Design and Analysis of Monolithic Microgripper

R.Bharanidaran, T.Ramesh

Abstract—Precision industries require high precision and controlled motion of microgripper. For this purpose compliant mechanism based monolithic microgrippers are used. In this study, a monolithic microgripper is designed adopting topological optimization method. MATLab code has been developed to derive the optimized shape of the monolithic microgripper. Post optimization process was carried out to overcome the manufacturing difficulties. Thickness of the microgripper was then designed using finite element method (FEM) to avoid out of plane sagging caused by the self-weight of the microgripper. The structural analysis using FEM was performed to obtain the Geometrical Advantage (GA) of the design. The proposed design of the microgripper proves that the out of plane motion is completely controlled as the thickness of the gripper is optimized and provides a better GA compared to the earlier designs found in the literature. This kind of design may be helpful to the designers who expect the gripping devices to be used in the situation where a minimum out of plane motion is required.

Index Terms— compliant mechanism, FEM, microgripper, topological optimization.

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1 INTRODUCTION

MANIPULATING the micro sized objects with high precision is the challenging task of the precision industries. Presently, large attention is drawn towards the design and fabrication of micro manipulating devices. Micro manipulating devices are to be designed in such a way that they are monolithic in shape and material compliance should be utilized in order to avoid wear and frictional error caused by traditional revolute joint. This will emphasize that the compliant monolithic microgripper can be precisely controlled in its motion. Literatures revels that there are many research works have already been carried out in the field of compliant mechanism and brought out various approaches and methodologies in designing the microgripper. Topology optimization [1], kinematic linkage model [2], intuitively [3] and pseudo rigid body model (PRBM) [4, 5] are the various techniques utilized by the researchers for developing their own designs of the microgripper. Among the various techniques, topology optimization is an efficient way of designing a compliant mechanism for multi-objective problems.

In this research work, an attempt has been made to design a monolithic microgripper adopting topology optimization method, and Solid Isotropic Material Penalization (SIMP) based method is used as the solver for the algorithm [6]. A MATLab code has been developed by modifying the 104 line MATLAB code [7] to design the compliant mechanism based microgripper. The topological design generated through the MATLAB program is not suitable for manufacturing. It requires post optimization are to be carried out so that the feasibility of the design proposed by the MATLab program could be utilized in the device. The concept of Post optimization is discussed in Ref. [8] in a detailed manner.

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- *R.Bharanidaran is currently pursuing doctoral degree in The Department of Mechanical Engineering in National Institute of Technology, Trichirappalli-620015, India. E-mail: bharanidaran123@gmail.com*
- *T.Ramesh is currently working as an Assistant Professor in The Department of Mechanical Engineering in National Institute of Technology, Trichirappalli-620015, India. E-mail: tramesh@nitt.edu*

Out of plane sagging of the design due to its self weight can cause severe problem in the precision motion of the microgripper. This effect may cause the gripper to bend and leads an inaccurate motion of the gripper. Hence, this could be reduced or eliminated to a safer level by optimizing a suitable uniform thickness of the gripper design [13].

The effect of self weight in the structure can also be included in the topological optimization technique. It generates an equivalent topologically optimized design which can have the capability of resisting the effect of out of plane sagging of the microgripper [14]. Topological optimization technique can also be employed to design a three dimensional geometry [15]. But once again the developed three dimensional topology design leads to manufacturing difficulties. In this study, another trial and error method after post optimization technique has been used to find optimum uniform thickness for the microgripper.

2 DESIGN OF MICROGRIPPER

Developing the design of highly controlled and precision microgripper must consider various design factors such as accuracy of motion and resolution of jaw movement, geometrical shape, and weight of the microgripper, grasping force of the jaws on the micro object, and importantly electrostatic force. In micro components, the electrostatic force is larger than the inertial force so it is to be included in the design process [9, 10]. From topology optimization method, two dimensional mechanism designs can be achieved, since thickness also important for high precision motion; appropriate uniform thickness can be found through minimizing the deformation due to self weight.

2.1 Topology Optimization

Topology optimization is the effective way of designing the compliant mechanism. SIMP method is used to solve the topology optimization problem. Here, limited volume of material is distributed over the design domain subjected to objectives and boundary conditions. The Figure 1 shows the initial structural design domain Ω, for microgripper compliant mechanism. Initial configuration of the design is considered as two

segments that the left side (the shaded portion) is for having the complete mechanism design and the right side (white area) is having jaws for exhibiting the output motions of the mechanism. The jaws length, the gap between the jaws is treated as the variables that can be freely modified according to the required size of the object. The objective function of the optimization here is to maximize the work performed on the spring that is maximizing the output displacement [8].
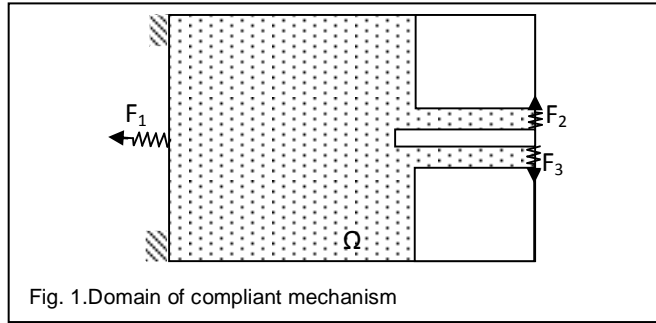

