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Material influence on displacement and stress of amplification compliant mechanisms flexure hinges

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Abstract: *Compliant amplification mechanisms with compliant joints are widely used in microelectromechanical systems (MEMS) and precision engineering because they can convert small input displacements into larger output motions with high accuracy. In this study, the influence of material properties on the displacement amplification and stress characteristics of a compliant amplification mechanism is investigated. The geometric model of the mechanism was first developed using SolidWorks, ensuring that the dimensions and configuration of the flexible joints follow the displacement amplification principle. Finite element analysis was then performed in ANSYS to evaluate the displacement and stress distributions within the structure under identical boundary and loading conditions. Three different materials were considered in the simulation, including Aluminum 6061-T6, Carbon Fiber Composite, and PZT-8 piezoelectric material. The results show that when Aluminum 6061-T6 is used, the mechanism produces an output displacement of approximately 0.68896 mm with a maximum stress of 55.397 MPa. For Carbon Fiber Composite, the displacement slightly increases to 0.68951 mm while the maximum stress reaches 60.178 MPa. In the case of PZT-8, the output displacement reaches 0.69053 mm and the maximum stress is about 56.896 MPa. These results indicate that material properties have only a minor effect on the output displacement of the mechanism but significantly influence the stress magnitude and distribution within the compliant joints. Therefore, appropriate material selection plays an important role in improving the structural reliability and mechanical performance of elastic amplification mechanisms.*

Keywords: *Amplification compliant mechanism, flexure hinge, finite element method, material, displacement, stress*

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I. Introduction

Compliant mechanisms are mechanical devices that transmit motion and force through the elastic deformation of a material instead of using traditional rigid joints. This characteristic allows for a reduction in the number of components, minimizes friction, and improves operational accuracy and reliability. Elastic mechanisms often utilize bending hinges to create the desired movement while maintaining structural flexibility, making them ideal for small-scale systems requiring high precision. Based on this principle, a 3D-printed micro-gripper [1] based on an elastic mechanism was designed using SOLIDWORKS and optimized using finite element simulation (FEA) to achieve the appropriate clamping force and displacement. The structure is fabricated from carbon fiber-reinforced PETG and driven by shape-memory alloy (SMA) wire. Simulation and experimental results showed a deviation of less than 5%, thereby confirming the accuracy of the design and its potential application in high-precision micro-manipulation tasks. Following studies on compliant mechanisms in micro-manipulation, a structural optimization method [2] considering the influence of size has also been proposed to reduce parasitic movement at the output gate. This method uses the theory of varying pair stress to construct a size-dependent finite element model and establishes a multi-objective optimization problem, where output displacement is maximized while parasitic movement is minimized under volume constraints. Design variables are updated using an optimization criteria algorithm, and the effectiveness of the method is confirmed through numerical simulations, showing a significant influence of size parameters on the design results. Furthermore, hybrid conformation mechanisms (HCMs) [3] have also been studied to reduce oscillating forces in micro-manipulations, particularly in ophthalmic surgery. A five-chain HCM integrating force-sensing clamps was proposed and modeled using a rigid pseudo-object model, and a dynamic interaction model between the mechanism and the held membrane was constructed. Through parametric analysis and optimization, experimental results with PDMS membranes showed that the oscillating interaction force was controlled at the milli-Newton level, demonstrating the potential for improved stability in precise micro-manipulations. In addition, six-axis force/torque sensors (FTS)[4] based on elastic mechanisms have been developed to improve sensitivity and reduce crosstalk in micro-force measurements. The sensor structure utilizes elastic beams combined with cantilever and flex beams, along with strain sensors arranged in a Wheatstone bridge to separate force and torque measurements. Simulation and experimental results show that both nonlinearity and crosstalk are small (below approximately 2–3%FS), demonstrating the effectiveness of the design in precise micro-manipulation and measurement systems. Similarly, the compliant mechanisms [5] were also applied in high-precision optical focusing systems. A secondary mirror positioning system with sub-millimeter travel and nanometer resolution has been developed using a fixed clamping elastic mechanism, modeled using a rigid pseudo-body model (PRBM) and integrated with a piezoelectric actuator. Experimental results show that the proposed model has high accuracy and meets the requirements for micro-motion control in optical systems. Furthermore, to improve motion amplification in precision positioning systems, a novel Z-shaped bending hinge (ZFH) [6] has been proposed and integrated into a two-degree-of-freedom XY positioning platform. The structure was analyzed using the elastic matrix method and the force balance principle, showing significantly improved amplification performance. Both simulation and experimental results confirm the accuracy of the model and the effectiveness of the design in micro-positioning applications. In addition, a two-degree-of-freedom micro/nano-positioning table [7] controlled by piezoelectric actuators (PEA) has been developed to achieve high accuracy in confined spaces. The system uses parallelogram and spherical amplification mechanisms to increase rigidity, reduce parasitic motion, and ensure separation of motion between axes. Modeling, simulation, and experimental results show that the positioning table achieves nanometer resolution and small motion error, demonstrating the effectiveness of the design in precise micro-positioning applications. Additionally, a complex lever-based compliant mechanism [8] was also studied to amplify displacement and enhance the sensitivity of the MEMS accelerometer. The mechanism was modeled using the rigid body method and validated through finite element simulation. The optimization results showed that the design can increase sensitivity and improve the dynamic performance of the accelerometer while maintaining minimal nonlinearity compared to traditional designs. In addition, an asymmetrical rhombohedral compliant amplification mechanism [9] was proposed for piezoelectric sliding-adhesive actuators to achieve long-stroke displacement with high resolution. The mechanism is modeled using a dynamic electromechanical stiffness matrix to analyze characteristics such as stroke, stiffness, and natural frequency. Experimental results on the prototype show that the system has a large stroke, stable speed, and good load-carrying capacity, demonstrating the mechanism's effectiveness in precision motion applications. Additionally, a bioplastic structure [10] inspired by pigeons (BioCM) has been proposed to improve the accuracy of flying vision calibration systems in digital lithography. The structure utilizes a differential lever amplifier and S-shaped flexible rods to increase amplification ratio and reduce stress during high-frequency operation. Experimental results show that this design enhances system stability and accuracy in the presence of disturbances.

