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Study of Flexural-based Multi-stage Asymmetric Microgripper

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Abstract

The current study developed a high-performance multi-stage flexural-based asymmetric microgripper, taking into consideration the increasing demands for flexure-based compliant devices in precision engineering, robotics, and biomedical applications owing to their optimized performance in precision positioning tasks. The conventional symmetric microgrippers cannot provide reliable gripping forces due to the assembly and manufacturing variances; thus, developing an asymmetric design is called for. A new design is presented here, based on using PZTs as the driving force, which is integrated with a lever mechanism, rhombic amplifier, and levered parallelogram mechanism to amplify the input displacement. FEA analysis indicated that the maximum jaw displacement is 311.64 µm and parasitic y-direction motion as low as 0.87% of the x-direction displacement. It obtained a first natural frequency, identified from modal analysis as 445.01 Hz, which gives dynamic stability. The factor of safety is 2.282. Optimization in performance is also carried out in leaf flexure hinge thickness.

Keywords: Asymmetric microgripper, Multi-stage compliant mechanism, Piezoelectric actuator (PZT), Lever mechanism, Rhombic amplifier, Parallelogram mechanism.

1. Introduction

Modern engineering, especially in micro-technologies, microelectronics, and motion control, is developing very fast. This fact influenced the development of flexural-based micro-manipulators and microgrippers. Microgrippers, as tools for manipulating objects in millimeter and submillimeter scales with high precision, emerged at the beginning of the 1980s as a part of micro-robotic research. Flexure-based compliant mechanisms have emerged as superior alternatives to rigid-body mechanisms because they transmit motion or force through material flexibility and elasticity. Because these mechanisms are made from a single piece of material, they have fewer parts, require no lubrication, and need minimal maintenance. Their compact design and lightweight construction make them ideal candidates in situations where size and weight may be a limiting factor. In addition, inherent flexibility in compliant mechanisms reduces wear and increases durability, which again makes them very suitable for aerospace, robotics, medical, and MEMS applications. Their flexibility and accuracy have positioned them as key factors in the continuous development of micro-manipulation technologies. These include electromagnetic, piezoelectric, electrostatic, electro-thermal, and shape memory alloy microgrippers. In general, magnetic microgrippers are applied in biotechnology and actuated by magnetic fields [1]. The piezoelectric microgrippers use piezoelectric materials whose expelling or contraction is dependent on a voltage applied to them; thus they have the advantages of small size, high sensitivity, and large output force [2][3]. SMA Microgrippers, developed for assembling microscopic parts, are formed with fingers grasping and an actuator that changes shape upon heating, together with a parallel elastic structure for the cooling and guiding of movement [4]. Since microgrippers can also be classified according to jaw arrangement, they can be listed as asymmetric, symmetric, and stepwise. The symmetric microgrippers are relatively easier to design and fabricate, having balanced internal stress and offering an enhanced working stroke; they may at times exert unbalanced force on an object, which might lead to the destruction of delicate objects [5]. Asymmetric microgrippers have independent jaws and would be well applied in the manipulation of asymmetrical objects [6]. Other innovations include stepwise microgrippers, which have separate actuators for each jaw, thus allowing symmetrical and asymmetrical operations that could enhance grip strength and stability [7]. The other classification of microgrippers can be made according to their degrees of freedom. Single DOF, also referred to as 1-DOF, involves jaws moving in only one plane and presents rather simple, low-cost designs that have fewer chances of failure [8]. On the other hand, 2-DOF mechanisms enable grabbing and rotation simultaneously, thus allowing more flexibility when irregular shapes have to be handled [9]. Critical tools for fine manipulation in the micro or nano domain are called

