MAE 294A Final Project

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***Abstract*—This paper introduces a novel design and analysis of a flexure-based micro-mirror capable of translating (piston motion) up and down, enabling precise modulation of the phase of light reflected from its surface. The proposed micro-mirror design leverages the advantages of flexure mechanisms to achieve high precision and reliability in phase modulation applications. A comprehensive analysis of the mechanical performance of the micro-mirror is presented, including theoretical validation and finite element simulations. The results demonstrate the effectiveness of the proposed design in achieving accurate and stable phase modulation over a wide range of operating conditions. Furthermore, potential high-impact applications of the flexure-based micro-mirror in fields such as optical metrology, adaptive optics, and telecommunications are discussed. Overall, this research contributes to the advancement of micro-optical systems by providing a robust solution for precise phase modulation, opening new avenues for innovative applications in various domains requiring high-precision optical control.**

***Index Terms*—Flexure Mechanisms, Micro-Mirror design, Finite element analysis**

I. INTRODUCTION

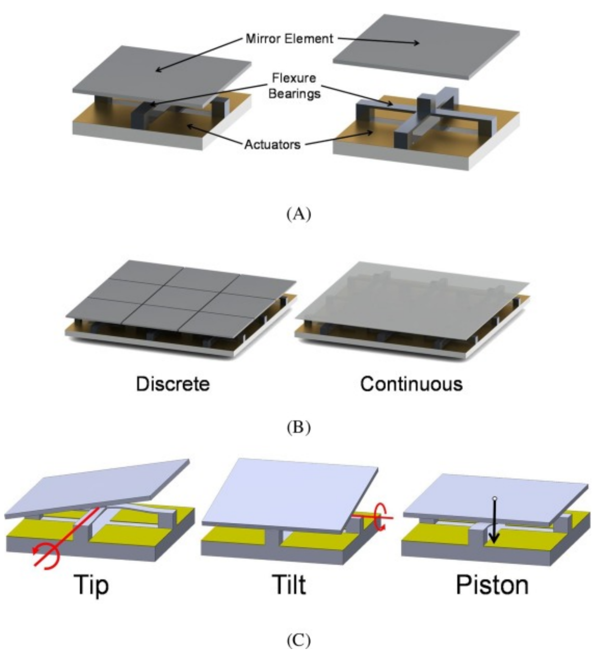


Fig. 1. Example micromirror design Y. Song et al.[1]

Micro-electromechanical systems (MEMS) have revolutionized various fields by enabling the development of compact, high-performance devices with applications ranging from telecommunications to biomedical sensing. Within this domain, micro-mirrors stand out as crucial components facilitating precise control and manipulation of optical signals at the microscale. These devices play a pivotal role in numerous applications, including optical switching, display technologies, laser beam steering, and more recently, in advanced optical modulation techniques.

A micro-mirror is a miniature mechanical device typically fabricated using MEMS technology, comprising a reflective surface supported by a microscale actuation mechanism. This actuation mechanism allows the mirror to precisely adjust its orientation, enabling control over the phase, direction, or amplitude of incident light. Among the diverse functionalities of micro-mirrors, phase modulation holds significant importance in various high-impact precision applications, including optical metrology, spectroscopy, and laser-based imaging.

The purpose of this project is to introduce a novel design for a flexure-based micro-mirror capable of translating (piston motion) up and down, specifically tailored for precise phase modulation applications. Phase modulation, a fundamental operation in optics, involves altering the phase of light waves to achieve specific objectives such as wavefront shaping, interference control, or signal modulation. By integrating flexure-based mechanics into the micro-mirror design, we aim to address key challenges associated with conventional approaches, including mechanical stability, accuracy, and reliability.

The importance of this project lies in its potential to advance the state-of-the-art in precision optical modulation technologies. Achieving precise control over the phase of light is essential for numerous scientific and technological endeavors. For instance, in optical metrology, phase modulation enables high-resolution measurements of distance, surface profiles, and refractive indices. Similarly, in adaptive optics systems, precise phase control is critical for correcting aberrations in optical systems, thereby enhancing imaging and communication capabilities.

