Development of Bridge and Lever Type Compact Compliant Mechanism for Micro Positioning Systems

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Abstract. Nowadays, for precision positioning applications (Micro-Electro-Mechanical Systems, Nano/Micro positioning devices), compliant mechanisms are extensively used over traditional mechanisms. Compliant mechanisms are joint less mechanism having merits as no wear and friction, no backlash and no lubrication. In this paper, a newly developed flexure hinge based bridge and lever type compact compliant mechanism has been proposed for the precision linear displacement applications. This mechanism can be used in the portable cameras for image stabilization, lens shutters, alignment and levelling devices, etc. The key performance parameters for developing the compliant mechanism are the input displacement/force, output displacement and amplification ratio. For designing compact amplified compliant mechanism (CACM), Pseudo-Rigid-Body-Model (PRBM) method is used. The finite element analysis of developed micro-displacement amplifier compliant mechanisms carried out by using ANSYS workbench. The analyses and experimentation is performed for the input displacement, output displacement and amplification ratio of mechanism. An input force range considered for analysis is in between 1 N to 50 N. All the results from analytical, simulation and experimentation are compared. The error in output displacement is observed up to 6% and the geometric amplification ratio for the mechanism is observed up to 6.5.

1. Introduction

Compliant mechanisms are extensively used over the traditional mechanism due to advantages like no lubrication required, no backlash, no friction. Also due to monolithic structure, a compliant mechanism saves assembly time. Many researchers and professionals working on these mechanisms, and explores plenty of designs according to need and application. In this literature, many in plane micro positioning flexure mechanisms are reviewed. For example, Yang li [1] developed a structure from material Al7075, of size 140 mm x 140 mm x 7 mm. This mechanism delivers maximum displacement of output stage is 64.2 μm. The geometric amplification of the mechanism is 3.7. Also JaroslavHricko [2] designed a compact compliant gripper mechanism of size 154.2 mm x 80 mm x 3 mm using polyamide material. A displacement delivered at the gripper tip by the mechanism is 8.5 mm. The amplification ratio achieved is up to 4.6. Guimin Chena [3] designed elliptical hinge based displacement amplifier compliant mechanism of overall size approx. 210 mm x 150 mm x 5 mm. The mechanism is made from the acrylic glass sheet and delivers 3 mm maximum output displacement. The amplification ratio achieved is up to 33.6 and Yangmin Li [4] designed and developed the flexure based parallel micro positioning stage from Al-7075 Alloy of overall dimensions are 75 mm x 75 mm...
x 6 mm. The capacity of output displacement of mechanism is 15.74µm. The amplification ratio achieved is 3.7.

To design compliant mechanisms, there are various methods [5] such as Pseudo Rigid Body Model (PRBM), Inverse Methods, structural optimization technique etc. In this paper, a bridge and lever type compact compliant mechanism is designed by Pseudo Rigid Body Model (PRBM) method. In PRBM, Flexure hinge of the mechanism is replaced by the torsion spring with equivalent stiffness and modeling is done by considering the classical rigid body model equations. According to need and applications, the first objective is to design and develop a compact sized compliant mechanism for linear displacement application and second is to enhance the Geometric Amplification (GA) ratio. The paper is organized as follows, after the briefing introduction, literature and objectives; section 2 describes the modeling of bridge and lever type compact compliant mechanism followed by the Section 3 as FEA analysis of optimized compliant mechanism. In section 4, an experimentation procedure is explained. In last results are plotted and draws some conclusions.

2. Modelling of Compact Amplifier Compliant Mechanism

A bridge and lever type compact compliant mechanism is shown in figure 1 (a). To carry out the PRBM, the hinges of the mechanism are replaced with the torsion springs as shown in figure 1 (b).

![Figure 1: (a) Proposed Compact Compliant Mechanism; (b) PRBM of Compact Compliant Mechanism](image)

A right circular flexure hinges are used for mechanism [6]. The compliance ratio of right circular hinges depends on the flexure hinge neck thickness (t) and radius of flexure hinge (r). Here t/R is considered as 0.5 ease of manufacturing.

The equation of stiffness of the circular hinge is,

\[ K_{efr} = \frac{2Ewt^{2.5}}{9rt^{0.5}} \quad (1) \]

where,
- \( w \) = mechanism thickness
- \( r \) = flexure hinge radius
- \( t \) = Flexure hinge notch thickness
- \( l \) = overhang distance of lever

\[ F_{in} = K_{system} \times \frac{x_{in}}{l^2} \quad (2) \]

Rearrange the equation 2 as,

\[ x_{in} = \frac{F_{in}l^2}{K_{system}} \quad (3) \]

The dimensions considered for the analysis are overhang distance of lever (l) is 5mm, thickness of mechanism (w) is 1.5 mm, neck thickness of flexure hinge is 1mm and radius is considered as 2mm for the analysis.
The output displacement of mechanism can be calculated by using the equation 4.

\[ x_{out} = x_{lever} + x_{bridge} \]  

(4)

A carbon steel material is selected due to its higher \( \frac{E}{\rho} \) value [7]. As this value is higher, it gives high rigidity and natural frequency. Following table shows the mechanical properties considered for further analysis.

| Parameter             | Unit   | Value |
|-----------------------|--------|-------|
| Yield stress (Syt)    | MPa    | 250   |
| Poisson's Ratio (\( \mu \)) | ------ | 0.3   |
| Density (\( \rho \))  | Kg/m³  | 7850  |
| Young Modulus (E)     | GPA    | 200   |

3. Optimized FEA Model

A simple rectangular shaped lever of the mechanism shows bending. To prevent such bending deformation of beam, a triangular shaped beam is adopted as shown in following figures. The simulation result of mechanism at 50N input force is shown in figure 2. Figure 2 (a) shows the maximum displacement of motion stage as 26.5\( \mu \)m in desired direction. An error motion in mechanism is shown in figure 2 (b) and (c) as 0.06\( \mu \)m and 0.005\( \mu \)m in Y direction and Z direction respectively. Last figure (d) shows the stress distribution in the mechanism. A maximum stress developed is 71.9MPa.