- Evaluating the Influence of Materials on Elastic Amplification Mechanisms. This study conducts a comparative analysis of the influence of different materials on the performance characteristics of an amplification mechanism using elastic joints in a MEMS system.
- Comparison of Three Materials with Different Mechanical Properties. Three materials, including Aluminum 6061-T6, Carbon Fiber Composite, and PZT-8 piezoelectric material, were analyzed in the same model to evaluate differences in displacement and stress.
- Finite Element Modeling Analysis under the Same Boundary Conditions. The model was built in SolidWorks and analyzed using the finite element method in ANSYS under the same boundary conditions and loads, ensuring objective comparison between the materials.
- Indicating the Degree of Material Influence on Displacement and Stress. The results show that the material only slightly affects the amplification displacement, but significantly affects the value and distribution of stress at the elastic joints.
- Providing a basis for material selection for elastic amplification mechanisms. This research provides a reference basis for selecting suitable materials to improve the reliability and mechanical performance of compliant amplification mechanisms.

II. Theoretical and methodological basis

2.1 Design displacement amplifier compliant mechanism

A compliant mechanism amplifier is a mechanical device that uses the elastic deformation of a material to amplify displacement or force from an input to an output. Structurally, the device is usually constructed as a single unit, consisting of main parts such as a fixed frame, elastic hinges, elastic connecting rods, and input-output components. The elastic hinges act as rotating joints, allowing the mechanism to move through the small bending of the material instead of the sliding or rotational movement of traditional mechanical joints. When a force or displacement is applied at the input, the elastic elements deform and transmit motion through the connecting rod system, thereby creating a larger displacement at the output. Thanks to its monolithic structure and lack of friction between the joints, the elastic amplifier has high accuracy and repeatability, good sensitivity, requires no lubrication, and is low-maintenance. However, because the operation relies on elastic deformation, the movement range is usually small and stress tends to concentrate in the hinge areas, so appropriate design is needed to ensure the durability and lifespan of the mechanism. The dimensions of the proposed mechanism are shown in Figure 1.