Fig. 1.Domain of compliant mechanism

Figure 1 shows the detailed information about the design domain with the applied forces and the necessary boundary conditions. Unit force F_1 is applied at the input spring. The objective function is to obtain a maximum output force F_2, and F_3 that is maximum output displacement U_{out}, at the output spring.

Topology optimization problem is written as;

Max (x):

$$-U_{out} = F_3{}^T U_1 - F_2{}^T U_1 = \Sigma_{e=1}^{n} [(x_e)^p u_3{}^T k_0 u_1 - (x_e)^p u_2{}^T k_e u_1] \qquad (1)$$

Subject to:

$$\frac{V(x)}{V} \leq f \qquad (2)$$

$$KU = F \qquad (3)$$

$$0 \leq x_{min} \leq x \leq 1 \qquad (4)$$

Where

U, F and K are global displacement force and stiffness matrix, respectively

k_e, u_e, are the elemental stiffness matrix, respectively

K_0 is the local stiffness matrix

N number of elements

p is the penalization power

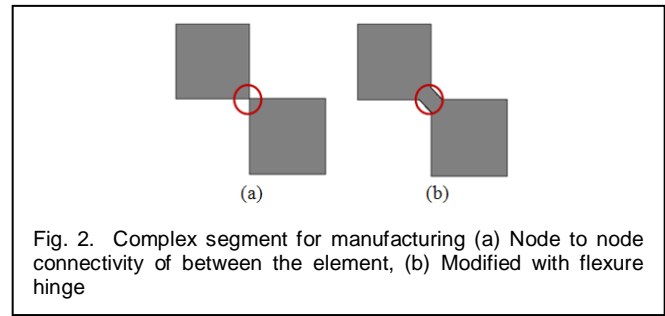V (x) and V is the material volume and design domain volume, respectively

f (volfrac) is the prescribed volume fraction

Initially the design domain is discretized and x is the design variable, x_{min} vector of minimum element relative density and other material properties are assumed as constant. This method, It distributes the material over the domain as relative density of the material that is, where the material is required to be presence the density is taken as 1 and where it is not, the density is considered as 0.001 [7].

2.2 Post design optimization

From the manufacturability perspective, the solution obtained through MATLab is required to be processed. For example, the Figure 2(a) shows the node - node connectivity developed in MATLab, which is not a sensible connection in practice. It requires a post design processing hence, modify the design with flexure hinges in the area where node to node connectivi-

ty are generated in the topological design as shown in Figure 2(b).

Fig. 2. Complex segment for manufacturing (a) Node to node connectivity of between the element, (b) Modified with flexure hinge
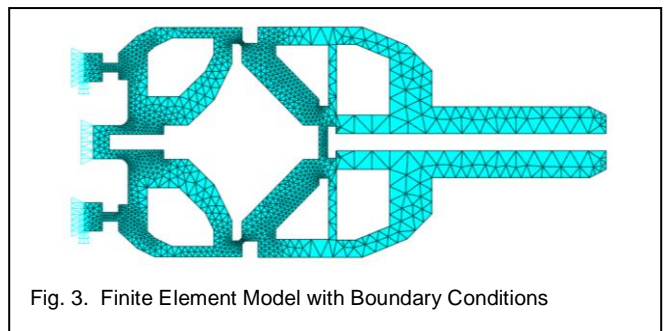
2.3 Optimization of uniform thickness

To optimize the uniform thickness for the proposed design, the effect of self weight in the structure is performed using ANSYS, a Finite Element Method software package. Solid model of the design is developed in the ANSYS software. Thickness of the microgripper is permitted to vary from 1 mm to 10 mm, to find the optimum uniform thickness of the gripper. The material considered for this analysis is bio-compatible stainless steel type 304 (Ref: Table 1 for the material properties) and it can also be used in the area of tissue engineering.

The solid model of the design is meshed with the 10 node tetrahedron element. The gravitational constant of 9810 mm/s² is set as input parameter. Analysis is carried out for all thicknesses of the microgripper.

