis of a Magnetically Actuated Silicon Nitride Micro-Shutter for Space Applications

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ABSTRACT

Finite element models have been created to simulate the electrostatic and electromagnetic actuation of a 0.5μm silicon nitride micro-shutter for use in a space-based Multi-object Spectrometer (MOS). The micro-shutter uses a torsion hinge to go from the closed, 0 degree, position, to the open, 90 degree position. Stresses in the torsion hinge are determined with a large deformation nonlinear finite element model. The simulation results are compared to experimental measurements of fabricated micro-shutter devices.

Keywords: MEMS, micro-shutter, silicon nitride, electrostatic, electromagnetic

1 Introduction

The Next Generation Space Telescope (NGST) is being developed to determine the origin of galaxies. To accomplish this, NGST needs a Multi-object Spectrometer (MOS) for Near Infrared (NIR) observations. In order to reduce the background noise during observation, the MOS must have field selection capabilities. The field selector will eliminate unwanted cosmic observations and leave only the object that the science team wishes to observe. One method being considered for field selection is a transmissive microelectromechanical (MEMS) micro-shutter array.

The micro-shutter array is created by etching a silicon wafer down to a 0.5μm silicon nitride membrane. The silicon nitride is etched away using a deep reactive ion etch (DRIE) procedure. What remains is an 80μm x 90μm shutter with a 90μm x 3μm torsion hinge, Figure 1. The overall dimension of the shutter pixel, including sidewalls, is 100μm x 100μm.

Early concepts of the micro-shutter array used electrostatic actuation for opening individual shutter pixels. Electrostatic/structural finite element models were developed to determine the voltage required for actuation. The analysis showed that the actuation voltage required was too high for space applications.

Figure 1: SEM images of the silicon nitride micro-shutter.

A magnetically actuated micro-shutter array was developed as a way to reduce the required operating voltage.

Two thousand angstroms of magnetic material, Fe-Co, is deposited onto the silicon nitride shutter. An electromagnet scans across the array and creates a strong magnetic field close to the magnet's centerline. The micro-shutters, which originally start closed, unstressed, and horizontal, rotate 90 degrees to the open position. (Fairly high stresses are developed in the torsion hinge on actuation.) Once the shutter is rotated to the open position, a much lower voltage is applied to the sidewall electrode and the shutter is captured electrostatically in the open position.

The ANSYS/Multiphysics[1] structural analysis program was used to perform the required coupled field analyses. Electrostatic/structural analysis was performed to characterize the electrostatically actuated micro-shutter. Electromagnetic/structural analysis was performed to characterize the electromagnetically actuated micro-shutter.

2 Electrostatic Analysis

A 2-D electrostatic/structural FEM was created using the ANSYS/Multiphysics structural analysis program. A structural model of the micro-shutter was created using a 2-D, plane strain, structural solid. The torsion hinge was modeled with a torsion spring. An electrostatic model of the air region surrounding the sidewall electrode and torsion hinge was created using a 2-D, 8-node, electrostatic solid (Figure 2). A contact line was placed in front of the electrode.

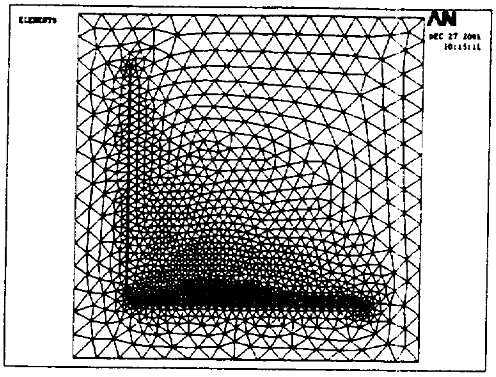

Figure 2: 2-D electrostatic elements surrounding the vertical electrode and the horizontal shutter.

A voltage is applied to the electrode and the solution iterates between the electrostatic and mechanical solutions until achieving convergence.

The analysis showed that a voltage in excess of 600 volts is required to bring the initially horizontal shutter to the open position. This voltage is too high for space applications. Our goal was to keep the voltage required to grab the shutter under 100 volts.

We performed an electrostatic parametric study and determined that we would have to rotate the shutter at least 80 degrees in order to satisfy this goal (Figure 3). We determined that the "grabbing" voltage could be decreased more if we were able to get the shutter as close as possible to 90 degrees. The electrostatic analysis also told us that the "holding" voltage limit was 15 volts. This is the voltage required to hold the shutter open assuming that the distance between the electrode and the shutter is 0.5μm.