The overall dimensions of the model are 128 mm x 50 mm x 8 mm. The thickness of the circular flexure hinge is 0.3 mm, and the distances between the flexure hinges are $l_1 = 5$ *mm*, l_2, = 7 mm and $l_3 = 108$ *mm* respectively: These dimensions are then used to build a 3D model using SolidWorks software, as shown in Figure 2.

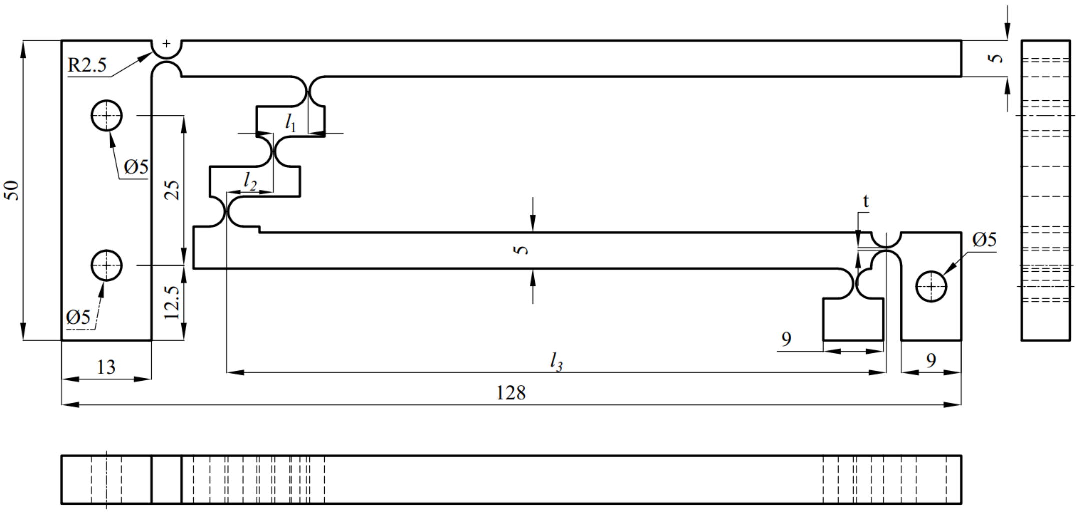


Figure 1 Dimension of the compliant amplifier mechanism model

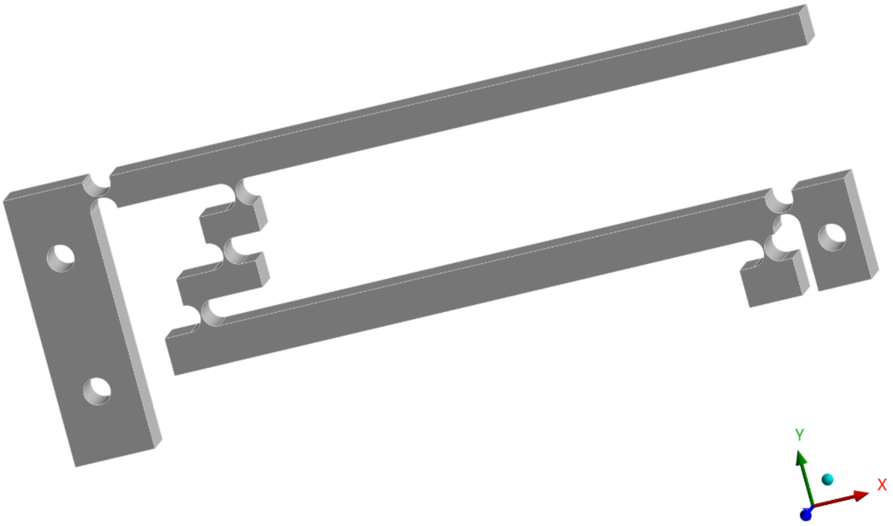


Figure 2. 3D model of a compliant displacement amplifier using flexure hinges

2.2 Finite element model

To evaluate the working characteristics of the mechanism, an analysis model was built using the Finite Element Method (FEM) with ANSYS Workbench software. This method allows for the analysis of stress distribution and working characteristics as the displacement capability of the elastic amplifier mechanism, under load conditions and different materials. The geometric model of the mechanism was meshed using automatic meshing. The average element size was chosen as 0.2 mm to ensure a balance between accuracy and computation time. After meshing, the model obtained approximately 1422663 quadrilateral elements and 5995490 nodes as presented in Figure 3. The fine element mesh helps to more accurately simulate the strain and stress distribution in the mechanism under load and different materials. Selection

