Actuation force analysis and design optimization of microshutter array by numerical simulation method

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Abstract

Next Generation Microshutter Array (NGMSA) is an electrostatically operated micro electro-mechanical system (MEMS) device for programmable spatial light filtering application. Original microshutter array (MSA), which is magnetically operated, was developed for the James Webb Space Telescope (JWST) NIRSpec multi-object spectrometer, and NGMSA inherited its design from the original MSA. Even though there has been incremental design changes in order to achieve stable electrostatic actuation, NGMSA operation still requires further study. Previous simulation efforts to model NGMSA’s actuation mechanics allowed to gain only general understanding of the behavior due to inadequate simulation and experimental methods. In this study, a novel electrostatic numerical simulation model is presented using COMSOL Multiphysics to accurately predict microshutter’s motion during actuation. The new model addresses all the issues that hinder realistic modeling. Current Microshutter Array yield and operation performance issues related to fabrication process are analyzed with this numerical model and a potential optimized design is proposed. The result shows that a few μm shorter shutter blade allows stable electrostatic actuation as well as better tolerance to the fabrication accuracy. Also, modified blade side shape reduces undesirable asymmetrical motions which cause failed stuck shutters.

1. Introduction

Microshutter array (MSA) [1–3] is a programmable spatial light filtering device originally developed for the James Webb Space Telescope (JWST) NIRSpec multi-object spectrometer. It’s a key technology which enables spectrum acquisition of multiple astronomical objects within JWST’s field of view by selectively transmitting the lights from the objects. The original MSA is magnetically actuated by a moving magnet and selected shutters stay open by electrostatic latching. A Next Generation Microshutter Array (NGMSA) [4–7] has been developed as an evolution of the JWST microshutter design which eliminates the complexity of magnetic actuation and achieves highly simplified operation by all-electrostatic actuation and latching.

NGMSA is a unique micro-electromechanical system (MEMS) electrostatic actuator device. Electrostatic actuation is one of the most popular methods for many MEMS actuators. There are several common types of electrostatic MEMS actuators including comb drive [8, 9], scratch drive [10, 11], parallel plate [12, 13], inchworm [14], impact drive [15] and repulsive force [16]. Almost all of these actuators undergo relatively small geometry changes during actuation, and the position of their moving parts can be well controlled by applied signal within their travel ranges. Also, many of the actuators show almost linear force variation within their travel ranges. Compared to those common MEMS electrostatic actuators, NGMSA’s moving shutter blade motion is extremely nonlinear and magnitude and direction of applied electrostatic force varies significantly by its position. A geometry like this is chosen to achieve maximum optical aperture (about 80% of total area) and minimize fixed grid area. None of common actuators mentioned above is able to provide such a large portion of active area for light transmission control.

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NGMSA inherited most of its design from original MSA with incremental changes necessary to achieve actuation by relatively weak electrostatic force compared to magnetic force. In order to achieve electrostatic actuation, the JWST MSA front and back electrodes, which were intended only for latching, are used to provide an actuation force. This is a valid mechanism for a single shutter. However, this idea does not work when those electrodes are fabricated within a bulk silicon frame with finite electrical conductivity. In each shutter, the silicon frame covers a larger area than either the front or back electrodes, and the gap between the moving shutter blade and silicon frame is so small that any voltage difference between these parts induces a significant amount of electrostatic force. Therefore, the shutter actuation is dominated by the electrostatic force between the shutter blade electrode and the surrounding silicon frame, while the back electrode mostly works for latching. This shutter blade—frame interaction has been causing multiple issues in NGMSA operation such as difficulty in actuation and deformation of the torsion bar resulting in interference between the shutter blade and the frame.

Understanding all of the electrostatic forces during actuation is essential for designing a reliable device. A preliminary electrostatic simulation model was developed in the previous study [5]. However, the old model did not have adequate fidelity to explain the full behavior of the device. We figured out that the previous model lacks several critical features necessary for accurate simulation. It does not have proper computation window and correct boundary conditions, and electrostatic force calculation is not properly defined. Also, critical model geometry and mesh are not refined enough.

