A numerical approach to design a compliant based Microgripper with integrated force sensing jaw

R. Bharanidaran and T. Ramesh

Abstract**—**Technological advancement in precision industries generates enthusiasm in engineers and scientists. Microgripper is an elementary device in precision manipulation of micro-objects. For precision manipulation of micro devices or micro assembly of components, the design of microgripper is a challenging task. Design of mechanism influenced micro devices are required new methodology. In this research work, an attempt has been made to develop a new compliant mechanism design of microgripper with force sensing jaw. Topology optimization technique has been used to derive the conceptual design of mechanism of microgripper. This conceptual design is post-processed, that is, the flexure hinges and smoothened edges are introduced in the senseless regions suitably to achieve the final design. Gripping force acting on the object is calculated introducing a cantilever jaw. Deflection of cantilever jaw is directly proportional to the gripping force acting on the object. A detailed study of the flexible cantilever gripping device and its behavior with various parameters of circular flexure hinges is performed and the gripping force is measured through finite element software ANSYS Workbench. First natural frequency of the micro gripper and out of plane sagging due to the self weight of the micro gripper is measured to ensure the effectiveness of design.

Keywords**—**Cantilever Jaw, Compliant mechanism, Finite Element, Flexure hinges, *M*icrogripper, Topology optimization.

I. INTRODUCTION

PRECISE manipulation of micro objects in micro assembly is the challenging task for the precision industries. Microgripper is the key component in micromanipulation of object sizes ranging from micro to nano meters. Design of microgripper must consider microphysics. The Physics involved in micro engineering is different from the physics of Macro Engineering. Effect of Surface forces dominants than the inertial forces of the devices [1]. Few researches have been carried out by considering surface forces of micro and nano devices [2]. In this work, size of the microgripper is in millimeter. Hence the microphysics is influenced negligible.

The motion of the microgripper is required to be precise and controlled. Conventional joints have many drawbacks such as backlash, wear, manufacturing error, assembly error, hard to manipulate in small range and frictional losses. Hence, it is not suitable for micro manipulating devices. Flexure hinges are the best one which replaces the conventional joints effectively in every the aspects. Flexure hinges are the regions that undergo limited rotation due its elastic and geometric properties [3]. To have monolithic design of microgripper (by means of compliant mechanism) various design approaches are employed such as Mechanism synthesis [4], [5], pseudo rigid body model [6], [7], [8], optimization technique [9], inverse methods [10] and intuitively [11], to name a few.

In this paper, a compliant mechanism has been designed through the topological optimization technique. Topology optimization is a technique that yields the primary design of compliant mechanism. This primary design suggested by the optimization technique is impossible to manufacture. Hence post optimization [12] is carried out. In this paper, post optimization technique is used to refine by varying flexure hinge parameters. Effects of flexure hinges in the microgripper design are evaluated through structural analysis performed using finite element software package. Finite element method (FEM) is the powerful method to evaluate the structural behavior of the micro structure [1].

Micro cantilever is explicitly used as sensor for various purposes like biosensor [20] force measuring sensor and so on [13]. In this research work cantilever mechanism is used to measure the griping force. Deflection of cantilever beam can be analyzed by various methods such as visually using microscope, theoretically, considering non-linear case neural network [19] and numerically using FEM. Gripping forces are analyzed against the flexure hinge parameters utilized for the arrival of gripping device design through FEM.

Free vibration analysis is performed to find the natural frequency [18]. Natural frequency and corresponding mode shapes are significant criteria to consider in the design stage to ensure safety. Fundamental frequency (first natural frequency) is the first resonance of the structure. When exciting frequency matches to natural frequency of the structure resonance occurs. Hence fundamental frequency should be high for microstructure.

Out of plane sagging in the microstructure must be avoided to attain a precise manipulation. Hence, Self weight of the micro structure is considered as other important criteria in the design and self weight analysis is carried to find the value of

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out of plane sagging [21]. The design process is clearly shown in the flow chart as shown in Figure 1.