In this investigation, three materials were selected to evaluate the influence of material properties on the performance of the mechanism, including Aluminum 6061-T6, Carbon Fiber Composite, and PZT-8 piezoelectric material. The main mechanical parameters used in the simulation were Young's modulus and Poisson's ratio. The values of these parameters are presented in the Table 1:

Table 1. Young's Modulus and Poisson ratios of materials

Material	Young's Modulus (E)	Poisson ratio (ν)
Al-6061-T6	69 GPa	0.33
Carbon fiber composite	75 GPa	0.32
PZT-8 piezoelectric	63 GPa	0.31

These material parameters are used as input data for the FEM model to analyze the stiffness and deformation of the mechanism under load.

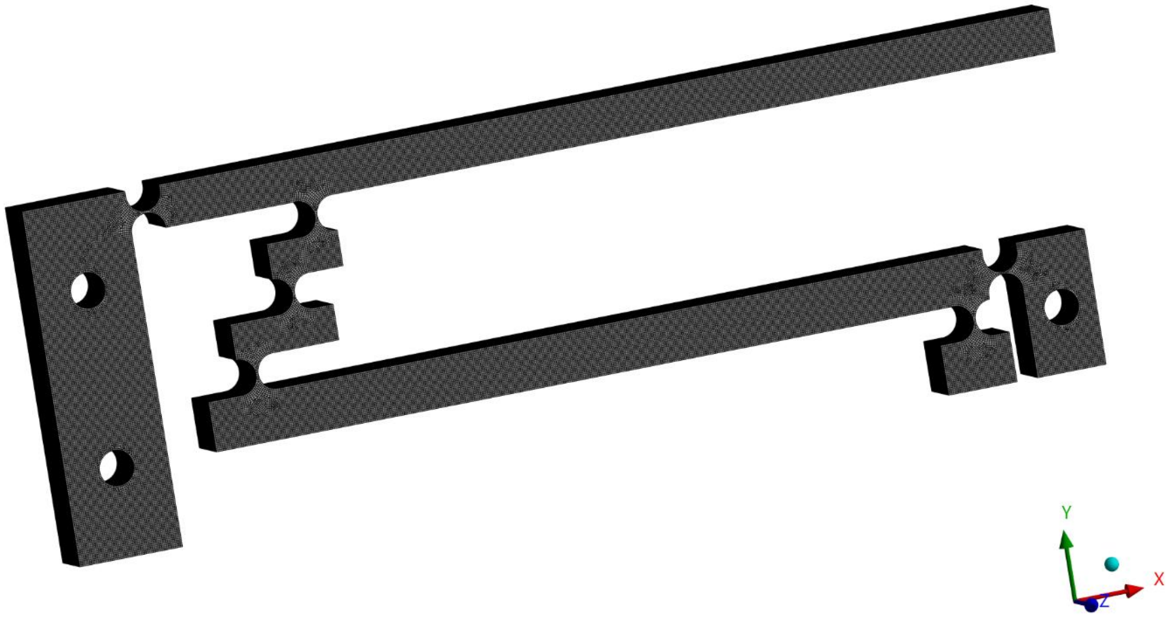


Figure 3. finite element model

In the simulation model, the mechanism was fixed using the Fix Support boundary condition at three connecting holes, simulating the clamping state of the mechanism in reality. This condition ensures that the degrees of freedom at the connection points are completely restricted. To activate the mechanism, a forced displacement of 0.01 mm is applied at face B of the mechanism. This displacement acts as the input load, allowing the mechanism's response to be evaluated through the distribution of strain and stress during operation.