In this paper, we report development of a much improved electrostatic numerical simulation model using COMSOL Multiphysics. This model accurately predicts actuation electrostatic force by addressing the problems mentioned above. The details of improvements will be discussed in the following section. Figures 1(a) and (b) show a unit microshutter structure from top-down and cross-section views. Figure 1(c) describes electrostatic force components studied with the new simulation model. Note that the frame is fixed in xyz coordinate, while y’ and z’ axes move with shutter blade. More detailed information about the device structure and the fabrication process can be found on these previous articles [6, 7].

We found that differences in the actuation behavior of each shutter is related to fabrication processing errors. More specifically, front to back misalignment causes significant variation in actuation response. This error is intentionally introduced into the new model and the resulting electrostatic force is calculated and compared to an ideal case. Finally, variations of the shutter blade design are tested to optimize the blade design for improved actuation response.

### 2. Numerical simulation model

A main goal of the NGMSA numerical simulation model is to predict the shutter blade angular position as a function of applied voltage. Ideally, the model should include both electrostatics and solid mechanics coupled...
Si3N4 layer thickness is negligible compared to other dimensions, making it a suitable component to save computation power by using geometrical symmetry. The vertical inside walls and bottom of the frame are assumed inactive, which means their top surface is at ground level; therefore, repeating conditions are applied on corresponding boundaries. All shutters repeat in the x-direction as a parameter and swept from 0° to 60°.

Electrostatic torque applied on a shutter blade is calculated as functions of blade angular position and applied voltage. Figure 3 shows how the mesh is defined around the shutter blade domain. A fine mesh is used in the electric field direction (normal to the blade surface) and is defined symmetrically around the shutter blade to effectively resolve the stiff field gradient and minimize mathematical error. The evenly spaced fine mesh continuously wraps around the rounded blade edge so that there is no singular node. In order to calculate applied electrostatic force within the actuation range, the shutter blade tilt angle is set as a parameter and swept from 0° to 60°. Note that the force profile at tilt angles greater than 45° is not critical for actuation because the shutter blade is most likely pulled to the backside wall in this range. The fine mesh domain surrounding shutter blade domain interferes with backside wall once the tilt angle exceeds 62°; therefore, it’s difficult to solve the model without significant modification of domain and mesh settings.

3. Original shutter design analysis

Electrostatic torque applied on a shutter blade is calculated as functions of blade’s angular position and applied voltage. A linear torque plot which represents torsion bar’s mechanical restoration torque is used to estimate shutter blade’s position at given shutter voltage. This mechanical torque plot is obtained from the best linear fitting of most recent experimental measurement of torsion bar stiffness. Note that this restoration torque plot is less stiff compared to the measured plot in the previous study [5]. We found that the micro force probe measurement setup which push down a shutter blade in vertical direction measures not only torsional component but also a portion of force that pulls the torsion bar in lateral direction. Represented stiffness plot in this study is measured by a modified method which measures only torsional component. Further study will follow to figure out accurate torsional stiffness and additional torsion bar properties.
Two non-ideal geometries are studied apart from the ideal geometry to estimate effect of fabrication processing error. Front to back alignment is the most problematic process that is susceptible to dimensional error. While most same-side processes are done within about a $1/4 \mu m$ accuracy, front to back alignment error is often as much as $1 \mu m$ or more. Considering that the gap between shutter blade and frame is $2-3 \mu m$, this amount of misalignment, which defines relative position of shutter blade and frame, is significant. We studied this misalignment effect by introducing frame geometry with intentional $1 \mu m$ shift in x and y directions.
3.1. Ideal shutter design

