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DESIGN AND TESTING OF FLEXURAL KINEMATIC MECHANISM USING LARGE WORKSPACE

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Abstract

Precise and accurate outputs are essential for assessing engineering applications in today's fast-paced and competitive engineering industry. Compliant mechanisms play a vital role in meeting the urgent need for precise motion. These mechanisms, which rely on the stiffness and mobility of their components, offer a way to enhance precision without compromising accuracy. However, failures in compliant mechanisms often arise from repeated movements of compliant beams in both in-plane and out-of-plane directions. To ensure a longer lifespan for compliant mechanisms with high deflection values, the elastic bending of beams leads to molecular deformation and generates motion.

Compliant mechanisms have found extensive use in modern applications such as biomedical scanners and micro-nano processing microscopes. Current biomedical scanners employ a ball screw mechanism for scanning in the X and Y directions, achieving a scanning range of 0.6 mm per movement. However, it takes a significant amount of time for the image to stabilize. On the other hand, a flexible mechanism allows for a 0.1 mm movement in each step. To meet the required 8 mm scanning range in both X and Y directions for biomedical scanners, a compliant mechanism can be employed. In this study, we experimentally and numerically analyze a compliant mechanism designed for linear motion in biomedical scanners. A static structural analysis is conducted to determine the linear displacement values using different materials such as steel, titanium alloy, and PLA (a type of plastic). Furthermore, a modal study is performed to determine the natural frequency of the system, aiming to enhance mechanism stability using the same materials. The compliant system can be operated below the resonance frequency, ensuring smoother motion compared to a ball screw mechanism. By adopting a flexure mechanism, we anticipate achieving an improved range of motion

Keywords: FEM, Compliant Mechanism, DSpace, Stiffness.

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1. Introduction

Compliant mechanisms are versatile systems that utilize flexible parts and joints to transmit motion. The systematic design methods of Howell and Lobintu have greatly contributed to the development of innovative compliant mechanisms. For precision applications like optical scanners, biomedical scanners, and micromanipulators used in robotic surgery, linear compliant mechanisms are crucial. The recurrent motions of compliant beams in both in-plane and out-of-plane directions are a common cause of failures in compliant systems [1]. To enable rotational movement in compliant mechanisms, axially bent hinges are employed. Extending the lifespan of the flexural mechanism becomes crucial when dealing with high deflection values.

A major drawback of conventional compliant mechanisms is end-to-end deflection, which can occur under different actuation forces. High axial stiffness values, high yield strength to modulus of elasticity ratio, and properly shaped hinge shapes can all help to reduce this displacement [2]. To offer a variety of motion and beam deflection, compliant mechanisms use multiple beam combinations [6]. Based on an instantaneous, non-linear analytical system and a transverse force charged beam with a variable contour thickness, new equations have been constructed for rotational stiffness, angular deflection, and rotational precision of various notch flexure hinges [1]. Over the past ten years, researchers have investigated various design elements and uncommon arrangements of beams and hinges to evaluate the range of motion [22, 23]. Many research have focused on increasing the range of motion (60 mm) while minimising parasitic errors, frequently by combining connections in parallel. Topology, form optimisation, and actuator choice were found by Qeingsong Xu [2] to be the three main variables affecting micro motion. For more flexibility, he advised the use of flexural joints, especially when joining series and parallel phases. In order to provide irregular shifting micro motion for nanocutting applications, Zheiwi Zhu [3] created a piezo-actuated triaxial compliant mechanism. Zhu established a displacement range for nanocutting of 37 nm by parallelizing ellipse and leaf hinges in place of right circular hinges. Ling's [4] work concentrated on a multistage compliant system with parallel beams and XY actuators. Under cyclic stress at 2395 Hz, he was able to move the beam 600 mm while preventing axial deflection of the beam with stiffeners. According to reports, some researchers advocate beam deflection with cross-axis motion. The geometrical requirements and material characteristics of these components, however, have the greatest influence on the XY scanning range of the compliant system [5-11].