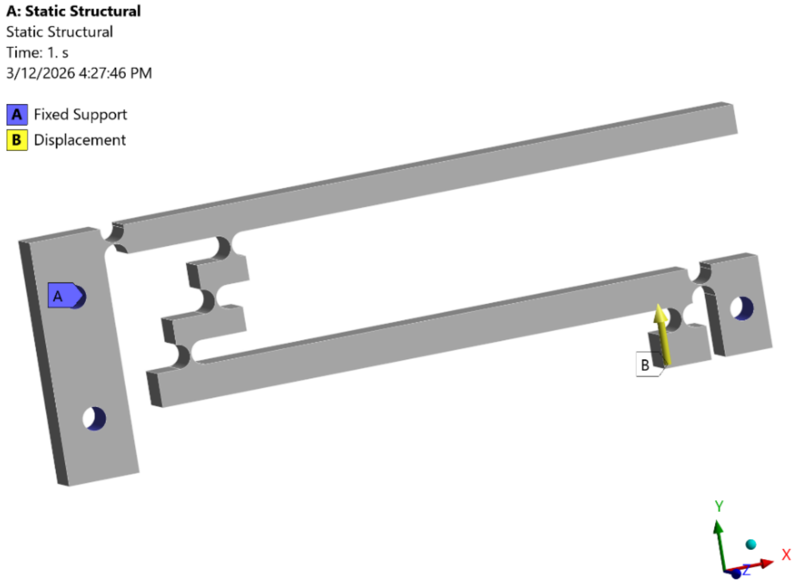
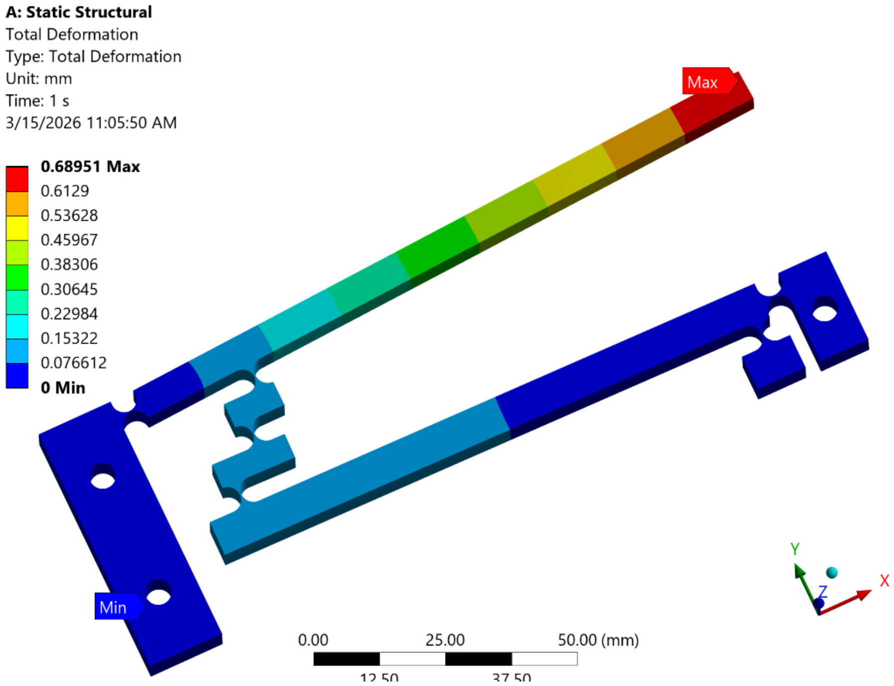