microgrippers. Traditional symmetrical microgrippers have large output displacement but may lead to damage of micro components owing to the unbalanced force distribution. The large-displacement asymmetric microgripper was developed with the use of a piezoelectric actuator due to the high demand for greater output displacement. It was in this way that it achieved the maximum of 224-μm output displacement with 11.2 times magnification. The verification of the results was given by a finite element software analysis [10]. Although the errors were 7.05% and 9.24% between the theoretical calculation and simulation, respectively, this new design allows micro-parts grasping with stability, enabling great potential in applications for micro-assembly, microsurgery, and biomedical applications [10].To further address challenges associated with symmetric microgrippers, a novel asymmetric flexible microgripper mechanism was proposed with the basis of flexure hinges, driving with a piezoelectric actuator for amplified displacement. It succeeded in manipulating fragile micro-components with a high displacement amplification ratio of 4.16 and a stepwise resolution of 7.50 μm, hence offering a safer way for micro-assembly [11]. Another microgripper was proposed, featuring a mechanism that includes a three-stage flexure-based displacement amplification, which results in a displacement amplification of 31.88, motion stroke of 218 μm, and a maximum grabbing force of up to 1993 mN, with a high resonant frequency of 1578.9 Hz to prove the precision in micro-manipulation tasks [12]. Accordingly, the three-stage displacement magnification mechanism with parallelogram and bridge-type mechanisms, which were introduced in one design optimized by FEA, reached an optimum displacement amplification ratio of 12.76 and a jaw positioning precision of ±2.158 nm [13].Other works in this area include the three-stage amplifier dual-mode microgripper with amplification of 10.41 and stroke of jaw motion of 118.34 μm [14] and a new asymmetric-type microgripper with four stages of amplification that attained a displacement amplification factor of 31.6 and maximum stroke of 632 μm during grabbing [15]. A 2-DOF microgripper capable of both gripping and rotation was designed with displacements in grabbing and spinning of 163.3 and 83.1 μm, respectively [16].A design of a microgripper for precise positioning, based on a parallelogram mechanism, minimized parasitic motion down to only 0.59% [17]. Another design proposed was the use of a four-parallelogram mechanism that can assure no parasitic motion in a piezoelectric-driven asymmetric microgripper. The maximum FEA result showed that the parasitic motion along the y-axis was only 0.012% [18].

2. Structure Design and Motion Principle of the Microgripper

Figure 1 shows a diagram of the main view of the microgripper. The size of the mechanism was 80.811 mm × 52 mm × 10 mm. In this multi-stage mechanism, there has been the use an of asymmetric right circular flexure hinge, a leaf flexural hinge, a grasping jaw, a lever amplifier, a rhombic amplifier, a lever parallelogram, a fixing hole, and a piezoelectric actuator. The rhombic amplifier and the lever amplifier are directly connected in series followed by a parallelogram lever amplifier to obtain a larger displacement amplification. For comparison, there has been the use of circular flexural hinges and the leaf flexural hinge was used. A piezoelectric microgripper was used for the input displacement. The deformation of the flexure hinges caused the microgripper to move. The jaws of the microgripper were arranged such that they were always parallel to one another and also prevented the rolling of the objects.