Figure 4(a) shows electrostatic torque applied to a shutter blade at given angular position with various blade electrode (column electrode) voltages (60 V–100 V, 10 V step). Back electrode (row electrode) and silicon frame are maintained at 0 V. At or near 0° blade position, the strong electric field interacts with the blade mostly on its bottom side, therefore strong torque is applied in forward direction. As tilt angle increases, however, strong electric field interaction occurs on front top edge (right top side of blade on figure 4(d)). This field component applies reverse directional torque effectively because of the long moment arm. The torque is minimized at around 20° position and increases as blade tilts down further. Once the blade position is greater than about 30°, the electric field strength on the front edge of the blade gradually drops as it move away from front side wall, and field interaction between back edge of the blade and adjacent silicon frame becomes dominant source of applied torque. Mechanical restoration torque by the torsion bar is shown on figure 4(a) to estimate shutter blade’s position at given voltage. Shutter blade stops at a position where electrostatic torque curve of applied voltage and restoration torque line intersect each other as tilt angle increases. In order to achieve full 90° actuation, electrostatic torque curve of maximum actuation voltage must exceed restoration torque within entire range. With the original design, the restoration torque is greater than electrostatic torque within normal operation voltages within angular position between 15°–35°, which means shutter blade cannot be actuated more than about 15° with static voltage signal. This behavior was observed on most of MSAs tested. One way to get over this torque bump is to accelerate the shutter blade and pass the bump using blade’s angular momentum. We have used this technique to actuate the original NGMSA by using fast rising high voltage (pulse actuation) method. Even though pulse actuation is working on some devices, it’s not a stable and reliable method of actuation. One of the biggest issue is that pulse actuation requires a large amount of power to provide high current. This issue could potentially limit large format array development. Another issue with pulsed actuation is that shutter blade motion is less controllable compared to static actuation. With pulse actuation, each shutter ends up with a different moving speed and momentum, due to variations in mechanical and electrical parameters among individual shutters. Some shutters that respond to actuation signal faster than other shutters eventually hit the back wall harder, which may lead to premature failure in the long run.

Radial direction force is also calculated to estimate amount of force applied to the torsion bar (figure 4(b)). If the torsion bar is not stiff enough to resist lateral deformation by this pulling force, the shutter blade becomes inoperable due to contact between the blade and the front side wall. Hence, it is important to minimize this force. Further study of the torsion bar mechanical properties will follow to enable optimization of the torsion bar design.
3.2. Fabrication error—Y misalignment

As mentioned above, the front-to-back alignment process is prone to relatively large dimensional error. It is important to understand the consequences of this misalignment to properly evaluate and troubleshoot the devices. Positive and negative y-directional shift is defined in figure 5(a). In a negative shift case, the front edge of the shutter blade gets closer to front side of the silicon frame. A positive shift produces the opposite effect. The gap between the blade front edge and the silicon frame gets wider than desired. This dimensional error affects electric field strength between the front edge of the shutter blade and the adjacent silicon frame, therefore the resulting electrostatic force applied on the shutter blade changes. The difference in electric field strength on front edge of a shutter blade is illustrated on figure 5(c).

Figure 5(b) show the electrostatic torque and radial force on a shutter blade when a 1 μm negative and positive misalignment happens. Positive misalignment results in overall increased torque and decreased radial force. When this happens, shutter actuation gets easier because of the reduced torque bump. The negative misalignment case shows the opposite trend. Torque gets extremely low, even negative, and radial force increases a lot. In this case, even accelerated shutter blade cannot go through the high torque bump, and high radial force immediately pulls the blade to front wall. The difference in actuation behavior between two cases may be exaggerated further by the radial force. While the overall magnitude of the radial force is about 3 times greater in the negative misalignment case, the difference in the actual radial force for a given voltage and estimated position from figure 5(b) is about an order of magnitude. According to our observations, well operating devices tend to show positive y-shift, while devices with negative shift actuate poorly. Several devices with negative y-shift over 0.5 μm are practically inoperable because most shutter blades cannot pass the torque bump or touch front side wall.

3.3. Fabrication error—X misalignment

For device fabricated exactly as designed, x-directional components of electrostatic forces on both left and right edges of a shutter blade balance each other and do not contribute to shutter blade’s motion. However, in the case of x-misalignment, the shutter blade is pulled to the near side wall by the resulting force imbalance on both sides. Figure 6(a) describes this x-misalignment effect. Force imbalance between $F_L$ and $F_R$ on a shutter blade causes z'-axial rotation respect to the torsion bar’s center point. Compared to the effects of y-misalignment, x-misalignment effects are rather difficult to observe during actuation since displacements in those directions are small. However, these unintended motions may cause a shutter blade to stick to the inside of the egg crate, which is one of the major failure mechanisms of the prior MSA technology.
In this section, electrostatic torque applied to a shutter blade with respect to the $z'$-axis is calculated when $1 \, \mu m$ x-misalignment happens. This effect is calculated by introducing an intentional $1 \, \mu m$ x-shift into the simulation model. Figure 6(c) shows the electric field strength on left and right side of the shutter blade. Field strength on the left edge (narrower gap) is greater than the right side edge (wider gap). The net $z'$-torque generated by the resulting $F_L$ and $F_R$ difference is plotted on figure 6(b). The torque rapidly increases within $0^\circ$–$5^\circ$ range and maintains a consistent value over most actuation range.