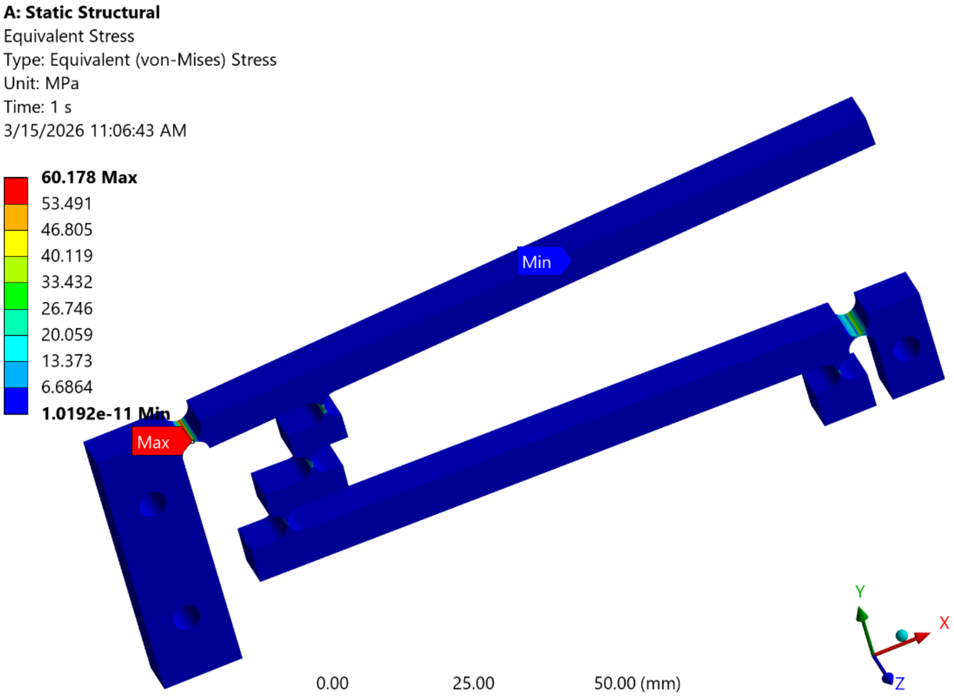
Figure 4. Set boundary conditions and load

III. Results and discussions

Finite element simulations performed using ANSYS show that the elastic amplification mechanism achieves stable displacement amplification when using different materials. The geometric model of the mechanism was built in SolidWorks and the same boundary and load conditions were applied to ensure consistency during comparison.