TABLE 1
MECHANICAL PROPERTIES STAINLESS STEEL-304

Symbol	Property	Magnitude
υ	Poisson's Ratio	0.3
E	Elastic Modulus	1.93×10^5 N/mm2
ρ	Density($\times 1000$ kg/m3)	8×10^{-6} kg/mm3

Fig. 3. Finite Element Model with Boundary Conditions

2.4 Structural Analysis

Structural analysis of microgripper is performed to study the deformation characteristic and to find the geometrical advantage of the proposed design. Finite element model of the gripper and the introduced boundary conditions are shown in Figure 3. The geometrical advantage (GA) of the topological design of the microgripper is measured from the movement of the holding jaws for the applied input displacement of 1 micron in negative x direction (pulling force).

3 RESULT AND DISCUSSION

The output window of the MATLAB code returns the optimized design of microgripper for the given initial design as shown in Figure 4.

From the manufacturing perspective, the MATLab generated design has node to node contact as shown in Figure 5(a), it is impossible to develop using any of the manufacturing processes and it also affects the smooth transfer of load from a member to another. So, the locations where the node to node contact segments generated in the optimized solution are modified as mechanical flexure hinge as illustrated in Figure 5(b). Post optimized model of the gripper is shown in Figure 6.
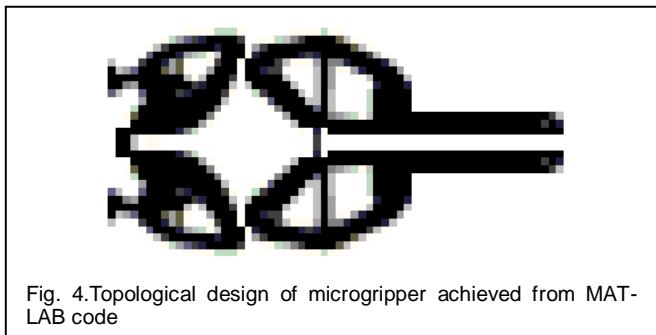

Fig. 4.Topological design of microgripper achieved from MAT-LAB code
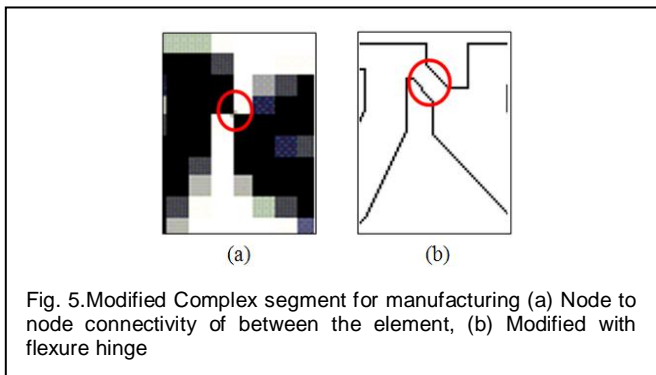

Fig. 5.Modified Complex segment for manufacturing (a) Node to node connectivity of between the element, (b) Modified with flexure hinge
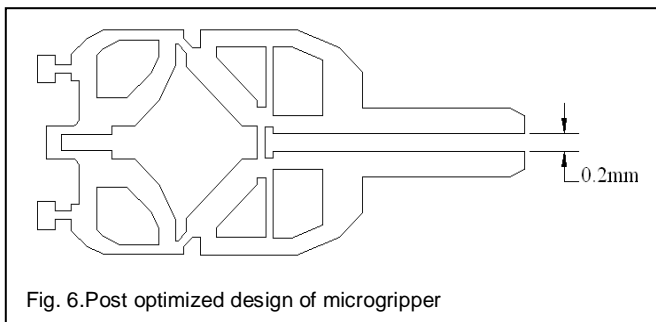

Fig. 6.Post optimized design of microgripper

The effect of self weight is analyzed in the structure and the out-of plane motion characteristic is also observed. The effect of thickness of the gripper against the maximum deformation in out – of plane due its own weight is observed and illustrated in Figure 7. It is observed from the plot, the percentage of variation of the out – of plane motion of the gripper surface is calculated and it reveals that the thicknesses 0.5mm and 0.6 mm produces a minor deformation out-of the plane. It is found from the graph that during the increases in the thickness of the gripper, the out-of plane motion is further reduced,