2. Kinematic Flexure Mechanism

To permit accurate motion with relative movement between the supporting frame and the motion stage, compliant mechanisms are created. The contrast between compliant and conventional systems is seen in Figure 1 [4]. A combination of beams and hinges is used in compliant systems to transfer motion in both the linear and rotational directions. A conventional crimping mechanism may be made smoother and more repeatable by substituting flexible strips for some of the joints in order to reduce backlash and friction [6-22]. Range of motion, stress, and deflection are a few performance parameters that may be used to assess the efficacy of compliant mechanisms [8]. However, the existence of stiff components that could lead to bending in the compliant mechanism's parts limits the range of motion in compliant mechanisms. Permissible loads and strains also impose constraints on the achievable range of motion [10].

The structure and composition of joints play a significant role in determining the extent of mobility. Changes in yield stress can result in plastic deformation, causing joint movement to become unpredictable and unstable. Therefore, both design factors and material characteristics influence the range of motion in joints [9]. In modern joints, a majority of deflection occurs in smaller cross-sectional areas. This approach is adopted because joints that undergo rotational movement often experience high levels of stress, which can lead to fatigue failure of beams. Circular, elliptical, and leaf hinges are commonly utilized in combination with beams to achieve this goal [13]. To ensure proper performance when an element is subjected to deflection, the slope of the deflected member must be accurately proportioned [15-22].

The creation of a linear compliant system for biological scanning is the subject of ongoing study. The current study stands out for its unique method of producing incremental linear range of motion by utilising a compliant mechanism. As a result, biomedical scanning systems are no longer required to use high-resolution sensors and controllers. This innovation has the potential to significantly improve the scanning capacities of biomedical equipment.

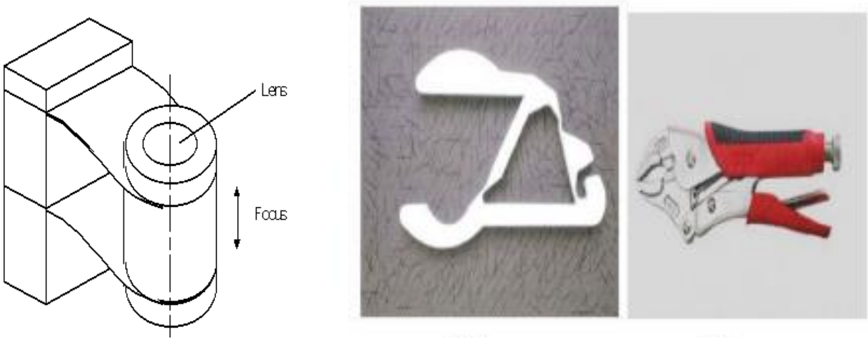

Figure 1 Compliant Mechanisms

The deformation, rotation and parasitic error motion in case of DFM unit is calculated by equation 1

$$\delta = \frac{FL^3}{12EI}\theta = t^2\left[\frac{1}{b_1^2} + \frac{1}{b_2^2}\right] \times \frac{\delta}{L}\epsilon = 0 \qquad (1)$$

Where

F= Applied force in N

L= Length of the beam in mm

E= Material Modulus of Elasticity for beam in N/mm^2

I= Moment of Inertia mm^4

T= beam thickness in mm

B=beam width in mm

The flexure compliant mechanism is developed using the above equations and further tested.

3. Mechanism Testing for Experimentation

In the experiment, a one-piece compliant mechanism using steel material is constructed, specifically employing parallel beams. The 8mm needed range of linear motion is made possible by the compliant mechanism, which has been particularly engineered to do so. The actuation force is produced by a voice coil motor as shown in Figure 2 and is applied in the experiment in ranges from 1 N to 40 N. An optical encoder is used to measure the linear displacement of the mechanism. The data controller and acquisition tasks are performed by Dspace, which is connected to the mechanism via a system combination. By converting the appropriate current-voltage signals, the mechanism is integrated with the graphical user interface (GUI).