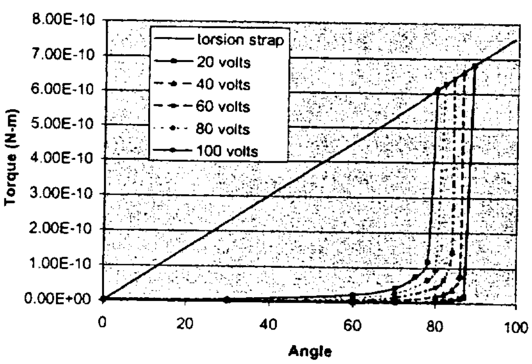

Figure 3: Electrostatics Parametric Study

3 Electromagnetic Analysis

Magnetic actuation was proposed as a way to open the shutter 80 degrees or more. Two thousand angstroms of magnetic material, iron-cobalt, was deposited on the shutter. An electromagnetic tri-pole was designed to give us a very strong magnetic field close to the centerline of the magnet.

ANSYS/Multiphysics was selected as the analytical tool since it has an electromagnetic and structural solver.

An electromagnetic model of the magnet, the magnetic material on the shutter, and the surrounding air region were modeled using a 2-D, 8-node, magnetic solid element. In order to keep the size of the model reasonable, a 2-D infinite boundary element was placed around the perimeter of the air region. (Figure 4)

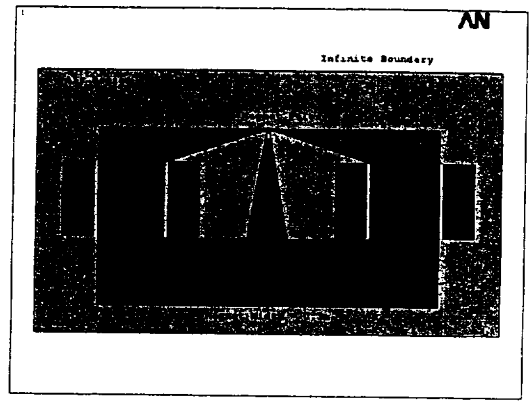

Figure 4: Areas representing the components in the electromagnetic analysis.

The structural model of the shutters was created using 2-D, plane strain, 8-node structural solid elements. The shutter elements were attached to a stiff spring. The spring was rigidly constrained. (The spring was incorporated to give relative, and not absolute, displacement information.) A close-up view of the shutters relative to the magnet is shown in Figure 5.

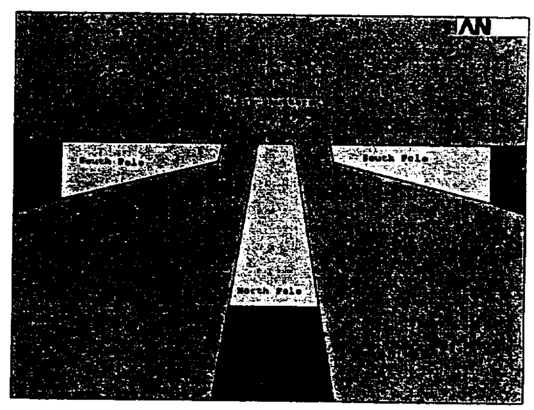

Figure 5: Shutter components relative to the magnet components.

The analysis was used to determine to what angle the magnet could open the shutter. Shutters were modeled at different angles and at different locations relative to the magnet centerline. The electromagnetic model was solved with a force flag on the shutter elements. The magnet's flux lines, and the magnet's flux density over the magnet's centerline, are shown in Figures 6 and 7.