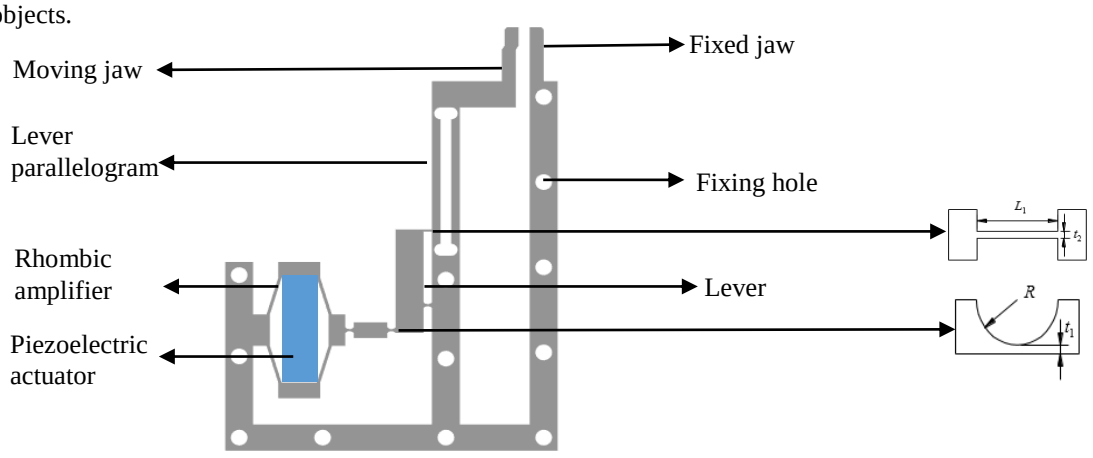


Fig.2.1. Main view of the microgripper

The microgripper uses a three-stage amplification mechanism. In the first stage, amplification is done by the rhombic amplifier. It has a symmetric structure. It consists of eight poles and eight hinges. Figure 2.2 shows how the rhombic amplifier deforms when input force is applied.

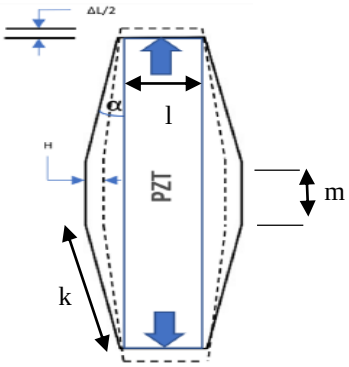


Fig.2.2. Rhombic amplifier before and after deformation

In this study, we assume all eight poles are rigid neglecting the elastic deformation during the working process. As shown in Figure 2.2 the black lines represent the flexible hinge in the initial state and dotted lines represent the flexible hinge after deformation. When input voltage is applied to the piezoelectric actuator, it will expand ΔL in the vertical direction. The opposite side of the fixed end of the rhombic amplifier will move 2H. Considering the symmetric shape of the structure, we can get the relationship between the input displacement of the piezoelectric actuator and the output displacement of the rhombic amplifier as Equation 1.

$$\left(k\,cos\alpha + \frac{\Delta L}{2}\right)^2 + (k\,sin\alpha - H)^2 = k^2 \tag{1}$$

After simplification,

$$H = k\,sin\alpha - k\sqrt{1 - \left(\frac{k\,cos\alpha + \Delta L/2}{k}\right)^2} \tag{2}$$

Where ΔL = d_{in1} = elongation of rhombic amplifier along the y-axis, 2H = d_{out1} = horizontal displacement of the pole opposite to the fixed pole of the rhombic amplifier towards the right direction.

$$Amp_1 = \frac{d_{out1}}{d_{in1}} = \frac{2H}{\Delta L} = \frac{2\left(k\,sin\alpha - k\sqrt{1 - \left(\frac{k\,cos\alpha + \Delta L/2}{k}\right)^2}\right)}{\Delta L} \tag{3}$$

The secondary displacement amplification was achieved at the lever mechanism. Output displacement d_{out1} of the rhombic amplifier is taken as input d_{in2} of the lever mechanism.

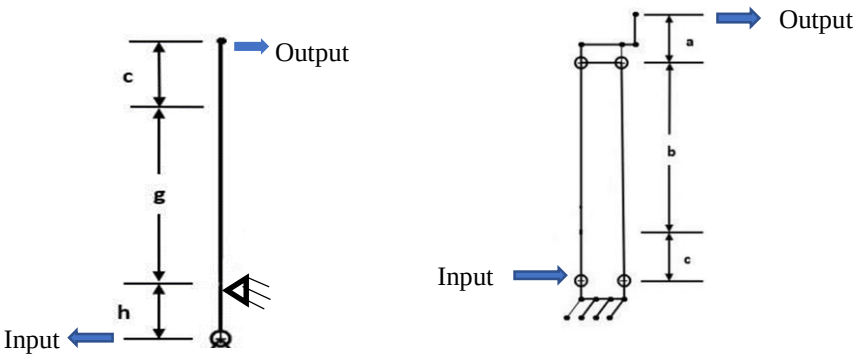


Fig.2.3. (a) First lever amplifier (b) Second lever amplifier

The output displacement of the lever can be calculated from Equation 4 and the amplification ratio can be calculated using Equation 5.