The current amplification is done with the help of linear current amplifier (LCAM), as the mechanisms move linearly when an actuator is applied. The displacement is measured using linear encoders, and the reading from the encoder is provided to Dspace. The mechanism is accurately constructed and aligned, and an optical sensor is added to the setup, which is connected to a controller and then to the computer. In the beginning, the computer creates a digital signal. Using a DAC (Digital to Analogue Converter) link, this digital signal is transformed into an analogue signal. A continuous analogue waveform that may be processed or sent further is created from the digital signal by the DAC. However, the signal produced by the dSPACE DS1104, which is 12 V and 7 mA, is not strong enough to drive the actuator (VCM). To address this, linear current amplifiers (LCAMs) are utilized to amplify the voltage signals into current signals with sufficient strength to drive the actuator.

The VCM (Voice Coil Motor) actuation force causes deflection in the motion stage of the compliant mechanism by successfully converting electrical current into mechanical force. Because of its high sensitivity, an optical encoder is utilised to detect motion stage deflection. This sensor converts the mechanical displacement into an electrical signal. The DAQ system's ADC (Analogue to Digital Converter) interface is then used to capture and gather the generated analogue voltage signal.

The experiment revealed that a 40 N actuation force resulted in a maximum displacement of 4.02 mm for the compliant mechanism.

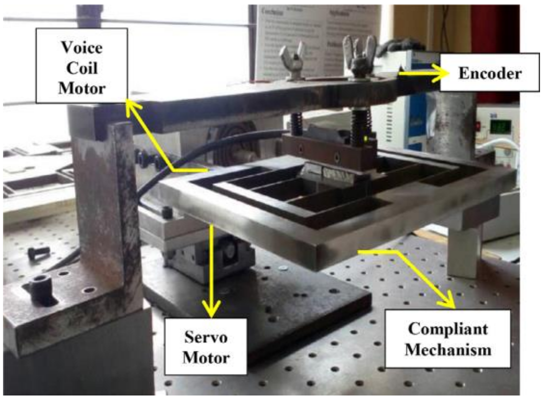

Figure 2 Experimental Setup

4. Validation of the double flexure mechanism and system integration

4.1 Analysis of static structures

The compliant mechanism's displacement in the x-direction is calculated by numerical analysis. The mechanism is shown geometrically using a 150 mm^2 cross-section. The scanner platform is impacted by the actuation force, which is applied at the fixed outer end of the mechanism. Various materials are taken into consideration for the study based on their maximum yield strength and elasticity. Three materials are selected: a PLA alloy with a Young's modulus of 4.107 GPa, a titanium alloy with a Young's modulus of 96 GPa, and steel with a Young's modulus of 200 GPa. The range of actuation forces employed in the study, which runs from 4 N to 30 N, is shown in general in Figure 3. Since biological scanners have an 8 mm maximum motion range, a force range of 4 to 30 N is needed to produce an 8 mm linear displacement. Figure 4 shows the Von Mises stress operating on the mechanism. The displacement in the x-direction and stresses in the compliant mechanism as a result total 60.24 MPa.

Based on Figures 5 and 6, the displacement values for steel, titanium alloy, and PLA material are 0.691 mm, 1.47 mm, and 1.928 mm, respectively, at an actuation force of 12 N. The displacement values for steel are 2.213 mm, titanium alloy is 4.42 mm, and PLA material is 6.01 mm for an actuation force of 40 N. These values are established using a numerical analysis that considers forces between 4 N and 40 N. A broader variety of linear motion may be seen in the PLA material.

Steel has the maximum rigidity (8.12 N/mm) when measured at a force of 30 N, followed by titanium alloys (5.125 N/mm) and PLA (5.125 N/mm). Steel is superior than the PLA material and the titanium alloy in terms of stiffness and strength.