Furthermore, the impact of the proposed flexure-based micro-mirror extends beyond traditional applications, offering innovative solutions for emerging fields such as quantum information processing, optical tweezers, and photonic integrated circuits. The ability to modulate light phase with high precision at the microscale opens doors to new possibilities in manipulating light-matter interactions, enabling breakthroughs in sensing, computing, and communication technologies.

In summary, this project aims to introduce a novel flexure-based micro-mirror design optimized for precise phase modulation, addressing key challenges in current optical modulation techniques. Through comprehensive analysis and experimental validation, we anticipate significant advancements in high-impact precision applications, fostering innovation and progress in diverse fields reliant on precise optical control.

II. PREVIOUS DESIGNS

One notable approach utilized in the design of high-speed micro-mirrors involves leveraging resonant frequencies to achieve fast actuation with minimal power consumption. Previous research efforts have explored different configurations and actuation mechanisms to harness resonant frequencies effectively. Among these designs, those with a single piston degree of freedom (DOF) have garnered significant attention due to their simplicity and potential for high-speed operation.

Several pioneering studies have demonstrated the effectiveness of resonant frequency-based micro-mirrors in achieving rapid piston motion. For instance, the work by Ulrich Hofmann et al. [2] introduced a micro-mirror design utilizing electrostatic actuation at resonant frequencies, enabling high-speed scanning for laser display applications. Similarly, the research by K. Khalil et al. [3] presented MEMS-based optical phase modulator with a single piston DOF, exploiting piezoelectric actuation to achieve precise phase modulation in optical communication systems.

III. Topology Synthesis

A. Freedom and Constraint space

We need the mirror to achieve a piston motion perpendicular to the reflective surface of the mirror. THis corresponds to the freedom space with only one translational motion. In the FACT chart, this corresponds the the system represented by 1 DOF Type 3. Below is the freedom and constraint space of the system:

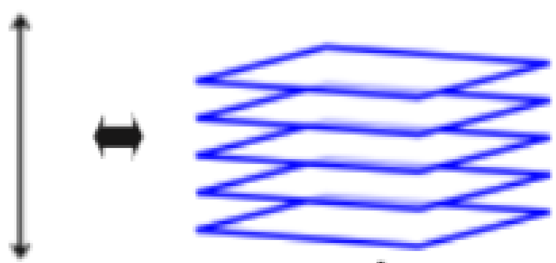


Fig. 2. Freedom and Constraint space of 1 DOF Type 3 system [4]

Using the method taught in the class, we need to select at least 5 constraint lines that satisfy the above constraint space. In order to retain the symmetry of the system for fabrication ease and avoiding parasitic error, we need to over-constraint our system. Hence, we decide on the following system.

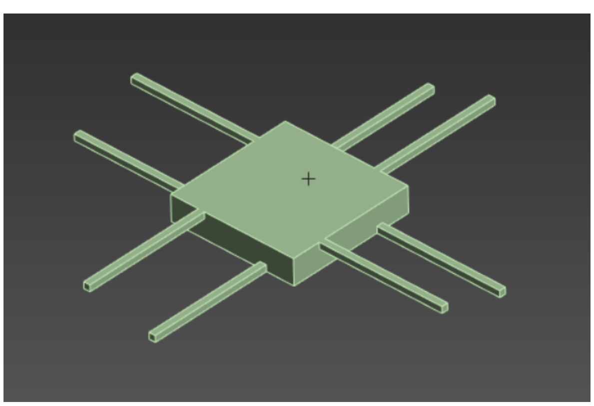


Fig. 3. Designed Flexure system for the micromirror

The flexure system designed for achieving a single degree of freedom (1 DOF) in the micro-mirror is engineered to ensure precise control over its motion while constraining unwanted degrees of freedom. This flexure system comprises carefully crafted flexure elements that dictate the mirror's movement along a single axis while effectively constraining other degrees of freedom. All the flexure wires are grounded at their other end. These flexure wires have the dimensions of 0.05mm $\times$ 0.05 mm $\times$ 1 mm.

The primary design consists of symmetrically arranged flexure wires surrounding the mirror platform. These wire are positioned to allow motion in the desired piston direction while restricting rotation and lateral translation. The four wire flexures in the upper plane restrict translation in the plane of the mirror and rotation along the perpendicular axis of the mirror plane. The other four wire flexures in the lower plane restrict the remaining two rotational motions leaving us with only one translation motion perpendicular to the mirror plane as required.