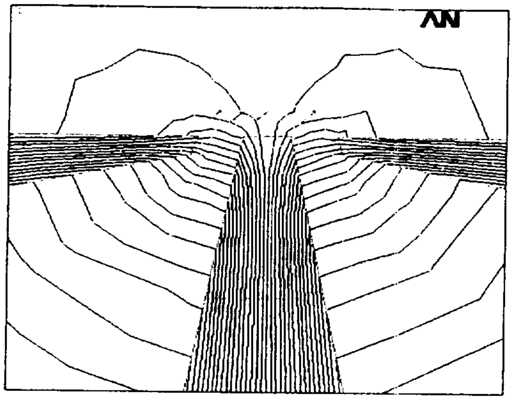

Figure 6: Magnetic Flux Lines

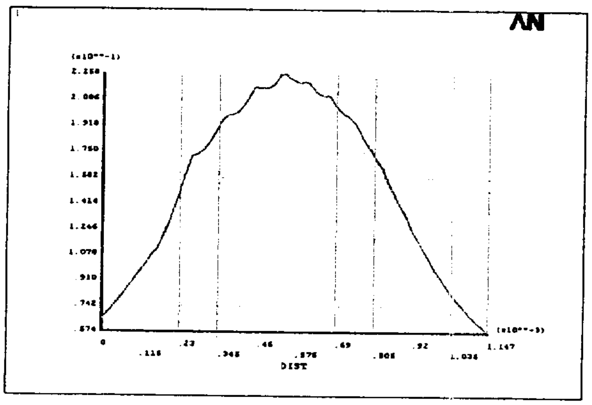

Figure 7: Magnetic Flux Density over Magnet Centerline

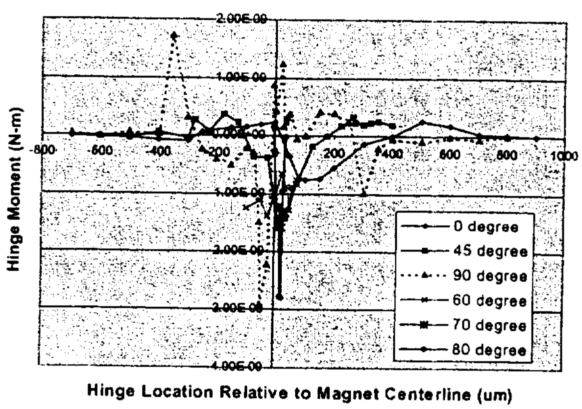

Figure 8: Hinge torque relative to the magnet's centerline.

The force flag saved the magnetic forces acting on the shutter elements. The model was then changed to a structural model. The magnetic forces were applied to the structural model and solved. The shutter's reaction torque was output and plotted relative to the distance from the centerline of the magnet. Since the shutter was essentially rigidly constrained, its small deflection did not significantly alter the magnetic field and therefore did not significantly alter the magnetic forces acting on the shutter. Therefore, the electromagnetic/structural solution did not have to be iterated. The hinge torque for an individual shutter, relative to its location to the magnet's centerline, is plotted in Figure 8.

In order to determine how much the magnet opens the shutter, the magnetic hinge moment has to be plotted relative to the stiffness of the torsion spring (Figure 9).

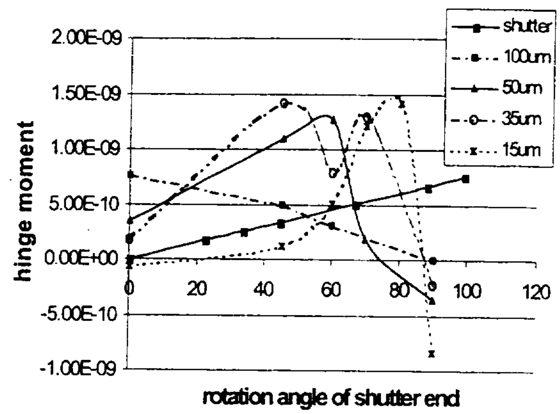

Figure 9: Shutter angle relative to distance from the magnet centerline.

Figure 9 tells us that the magnet will open the shutter 86° when the shutter's torsion hinge is 15μm from the magnet's centerline.

4 Test Results

Figure 9 shows that the magnet will open the shutter at least 86 degrees. Figure 3 shows that if the shutter is rotated 86 degrees, it will take only 43 volts to electrostatically capture the shutter. Additional electrostatic analysis predicts that a captured shutter will release at a voltage of 15 volts.

Lab tests of this shutter and magnet configuration show a 50 volt capture voltage and a 23 volt release voltage.

5 Stresses

Silicon nitride is a brittle material and is linear elastic until failure. The analysis used a Young's Modulus of 254 GPa and a Poisson's ratio of 0.23. The fracture strength of 0.5μm test coupons was measured to be approximately 6.4 GPa .[2]

A FEM of a single micro-shutter was created using elastic shell elements. An elemental pressure was applied normal to the shutter. Since this is a large displacement problem, a nonlinear solve was performed. The shutter pressure was iterated until the shutter displaced to the full open position. Once the shutter displaced to the full open position, the stresses in the torsion hinge were determined. The torsion hinge has a torsional shear stress of 1.5 GPa when its in the open position (Figure 9).