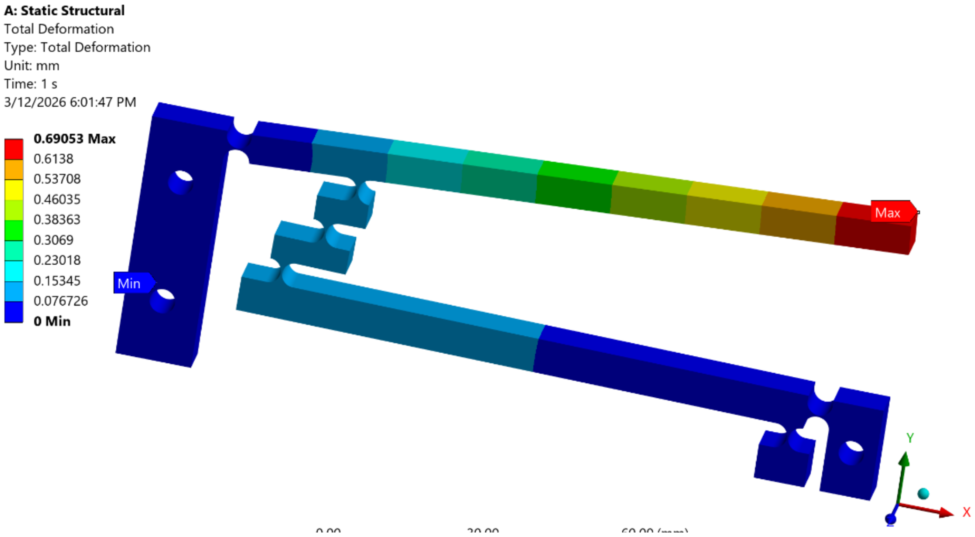
a) Displacement



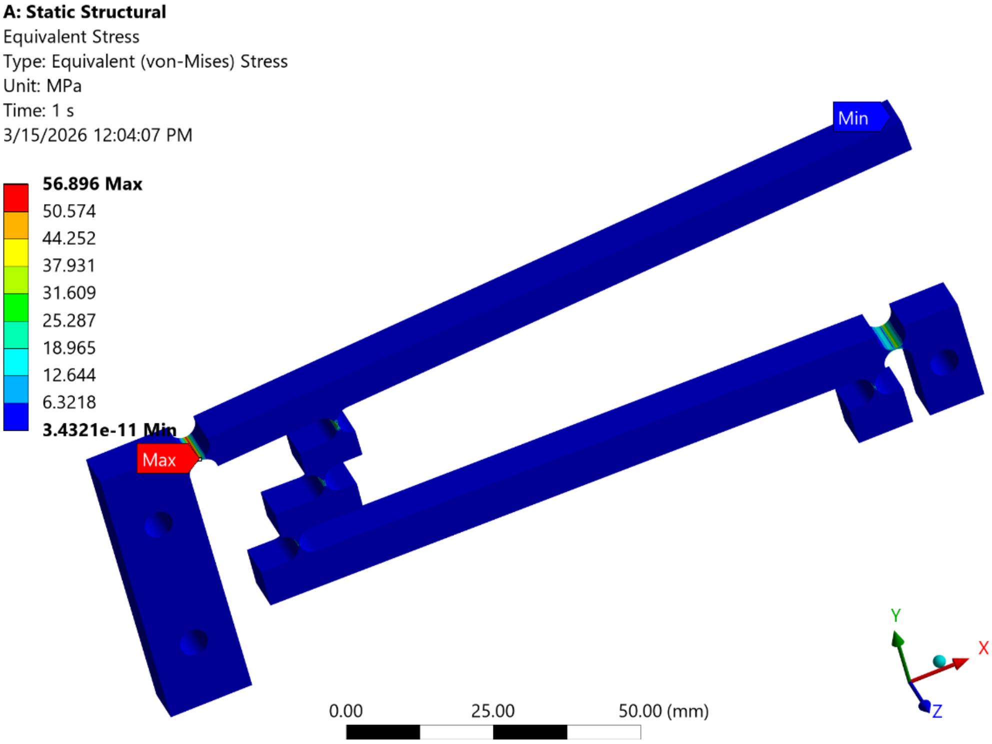
b) stress

Figure 5. Finite element analysis results with carbon fiber material

For Aluminum 6061-T6, the mechanism achieved an output displacement of approximately 0.68896 mm, with a maximum stress of approximately 55.397 MPa as demonstrated in Figure 5. When replaced with Carbon Fiber Composite, the output displacement increased slightly to 0.68951 mm, however, the maximum stress increased to 60.178 MPa as recorded in Figure 6. In the case of using PZT-8 piezoelectric material, the output displacement reached a maximum value of approximately 0.69053 mm, while the maximum stress reached 56.896 MPa as as revealed in Figure 7.