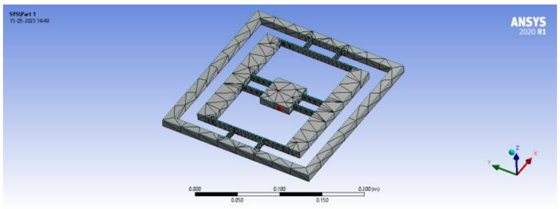

Figure 3 Mesh Model for Experiment

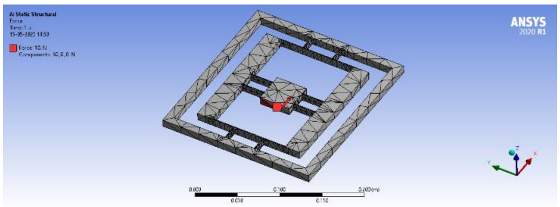

Figure 4 Applied Force on Motion Head

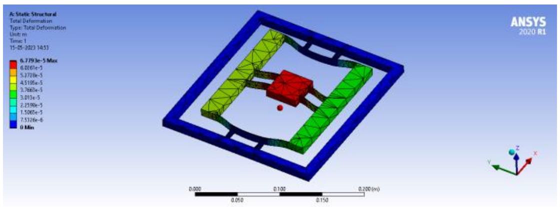

Figure 5 Total Deformation

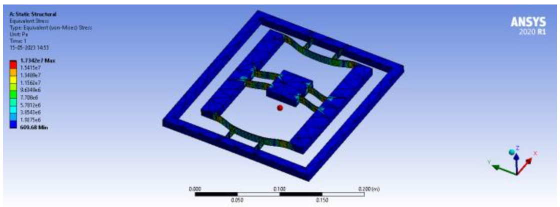

Figure 6 Vonmises Stress on Mechanism

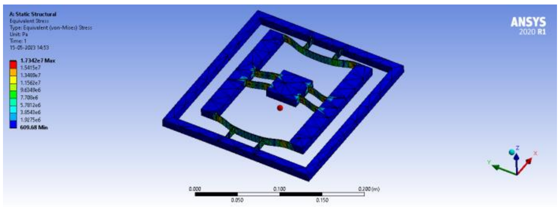

Figure 7 Equivalent Stresses

4.2 Modal analysis of the mechanism

The stability of flexure mechanism is crucial to consider the natural frequency. A modal analysis of the compliant mechanism is conducted using various materials, including Steel, Titanium alloy, and PLA material, to determine the frequencies of the first three mode shapes.

Based on Figures 8, 9, and 10, the frequencies of the first, second, and third modes for the steel material are found to be 46.35 Hz, 103.6 Hz, and 292.6 Hz, respectively. The natural frequencies of Steel, Titanium alloy, and PLA material are summarized in Table 1.

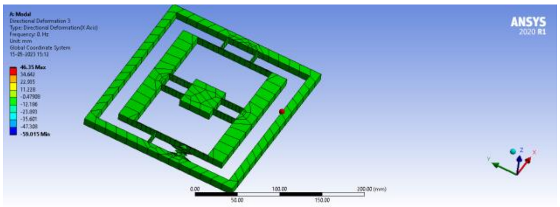

Figure 8 1st Mode of Frequency

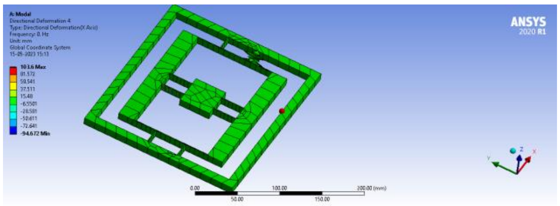

Figure 9 2nd Mode of Frequency

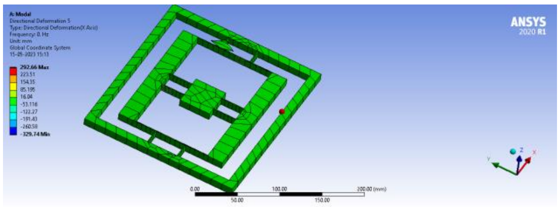

Figure 10 3rd Mode of Frequency

Table 2 demonstrates that steel material exhibits lower displacement values than Titanium alloy and PLA material in the first three mode shapes. Consequently, when subjected to repeated operations, steel material demonstrates greater stability compared to Ti alloy and PLA material. However, PLA material is suitable for constructing a compliant mechanism intended for erratic operations that require a broad range of displacements.

