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

James P. Loughlin\textsuperscript{a}, Rainer K. Fettig\textsuperscript{b}, S. Harvey Moseley\textsuperscript{a}, Alexander S. Kutyrev\textsuperscript{b}, D. Brent Mott\textsuperscript{a}

Simulation: Timothy Carnahan\textsuperscript{a}

\textsuperscript{a}NASA/Goddard Space Flight Center, Greenbelt, MD 20771
\textsuperscript{b}Raytheon ITSS, Greenbelt, MD 20771
Next Generation Space Telescope (NGST)

- **Next Generation Space Telescope**
  - Mission: Investigate Galactic Origins
  - Key Instrument: NIR MOS
    - Near Infrared Multi-Object Spectrometer
  - MOS Requirement:
    Addressable “Field Selector”
Micro-shutter Attributes and Requirements

- **Pixel Size Requirement**: 100µm x 100µm
- **Torsion Strap**: 90µm x 3µm x 0.5µm thick
- **Mirror Material**: Silicon Nitride
  - silicon nitride is linear until fracture
- **Operational Temperature**: 30°C
- **Rotation**
  - micro-shutter will rotate 90° to the open position
  - micro-shutter will be closed in the off position
Micro-shutter Array
Electrostatic Analysis

• 2D Structural/Electrostatic FEM Using ANSYS/Multiphysics v5.7

0 Volts

625 Volts
Electrostatic Analysis

- ANSYS Predicts 625+ Volts Required for 90º Actuation
  \[ \text{Limit} \approx 100 \text{ V} \]
- Parametric Study for Determining Max. Rotation with Limiting Actuation Voltage:

\[ \text{Electrostatic Forces} \]

\[ \text{Torque (N-m)} \]

\[ \text{Angle} \]

- 100 V Limit Allows for 10º rotation, from 80º to 90º
Mechanical Operation

- Produced by Timothy Carnahan, GSFC Code 542
Electromagnetic Analysis

- Proposed Tripole Electromagnet

Magnet Width = 0.03m
Micro-shutter Size Relative to Magnetic Poles
Electromagnetic Analysis

- $d =$ distance between shutters and magnet; $40\mu m = d = 120\mu m$
- peak magnetic flux density = 0.23 tesla at magnet centerline
Deflected Micro-shutters

- Magnetic forces are Applied to the Micro-Shutters.
- The force deflects and rotates the Shutters.
Electromagnetic Analysis

- Shutter Hinge Reaction Torque Relative to Magnet Centerline
Electromagnetic Analysis

• Shutter Hinge Reaction Torque (N-m) vs. Angular Deflection

![Graph showing Shutter Torsion Strap](image)

- Torsion Strap K
- 100um
- 50um
- 35um
- 15um

- Rotational Moment vs. Rotation Angle of Shutter Tip
Model Correlation

• Electromagnetic FEA Indicates Maximum Achievable Degree of Rotation = 86º

• Electrostatic Parametric Study Indicates Required Voltage to Capture Shutter (at 86º Position) = 43 V
  – Lab Tests Show “Capture” Voltage = 50 V

• Electrostatic FEA Indicates 15 V Required to Maintain 90º “Open” Position
  – Lab Tests Show “Release” Voltage = 23 V
Stress Analysis

- 3D Structural FEM Using ANSYS/Multiphysics v5.7
- Assumed Silicon Nitride Fracture Strength = 6.4 GPa\(^1\)
- Peak Resultant Stress = 1.5 GPa

\(^1\) Shear Stresses on the Open Shutter

\[\text{NODAL SOLUTION}\]
- \text{STEP} = 1
- \text{SUB} = 20
- \text{TIME} = 1
- \text{STY} = \text{(AVG)}
- \text{RSTY} = 0
- \text{DEX} = -117.249
- \text{SMH} = -1666
- \text{SHX} = -1556

\[\text{FEMCI 2002}\]
Many SiN cantilevered test samples were manufactured and tested.

Probability of failure is dependent on the surface area of the test structure relative to the surface area of the device.

\[
\frac{\text{test}}{\text{torsion}} = \left( \frac{\text{Surface Area}_{\text{test}}}{\text{Surface Area}_{\text{torsion}}} \right)^{1/m}
\]

Stresses in the 3 m x 0.5 m torsion strap are approximately 1500 MPa when the shutter is open.

The Probability of Failure at 1500 Mpa is 9.48e-5. (99.99% success rate)
Conclusions

• FEA Predicts:
  – Electromagnetic Tripole Will Open a Magnetized Shutter to 90° Position
  – Shutter Electrostatically Captured When Opened >80° Using <100V
  – Shutter Maintained at 90° for 15V
• Test Data Correlates with Predicts
• Coupled-Field FEA May Be Used for Design Optimization
References