Further study of the torsion bar's stiffness in $z'$-axial direction is necessary to derive a design criteria for reliable operation. Note that the maximum $z'$-axial torque at 100 V is comparable to the x-axial torque required for shutter blade to latch on the back wall. Considering the torque scale in the x-axis direction, this $z'$-axial torque resulting from $1 \, \mu m$ misalignment is significant.

4. Shutter blade design optimization

The above analysis shows that the original NGMSA design is prone to significant variation in actuation behavior under moderate processing errors. One way to mitigate this problem is to increase the gap distance between the shutter blade’s front edge and the facing silicon frame. With an adequate amount of shutter blade length
shorting, actuation torque produced by normal operation voltage is able to exceed restoration torque within entire actuation range, eliminating need for pulsed actuation. Also, a shorter shutter blade is more forgiving to moderate processing errors. Shutter blade and frame gap modification can also be applied to both side edges to reduce z’-torque. In this section, variation of actuation torque as a function of shutter blade length is studied to find an optimal blade length. z’-torque by modified shutter blade designs are also studied and compared to original design case.

4.1. Actuation torque by shorter shutter blade
Shutter blades with 1 μm, 2 μm and 3 μm reduction in length in the y-direction are studied. Actuation torques and radial forces calculated from the electrostatic model are shown on figure 7. All three designs show improved actuation torque profiles and reduced radial forces compared to original case shown in figure 4. A 2 μm shorter blade shows effective improvement of performance with only minimal amount of active area reduction. It can be actuated at voltage around 90 V, and would be tolerable to negative y-misalignment, and is similar to the 1 μm shorter case, with slightly increased actuation voltage.

4.2. Z’-torque by narrower shutter blade
z’-torque of 1 μm x-misalignment condition is studied with several shutter blade designs. Since z’-axial restoration torque data is not available at the moment, the magnitude of the z’-electrostatic torque by 100 V shutter blade voltage are compared relatively. Figure 8 shows z’-torque at 100 V by original shutter blade design and two modified blade designs. A 2 μm reduction reduced the z’-torque about 40%. In case more reduction of

![Figure 6](image-url)
torque is necessary with minimal sacrifice of active area, a 'keystone' shape can be used. This blade design has narrower front end compared to back end, which reduce electrostatic force at the front side corners where moment arm is the longest. Also the design provides more clearance in the event that a z'-axial tilting motion occurs, therefore chances of touching sidewall or diagonal sticking are minimized.

5. Conclusion

NGMSA enables simple and effective spatial light filtering operation by eliminating complexity of magnetic actuation of the original MSA. Previous effort failed to achieve an accurate model because several critical details were not properly implemented. An improved electrostatic numerical simulation model which resolves critical previous issues are reported. Electrostatic actuation torque of the current NGMSA shutter blade design and its variations due to moderate processing errors are studied. Result shows that with the current blade design, reliable electrostatic actuation cannot be
achieved because electrostatic actuation torque is not strong enough to overcome mechanical restoration torque. Also, actuation torque behavior significantly varies by small fabrication errors. Several modified shutter blade designs are studied to improve reliability of NGMSA operation using purely electrostatic actuation. A few microns shorter blades can be easily actuated by effectively reducing reverse directional torque components. Modification of lateral blade edges also reduces torque which induces undesirable side way tilt which causes actuation problems or stuck shutters. We are able to conclude that a shutter blade with 2–3 μm shorter and about 2 μm narrower or slightly trapezoidal shape would effectively achieve truly electrostatic and more reliable actuation compared to the existing design. 

The torque analysis performed in this study relies on the experimentally measured restoration torque of the torsion bar. Further study with a proper measurement method is needed for more accurate actuation behavior prediction as mentioned in this article. More experimental data of torsion bar will also lead to a working torsion bar mechanical response model, which will be an important step toward a complete electromechanical simulation model.

Fabrication of new NGMSA devices with modified shutter blades will follow to confirm the improvements predicted in this study.

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