Table 1 Modal Analysis of the Compliant Mechanism

Mode	**Frequency of the mechanism in HZ**		
	Steel	**Titanium**	**PLA**
1	46	40.56	47.12
2	103.6	100.22	104.12
3	292.6	282.39	295.13

Table 2 Mechanism Displacement in mm

Mode	**Displacement of the mechanism in mm**		
	Steel	**Titanium**	**PLA**
1	67	83	110
2	88.12	120	162.2
3	62	84	121.35

In Identification of Design Flaws and Weaknesses: Modal analysis aids in detecting potential design flaws or weak areas in compliant mechanisms. It helps identify stress concentrations, excessive deformation, or areas prone to failure under dynamic loads. This information allows engineers to refine the design and enhance the overall performance and durability of the mechanism. Dynamic System Integration: Modal analysis facilitates the integration of compliant mechanisms into larger dynamic systems. By understanding the modal behaviour, engineers can account for the interaction between the mechanism and its surrounding components, minimizing unwanted resonances and ensuring proper functioning of the entire system. Modal analysis plays a crucial role in the study of compliant mechanisms by providing insights into their dynamic behavior, aiding in design optimization, validating simulations, identifying weaknesses, and enabling seamless integration into larger systems.

The stiffness model is calculated by equation 2

$$K = \frac{F}{\delta} = \frac{12EI}{L^3} \qquad (2)$$

Where,

δ = Deformation, mm;

F = Applied force, mm;

L = Beam Length, mm;

E = Young’s Modulus, N/mm^2;

I = Moment of area of the beam, mm^4

5. Result

This study primarily focused on analyzing the frequency and linear displacement of compliant mechanisms, specifically the DFM mechanism. Three distinct materials—steel, PLA, and titanium alloy—were used in experimental and numerical studies. Ansys 2020 was utilised for the numerical analysis, and experimental measurements were used to confirm the numerical results in the x-direction.

According to the results of the numerical simulations, the linear displacement for steel material was found to be 2.921 mm with an actuating force of 40 N. Similar to how titanium alloy and PLA material displayed displacements of 5.05 mm and 6.12 mm, respectively, under the same 40 N strain, numerical studies revealed. For the specified force range, the highest and minimum percentage errors in the x-direction, as shown in Figure 11, were found to be 4.17% and 0.62%, respectively.

The stiffness values were also determined for each material at an actuating force of 12 N, with steel having a stiffness of 14.029 N/m, titanium alloy having a stiffness of 8.27 N/m, and PLA material having a stiffness of 6.14 N/m. It was found that steel exhibited higher stiffness when the compliant mechanism moved in a linear direction.

The compliant mechanism's intrinsic frequency was discovered to be 90 Hz by modal analysis. The displacement values at the natural frequency are shown in Figure 12 with steel having a displacement of 90 mm, titanium alloy having a displacement of 120 mm, and PLA material having a displacement of 142 mm. It is important to note that a steel mechanism has a lesser displacement. Consequently, a steel complying mechanism would be more stable.

According to the study, compliant mechanisms are made to function below the natural frequency of 140 Hz in order to prevent resonance.