The reflective surface can be mounted on top of the mirror platform. Hence translation is allowed perpendicular to the mirror surface as required. The dimensions of the mirror platform are: 1 mm $\times$ 1 mm $\times$ 0.2 mm. If the top surface of the mirror platform is completely covered in a reflective surface, the surface area of the mirror will indeed be 1 mm^2.

B. Properties of this flexure system

Since the system only has one body that is connected to ground through multiple wire flexures, it is a **parallel** system. Hence it is also **not under-constrained**. The number of degrees of freedom this system possesses is 1 while there are 8 wire flexures restricting it's other degree of freedoms. Hence this system is **over-constrained** by 3 wire flexures.

C. Material Selection

The most common MEMS material is polysilicon, and it is also the most tested one. Hence we will design the whole system using this material. Below are the mechanical properties of the material as mentioned in the MEMS handbook by W. Sharpe.[5]

Density: 2330 kg/m^3
Young's Modulus E: 169 GPa
Poisson's ratio: 0.23
Bulk Modulus: 94 GPa
Shear Modulus: 64.75 GPa

D. Actuation

The magnetic actuation mechanism proposed for the flexure-based micro-mirror system operates on the principle of electromagnetic induction to induce motion in the mirror platform. This process involves passing an alternating current through a special conductive coating on the boundary of the mirror, which is situated within a magnetic field.

The magnetic field is generated using permanent magnets or electromagnets strategically positioned around the mirror platform. These magnets create a uniform magnetic field in the vicinity of the mirror, providing the necessary energy for actuation.

When an alternating current is applied to the conductive coating on the mirror boundary, it interacts with the magnetic field, resulting in the generation of Lorentz forces. According to Faraday's law of electromagnetic induction, the changing magnetic field induces an electromotive force (EMF) in the conductive coating, causing an electric current to flow through it. This process is described in detail in a research paper by N. Abelé et al.[6]. The figure below showcases the process in a simple manner.

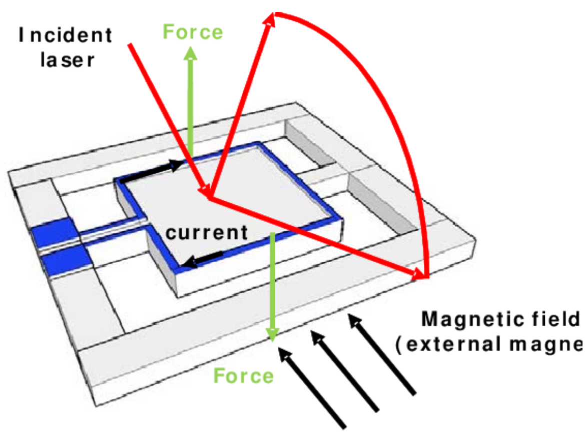


Fig. 4. MEMS mirror magnetic actuation principle N. Abelé et al.[6]

As the alternating current passes through the conductive coating, it experiences periodic changes in polarity, leading to the generation of alternating Lorentz forces. These forces exert a pushing and pulling effect on the conductive coating, consequently inducing motion in the mirror platform.

The alternating polarity of the current results in oscillatory motion of the mirror, which is precisely controlled to achieve the desired vibration frequency and amplitude. By modulating the frequency and magnitude of the alternating current, the motion of the mirror platform can be finely adjusted to meet specific requirements, such as phase modulation for optical applications.

IV. Design Characterization

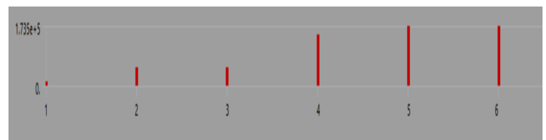
A. Calculating Natural Frequencies using twist-wrench mass and stiffness matrix

Using the MATLAB code given in the course module, we calculated the stiffness matrix and hence the theoretical natural frequencies of this flexure system.