$$Amp_2 = \frac{d_{out2}}{d_{in2}} = \frac{c+g}{h} \tag{4}$$

$$d_{out2} = \frac{(c+g)d_{in2}}{h} \tag{5}$$

Output displacement d_{out2} of the lever mechanism was applied to the input d_{in3} of the levered parallelogram mechanism. This mechanism works as the third stage displacement amplification. The output displacement of the levered parallelogram can be calculated from Equation 6 and the amplification ratio can be calculated from Equation 7.

$$d_{out3} = \frac{(a+b)\, d_{in3}}{c} \tag{6}$$

$$Amp_3 = \frac{d_{out3}}{d_{in3}} = \frac{a+b}{c} \tag{7}$$

Combining Equations 3, 5, and 7, we can get the total displacement amplification as,

$$Amp = Amp_1 \times Amp_2 \times Amp_3$$

$$= \frac{2\left(k\sin\alpha - k\sqrt{1-\left(\frac{k\cos\alpha + \Delta L/2}{k}\right)^2}\right)(c+g)(a+b)}{\Delta L\, h\, c}$$

3. Geometrical Modeling and Design Parameters

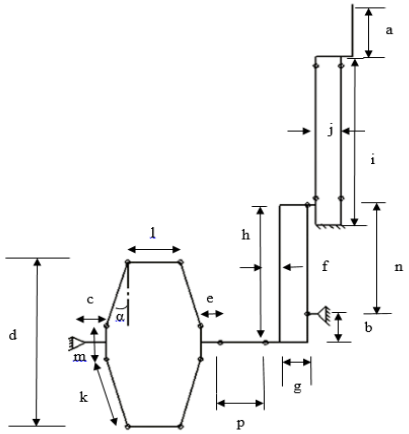


Fig.3.1. Geometrical model of the microgripper

Table 3.1. Design parameters (All lengths are in mm)

Parameter	Value	Parameter	Value
k	7.159	h	20.20
b	6	i	27.5
c	3	j	5
l	7.5	a	12.8
e	3	d	20
f	1.5	m	6
g	5	α	12.095°
p	6	n	14.2

The thickness of the microgripper = 10 mm

4. Finite Element Analysis

Static structural analysis traced the response of components under static loading, focusing on deformations, stresses, and strains. Then stress and deformation analysis in the compliant microgripper using ANSYS-a finite element tool. The material (Aluminum 7075-T651) is selected in ANSYS Workbench 23, followed by meshing, applying boundary conditions, and performing the analysis. In this study, 0.60 mm of element size is taken for meshing. The mesh model of a flexure-based compliant microgripper is observed to have 329616 nodes and 69282 elements. Necessary boundary conditions had been set before simulating the. Fixed support was applied in 12 holes in the base of the microgripper. 30 µm input displacement was used along the z-axis to imitate a piezoelectric actuator's action. The SA050520 stack actuators from PiezoDrive are high-performance multilayer actuators with polymeric coating for increased reliability and protection. These were designed for long-range, high-force, nanometer resolution, and high-speed applications. The actuator of this particular study had a dimension of 5x5x20 mm. The following figures are the input and output results of deformation and von-mises stress from the analysis:

The total deformation of the flexure-based compliant micrograpper involves plastic and elastic deformations, which depend on the type of material and mechanical behavior. For instance, with a 30-µm input displacement, there was a deformation of 311.64 µm. The amplification ratio is above 10. Again from the von-mises stress analysis, it is found that the maximum stress is 220.46 MPa which indicates that the mechanism is rigid and the safety factor is found to be 2.282.