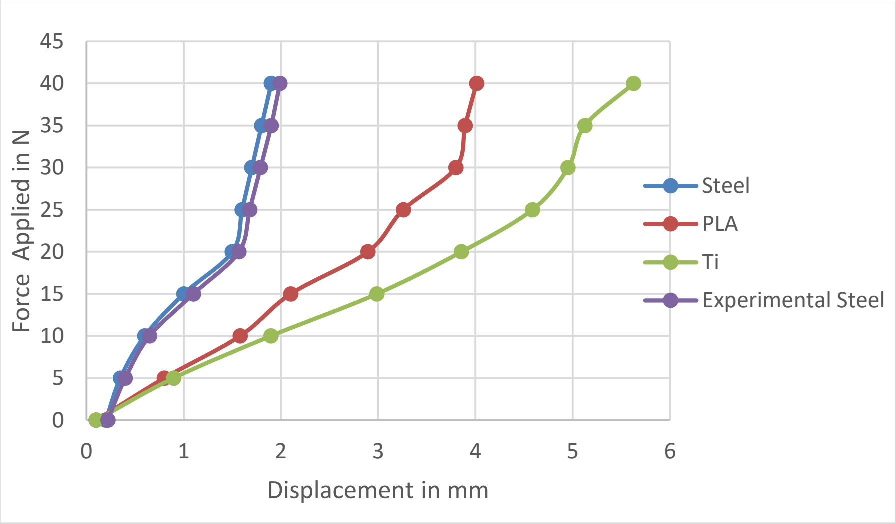

Figure 11 Plot of Force vs Displacement

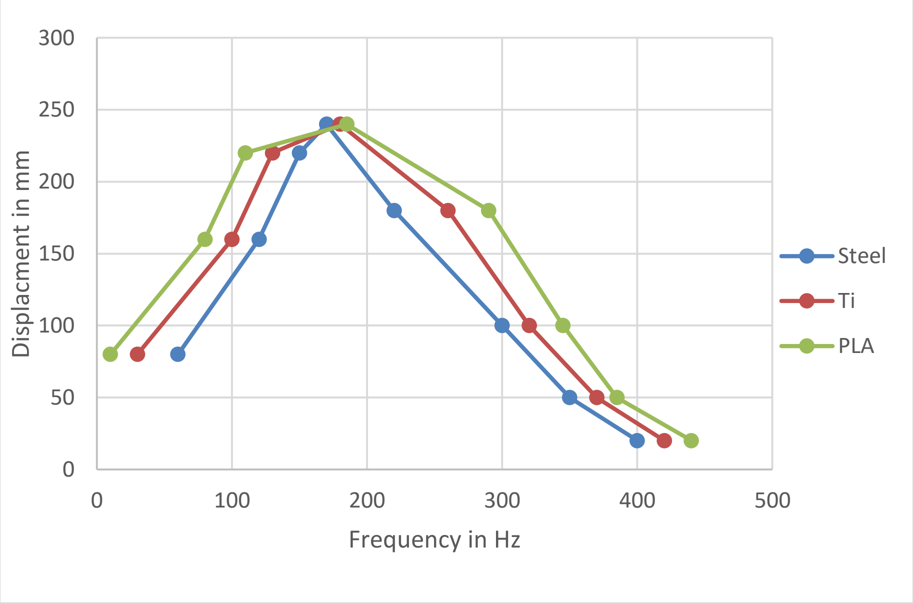

Figure 12 Plot of Displacement vs Frequency

6. Conclusion

It has been shown that PLA material provides for a maximum range of motion of 6.012 mm in the X direction by the use of a compliant mechanism and doing both experimental and computational analysis. Steel outperforms PLA and titanium alloy in terms of stability for compliant devices because of its hard and unnatural behaviour. The smallest error rate for the experimental and numerical values for steel is 0.6%. The compliant system's inherent frequency has been identified by modal analysis as 140 Hz. Therefore, compliant mechanisms should function below this 140 Hz frequency limit to avoid resonance. The results of this study might help create a rotating scanning platform with a compliant mechanism for use in biomedical applications. Future development and testing of the mechanism's speed and scanning range is possible.

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