Mode	Natural Frequency (Hz)
1	11356.51
2	55638.68
3	55638.68
4	152794.94
5	173248.77
6	173248.77

B. Finite Element Analysis

We used Ansys software for modal analysis of this flexure system. We got the following natural frequencies. They are plotted for comparison.



	Mode	Frequency [Hz]
1	1.	12579
2	2.	52879
3	3.	53124
4	4.	1.4681e+005
5	5.	1.7295e+005
6	6.	1.7351e+005

Fig. 5. Natural frequencies of the six modes using FEA

We see that the frequencies calculated theoratically are close to those calculated using FEA but do not match closely. The discrepancies observed can be attributed to several factors, including:

- Theoretical calculations often rely on simplified models and assumptions to derive analytical expressions for natural frequencies. These assumptions may not fully capture the complexities and intricacies of the actual system, leading to discrepancies when compared to FEA results. For example, theoretical models may neglect certain non-linearities and geometric complexities present in the real-world system.
- Since the model size may be small, the quality of the mesh used in FEA can significantly impact the accuracy of results. Inadequate mesh resolution or irregular mesh elements can lead to numerical errors and inaccuracies in natural frequency predictions. Ensuring proper mesh refinement and quality is essential for obtaining reliable FEA results that closely match theoretical expectations.
- FEA models may involve simplifications or assumptions necessary to reduce computational complexity. These simplifications, such as neglecting certain geometric features or approximating complex behaviors, can affect the accuracy of natural frequency predictions compared to theoretical calculations.

1) Deformation in the first mode: The figures below show the deformed CAD model using modal analysis for the first mode. As expected, the first mode is the required piston DOF. We see in the figures that the translation is indeed perpendicular to the reflective surface.

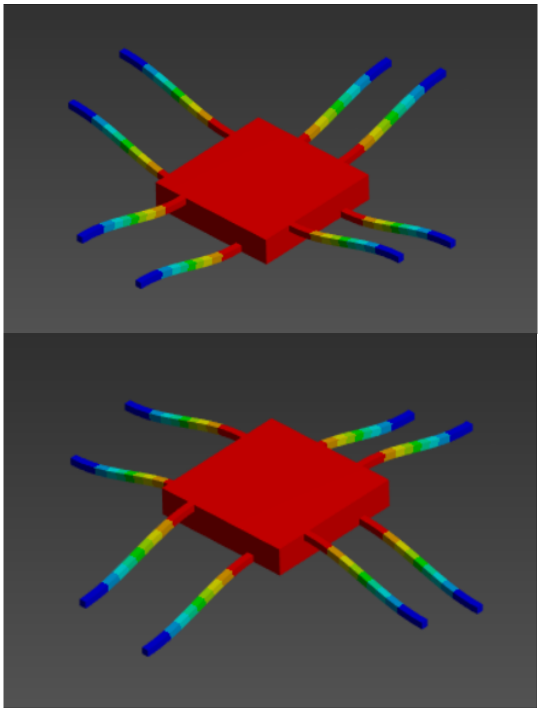


Fig. 6. Deformations in the system in the first mode

2) Deformation in the second mode: The figure below shows the deformed CAD model using modal analysis for the second mode. We see that the deformations in this mode are much less than those in the first mode.

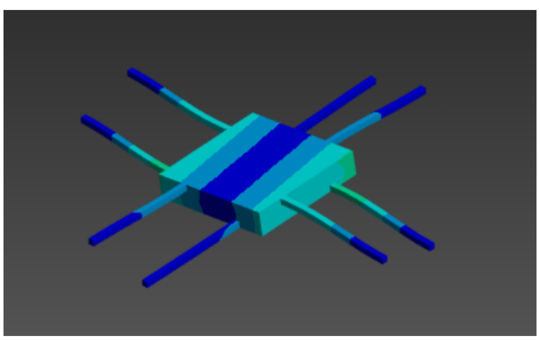


Fig. 7. Deformations in the system in the second mode

The third mode will have deformation range similar to that of the second mode since the second and the third mode are the rotations perpendicular to each other in the plane of the reflective surface. Since the system is symmetric in this regard, they have the same natural frequency and deformation patterns.

The fourth, fifth and sixth modes can be ignored since they have natural frequencies that are a magnitude higher than the second and third mode.