![Figure 2. Simulation results of mechanism (a) X directional deformation, (b) Y directional Deformation, (c) Z directional Deformation and (d) Equivalent Stress.](image-url)
4. Experimentation of Mechanism

Experimentation is performed to compare analytical and simulation results. The block diagram of experimental set up is shown in figure 3. The mechanism is actuated by the linear precision micrometer based actuator. An applied force can be recorded using Arduino controlling unit. An output displacement value for corresponding input force has been recorded by using digital dial gauge with LC 0.001mm. The analytical results obtained for the force range 1N to 50N are compared with the simulation and the experimental results. A comparative representation of Input force vs. Output displacement is shown in figure 4. The numerical data is given in Appendix.

![Figure 3. Block Diagram of Experimental set up](Image 3)

5. Result and discussion

Simulation and experimentation results are examined for the displacements. The output displacement results are plotted w.r.t input force.

It has been observed that,

- The maximum displacement in the desired direction is 26.5 µm when input force is 50N.
- The parasitic error motion values of motion stage at the same force are approximately 0.06µm in Y direction and 0.005µm in Z direction which are negligible. It means that the movement of motion stage is perfectly linear.
- The maximum stress developed in the mechanism is around 72 MPa when 50N load is applied. Therefore the mechanism is safe for maximum operating conditions.
- The Geometric amplification (GA) ratio achieved for plain carbon steel material is 7.2 by simulation and 6.5 is by experimentation. It is twice than the existing mechanisms proposed by various researchers.
- The overall size of developed compliant mechanism is 70 mm X 50mm X 1.2 mm. therefore it is called as compact.
- The variation in the output values of displacement by simulation and experimentation is up to 6%. This variation in the result occurs due to the variation in material structure, errors associated in building the setup (Alignment error) and error associated with the instruments used for testing. Also human errors associated during the actuation of mechanism and recording the values of displacements.
6. Conclusion
A compact model of compliant mechanism has been developed using PRBM and results are corroborated with the simulation and experimental results. The design and modelling get simplified due to the use of spring (energy) equation in the PRBM. The developed mechanism has been tested for the force range of 1N to 50N; it has been observed that the maximum stress level is within the range of Syt. Results values of displacement obtained by the FEA simulation are in close range with the values by experimental result. Therefore FEA analysis is important prior to the experimentation. Both Lever type and Bridge Type of mechanism used in combination successfully, which compiles the characteristics of both mechanisms and forms stiff and compact size mechanism. Such mechanisms can be used for MCB’s, electric switches for multiple connections also used for micro levelling and micro positioning devices.

References
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Appendix A

A.1. Result values of Input Displacement, Output displacement and Amplification Ratio

| Force (N) | Equi. (Von Mises) Stress (MPa) | FEA Simulation | Experimental (Expt.) | Geometric Amplification (GA) Ratio |
|-----------|---------------------------------|----------------|----------------------|-----------------------------------|
|           | FEA Sim. | Experimental | FEA | Expt. |
| 1         | 1.4385   | 7.34E-05     | 5.31*E-04 | -   | -   | 7.23 | - |
| 2         | 2.8769   | 1.47E-04     | 1.06*E-03 | -   | -   | 7.23 | - |
| 3         | 4.3154   | 2.20E-04     | 1.59*E-03 | -   | -   | 7.23 | - |
| 4         | 5.7538   | 2.93E-04     | 2.12*E-03 | -   | -   | 7.23 | - |
| 5         | 7.1923   | 6.73E-04     | 2.65*E-03 | -   | -   | 7.23 | - |
| 6         | 8.6307   | 9.40E-04     | 3.18*E-03 | -   | -   | 7.23 | - |
| 7         | 10.069   | 5.73E-04     | 3.71*E-03 | -   | -   | 7.23 | - |
| 8         | 11.508   | 7.87E-04     | 4.24*E-03 | -   | -   | 7.23 | - |
| 9         | 12.946   | 4.60E-04     | 4.77*E-03 | -   | -   | 7.23 | - |
| 10        | 14.385   | 7.34E-04     | 5.31*E-03 | -   | 5.00*E-03 | 7.23 | - |
| 15        | 21.577   | 1.10E-03     | 7.96*E-03 | -   | -   | 7.23 | - |
| 20        | 28.769   | 1.47E-03     | 1.06*E-02 | -   | 1.00*E-02 | 7.23 | - |
| 25        | 35.961   | 1.83E-03     | 1.33*E-02 | -   | -   | 7.23 | - |
| 30        | 43.154   | 2.20E-03     | 1.59*E-02 | 2.50*E-03 | 1.50*E-02 | 7.23 | 6.00 |
| 35        | 50.346   | 2.57E-03     | 1.86*E-02 | -   | -   | 7.23 | - |
| 40        | 57.538   | 2.93E-03     | 2.12*E-02 | 3.00*E-03 | 2.00*E-02 | 7.23 | 6.67 |
| 45        | 64.73    | 3.30E-03     | 2.39*E-02 | -   | -   | 7.23 | - |
| 50        | 71.923   | 3.67E-03     | 2.65*E-02 | 4.00*E-03 | 2.50*E-02 | 7.23 | 6.25 |

* As the movement of Input link and Output link are in opposite direction, so output displacement carries negative sign but real values are considered for calculation.

**An experimental Input displacement values are measured by using the optical microscope and sylvac digital dial gauge of LC0.001mm.