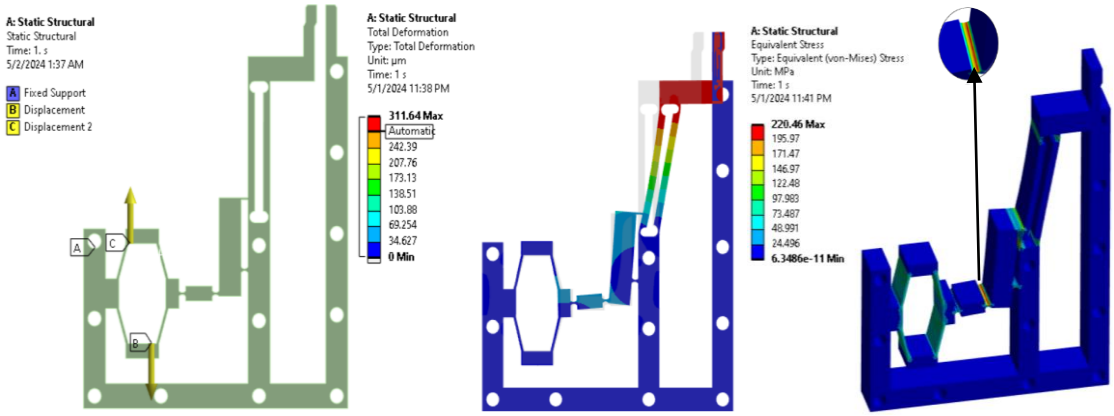


Fig.4.1. Boundary condition, deformation, and stress analysis of asymmetric micrograpper

5. Modal Analysis

Modal analysis is a means of studying the natural frequencies, mode shapes, and other dynamic characteristics of a structure, usually through the use of software such as ANSYS Workbench. This helps in designing the structure to minimize unwanted vibrations, enhance durability, and improve efficiency. A structure vibrates at natural frequencies that depend on loads, boundary conditions, mass, and stiffness. The natural frequency of the micrograpper from this study was 445.01 Hz.

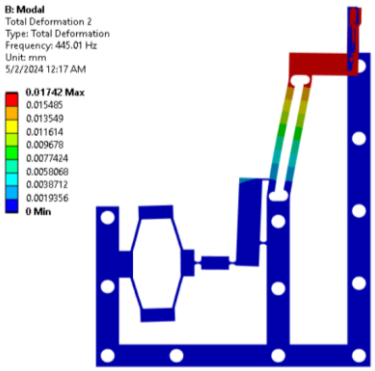


Fig.5.1. Modal analysis of compliant micrograpper of frequency 445.01 Hz

6. Effect of Variation of Leaf Flexure Thickness

Results are given in this graph about the influence of thickness on results. The thickness of the hinges are 0.40, 0.50, 0.60, 0.70, and 0.80 mm.

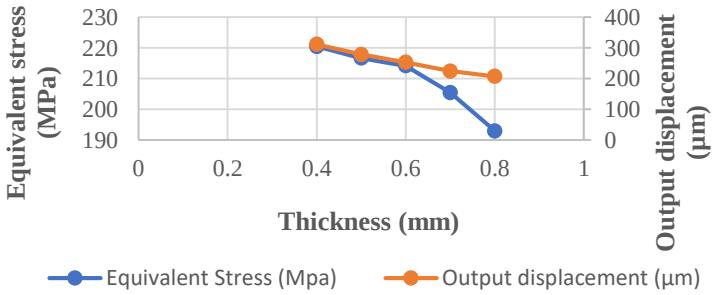


Fig.6.1. Thickness vs. equivalent stress & output displacement for leaf flexure

By increasing the thickness, with the same input displacement, the displacement of the output decreases. More thickness increases the stiffness; hence, it deforms less, and equivalent stress decreases due to the bigger area, which again restricts the output motion.

7. Parasitic Motion of the Microgripper

The parasitic motion occurs when x-direction jaw motion results in undesired y-direction movement. A jaw motion of 306.9 µm was obtained from a 30 µm input displacement, while experiencing an average parasitic motion of 2.6964 µm in the y-direction, giving a parasitic motion of 0.87%.

8. Conclusion

In this work, a multi-stage flexural-based asymmetric microgripper for precision tasks had been successfully designed. With PZT actuation, it contains a lever mechanism, a rhombic amplifier, and a levered parallelogram in its design. The jaw displacement achieved by the design is 311.64 µm with only 0.87% parasitic motion to offer stability and effectiveness in object manipulation. Meanwhile, the modal analysis confirms dynamic stability, with a first natural frequency of 445.01 Hz. The robust design is well suited to high-precision applications, including microsurgery, micro-assembly, and biomedical manipulation tasks.

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