V. Fabrication Process

The fabrication process of the flexure system, which includes the micro-mirror platform and the surrounding flexure elements, involves several steps to ensure precision and reliability. Although, the whole system is made up of the same material, it cannot be cut out from a single workpiece since it is not completely 2 dimensional. Hence we seperate this system in three layers. We then combine these pieces together to get the full flexure system. The three layers are shown below.

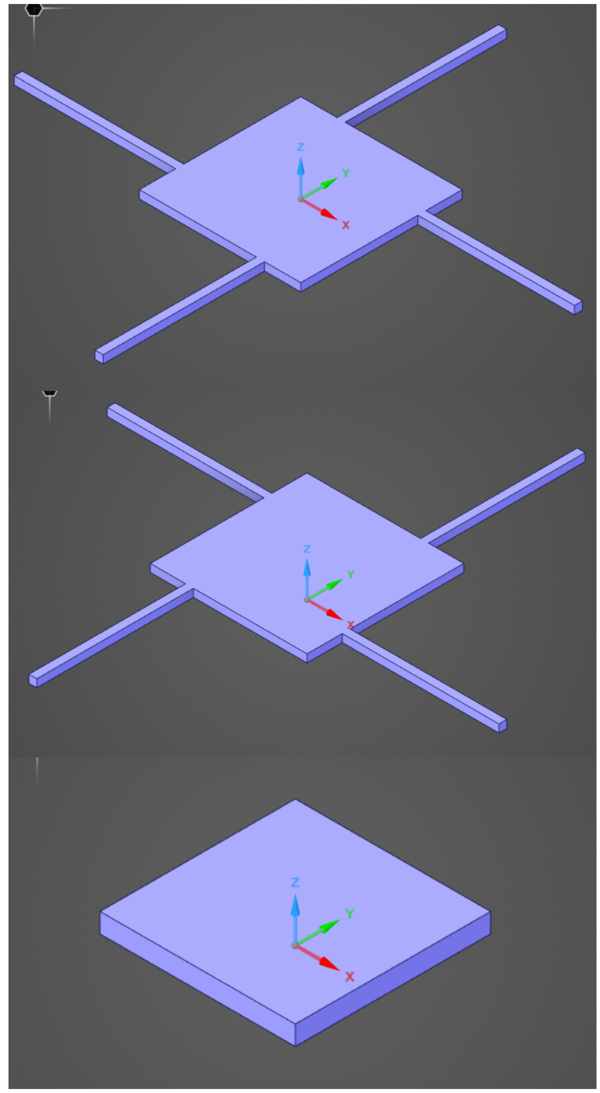


Fig. 8. Flexure system divided into three layers that need to be fabricated seperately

Since we already decided that the system will be made up of polysilicon, there is no need to do the material selection process again. The CAD models for all the layers have already been developed and can be used for the fabrication processes.

In a microfab setting, the fabrication process often starts with the deposition of a polysilicon layer onto a substrate using vapor deposition techniques. Once the polysilicon layer is deposited, photolithography is employed to define the pattern of flexure elements and mirror platform on the polysilicon layer. Subsequent etching is typically achieved using deep reactive ion etching (DRIE) or another etching technique compatible with polysilicon to selectively remove material and form the first layer.

The second layer needs a little bit of modification before they can all be put together. We need to apply the conductive coating on the second layer to allow the current to flow through it thus making it possible for us to implement magnetic actuation. Polysilicon surfaces can be coated with conductive materials such as metal films (e.g., gold, aluminum) using PCB fabrication techniques in a microfab.

Once all layers are fabricated, they are aligned and bonded together using thermal bonding. Polysilicon bonding typically requires careful surface preparation and annealing to ensure strong and reliable bonds between layers.

VI. Conclusion

In this project, we have successfully designed, and analyzed a flexure-based micro-mirror system with magnetic actuation for precise phase modulation applications. We also described a suitable fabrication process that may be used to make this system.

Finite element analysis provided valuable insights into the mechanical behavior and performance of the micro-mirror system. Through modal analysis, we were able to gain insight on the natural frequencies of this system. Additionally, theoretical calculations based on twist-wrench mass and stiffness matrix allowed us to validate the results from FEA.

Acknowledgment

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References

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