but the percentage deviation is reduced and further it indicates that there is no significant effect in the percentage deviations in the value of the out-of plane motion. Hence, it is concluded that the thickness value falling between 0.5 mm and 0.6 mm will be considered as the optimum thickness of the gripper.
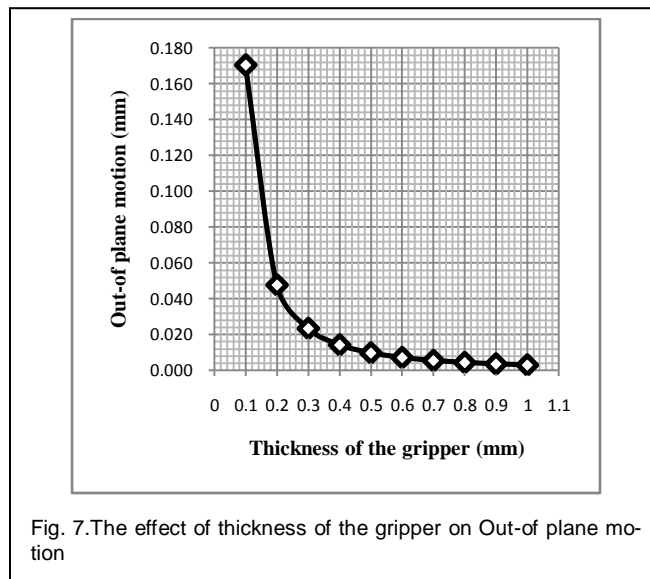

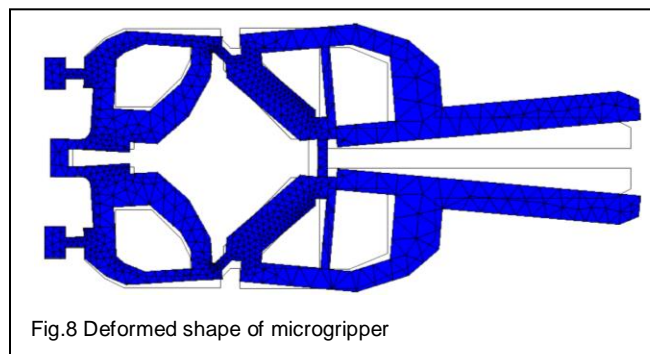Fig. 7.The effect of thickness of the gripper on Out-of plane motion
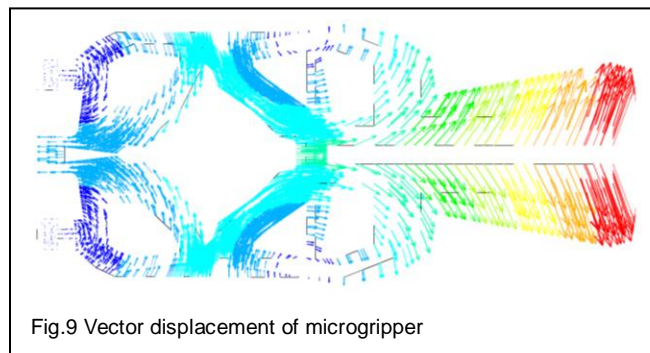

Fig.8 Deformed shape of microgripper

Fig.9 Vector displacement of microgripper

Structural analysis of 0.5 mm thickness microgripper shows that one jaw of the gripper moves to a maximum of 0.0065 mm and the overall opening of the jaws are measured as 0.0130 mm as shown in Figure 8. The Geometrical Advantage of the microgripper is calculated as;

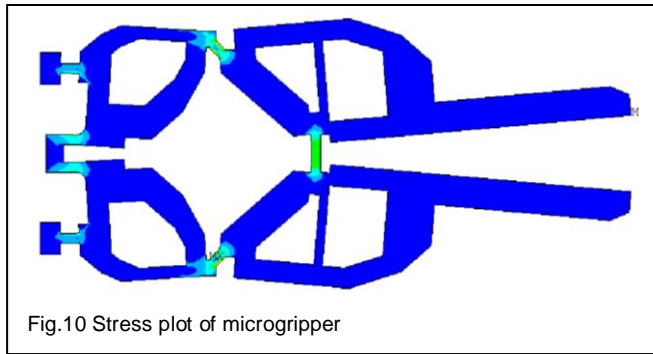$$GA = \frac{output\ displacement}{input\ displacement} = 13.0$$

Fig.10 Stress plot of microgripper

Figure 9 shows the vector plot of the displacement which gives the knowledge on how the rotary motion is developed in the mechanism with respect to flexure hinges. Flexure hinges act as a pin joint in this compliant mechanism. Figure 10 shows von-misses stress developed in the design, maximum stress occurs at the flexure hinge region and the value is lower than the yield stress which shows the conformity of the design.

5 CONCLUSION

The proposed optimum design has passed through various steps, which enhances the effectiveness of microgripper design in many aspects. The initial design domain is optimized to achieve the mechanism topology. The optimized result provides the knowledge of the motion of links in the design. The optimized result required to be modified from the manufacturing aspects, Post optimization was carried out in the design to achieve the manufacturing feasibility. To add thickness for the design, the optimum thickness is found from the deformation results of self-weight analysis for various thicknesses. Microgripper was further analyzed structurally for the input displacement, the output displacement of jaws are measured. Geometric Advantage of the design shows the promising value of the proposed design. Scaling the dimensions to macro level, it can be used where the large displacement is required.

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