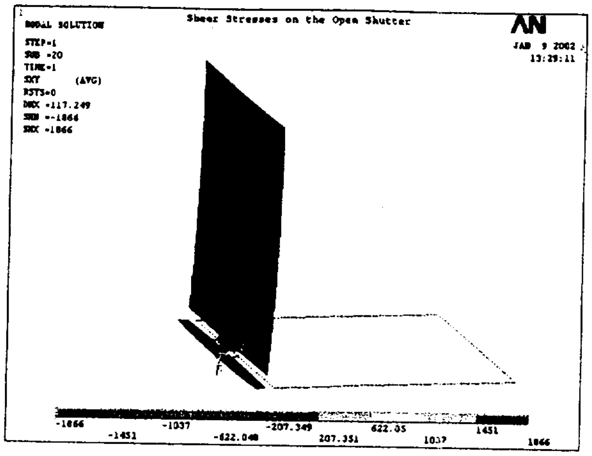

Figure 9: Shear Stresses in the Open Shutter

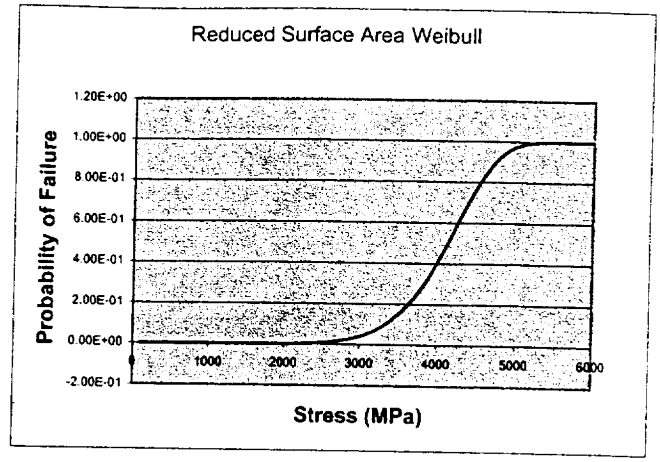

Figure 10: Weibull Distribution

6 Weibull Fracture Probability

W. Weibull observed that the strength of brittle materials is controlled by the presence of randomly distributed defects, and that failure is controlled by the largest, most severely stressed defect. Failure occurs when a defect in one particular element of the body reaches a critical loading. [3,4] Therefore, for a brittle material like the silicon nitride in the micro-shutter, failure may occur at a stress level significantly below the 6.4 GPa fracture strength.

As part of our test plan, we tested many silicon nitride cantilever beams and determined their stress at failure.[5] A Weibull probability of failure distribution curve was created from this data to determine how many micro-shutters would survive initial actuation ("infant mortality rate"). We accounted for the fact that the probability of failure is dependent on the surface area of the test structure relative to the surface area of the device.

$$\frac{\sigma_{test\,-\,cantilever}}{\sigma_{torsion\,-\,hinge}} = \left(\frac{SurfaceArea_{cantilever}}{SurfaceArea_{torsion}}\right)^{1/m}$$

In this equation, m equals the Weibull modulus. The Weibull distribution is plotted in Figure 10. With a torsional shear stress of 1.5 GPa on the torsion hinge when the shutter is open, the probability of failure is 9.48e-5 (99.99% success rate).

7 Conclusions

Electrostatic and electromagnetic finite element analysis has been performed on a silicon nitride micro-shutter. The analysis predicted that an electromagnetic tri-pole would open a magnetized micro-shutter. The analysis also predicted that once the shutter was open more than 80 degrees, a reasonable voltage could be applied to a sidewall electrode to capture the shutter. Additional electrostatic analysis predicted the micro-shutter's release voltage. Lab tests correlated the analytical predictions to experimental results.

The finite element analysis can now be used to optimize the shutter's size parameters, the placement of the shutter's magnetic material, and the characteristics of the actuating electromagnet.

Large deflection, nonlinear finite element analysis, coupled with Weibull statistics, predict a 99.99% success rate for the first actuation of the micro-shutters.

8 References

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