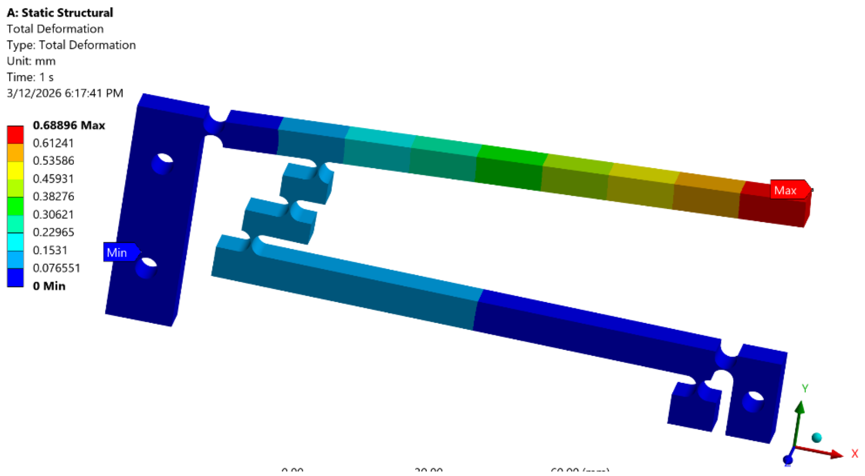
a) Displacement



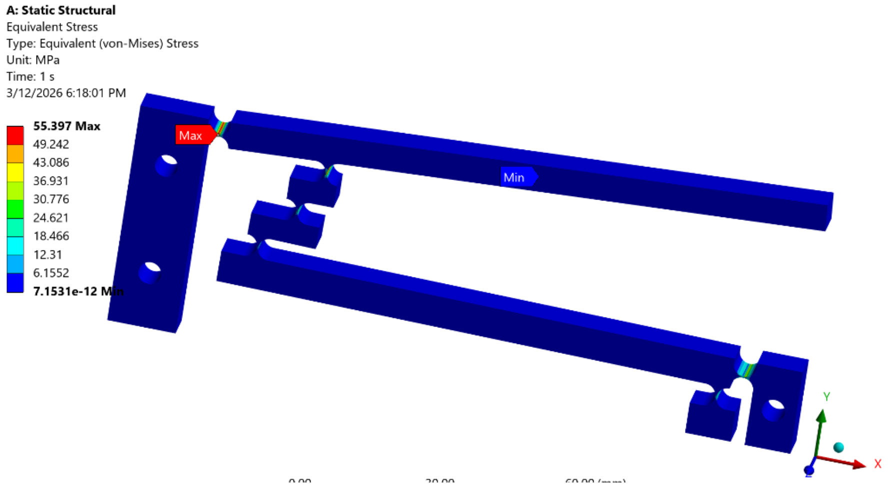
b) stress

Figure 6. Finite element analysis results with PZT-8 piezoelectric material

Comparison of results indicated that the difference in output displacement between the three materials is relatively small, with a difference of only about 0.00157 mm between the lowest and highest values. This suggests that the displacement amplification characteristics of the mechanism mainly depend on the geometric structure and design of the mechanism, while the influence of the material on amplification is negligible.



a) Displacement



b) Stress

Figure 6. Finite element analysis results with Al-6061-T6 material

However, the difference in maximum stress between the materials is quite significant. Carbon Fiber Composite showed the highest stress value, which may be related to the stiffness characteristics and strain distribution in the structure. Meanwhile, Aluminum 6061-T6 showed a lower stress value, indicating a more stable stress distribution in the mechanism. PZT-8 material showed results intermediate between the two cases.

Overall, the analysis results show that material selection does not significantly alter the displacement amplification capability of the mechanism, but it does significantly affect the stress level in the elastic joints, thereby directly impacting the strength and reliability of the system. Therefore, in the design of elastic amplification mechanisms, material selection needs to be carefully considered to optimize both mechanical performance and structural strength.

IV. Conclusions

This investigation analyzed the performance characteristics of an elastic amplification mechanism using flexible joints in precision mechatronics and MEMS systems. The geometric model of the mechanism was constructed using SolidWorks software and analyzed using finite element analysis (FEM) in ANSYS to evaluate the displacement and stress distribution within the mechanism. Three materials—Aluminum 6061-T6, Carbon Fiber Composite, and PZT-8 piezoelectric material—were selected to compare the influence of material properties on the mechanism's performance. Simulation results showed that the output displacement of the mechanism reached approximately 0.68896 mm, 0.68951 mm, and 0.69053 mm for the three materials, respectively. The difference in displacement was relatively small, indicating that the material only slightly affected the mechanism's displacement amplification capability. However, the maximum stress values in the structure differed significantly between the materials, reaching 55,397 MPa, 60,178 MPa, and 56,896 MPa, respectively. This indicates that the mechanical properties of the material significantly influence the distribution and magnitude of stress at the elastic joints. The research results contribute to providing a reference basis for selecting suitable materials in the design of elastic amplification mechanisms to ensure the durability and reliability of the system.

This study aims to build a model of an elastic amplifier mechanism using flexible joints for applications in precision mechatronics and MEMS systems. It performs numerical analysis using the finite element method to evaluate the displacement and stress characteristics of the mechanism. It compares the effects of three different materials: Aluminum 6061-T6, Carbon Fiber Composite, and PZT-8 piezoelectric material under the same boundary and load conditions. It shows that the material has a negligible effect on the amplifier displacement but a significant effect on the stress in the mechanism, especially at the elastic joints. It provides a reference basis for material selection in the design of elastic amplifier mechanisms to improve durability and performance.

Further research into other materials with high mechanical properties, such as titanium alloys or advanced composite materials, is needed to optimize the mechanism's performance. Optimize the shape and size of the elastic joints to improve the displacement amplification coefficient and reduce stress concentration. Combine piezoelectric materials such as PZT-8 with the amplification mechanism to develop high-precision micro-displacement actuators. Conduct practical experiments to verify simulation results and evaluate model reliability. Expand research to include the kinematic and vibrational analysis of the mechanism in precision control applications.

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