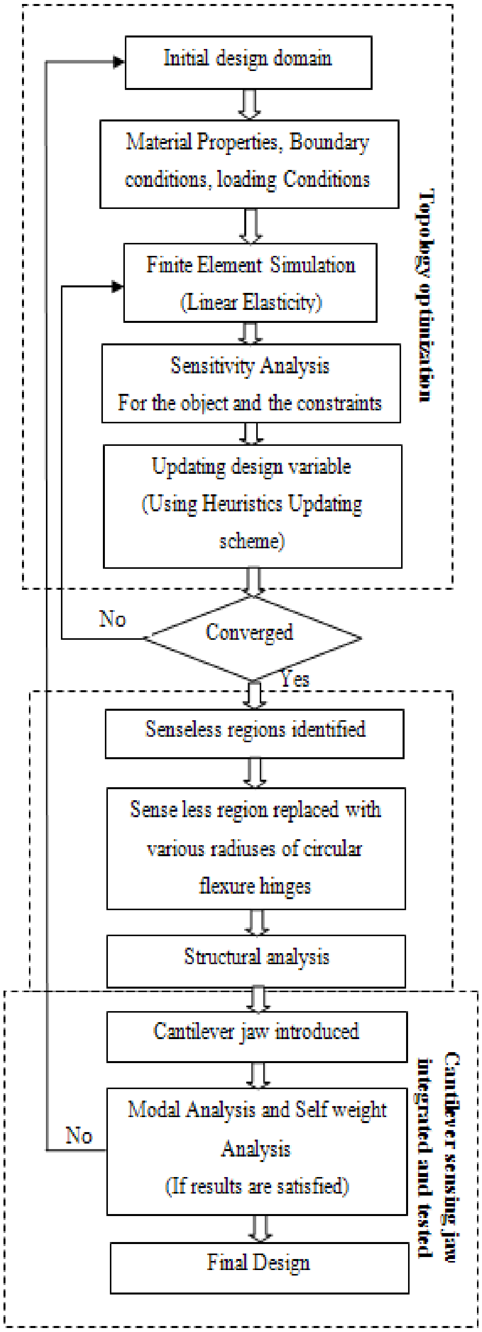


Fig.1 Design methodology of compliant mechanism based microgripper

II. DESIGN OF MICROGRIPPER

Designing a microgripper is an interesting and challenging task of the designer working in micro scaled objects. The mechanism part involved in the microgripper has many aspects of microphysics. It is tough to design, manufacture and assemble a component at micron level. Hence, a compliant based mechanism design is an appropriate technique for evolving the designs of micro sized components.

Primary design of compliant mechanism is developed using topology optimization code. An open source for mechanism design developed in MATLAB [9] is modified according to the requirement of the design. Output of the MATALB provides the scheme of the mechanism. In general, mechanism is made of links and joints. Number of links, number of joints and length of the links required for formulating the mechanism are found from the MATLAB output.

The conceptual design generated in the MATLAB is required to be post processed to fulfill the requirements of manufacturability of the design [12]. Hence, the flexures are introduced in the conceptual design of gripping device to overcome the manufacturing difficulties. Flexures are responsible for the controlled and precise motion of microgripper. The selection of a suitable flexure requires high attention. Gripping force and geometrical advantage of the microgripper are the key parameter in this design. These parameters are tested by varying radius of flexures design. In the final design, first natural frequency and out of plane sagging due to its self weight are computed through Finite Element Method.

A. Topology Optimization

Topology optimization is the logical method of obtaining the compliant mechanism design. In this optimization method, the initial design domain is topologically optimized to attain the objective subject to the constraints considered for optimization. The main Objective of the problem is to maximize the mutual potential energy (MPE) of the mechanism.

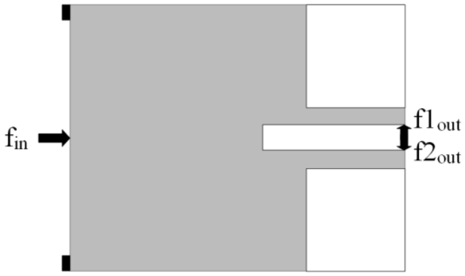


Fig.2 Initial design Domain

The MATLAB code developed by O. Sigmund [9] is modified according to the requirements of the design domain and the necessary constraints are considered in this research work to arrive with an appropriate shape of the microgripper. The initial design domain is dicretized into 2400 finite number of elements (60 number of elements horizontally and 40 numbers of elements vertically are considered). Solutions of the initial design domain for the given boundary conditions are achieved using finite element method.

Solid Isotropic Material with Penalization (SIMP) approach has been used by O. Sigmund [9] and he has used the Optimality criteria method to solve the optimization problem. SIMP method was an alternate approach to other methods of topology optimization such as homogenization method. In SIMP method, ‘E’ is Young’s modulus depends on density, young's modulus 'E_0' is assumed as 1 and uses penalization 'p' to make intermediate densities 'ρ'.

$$E_i = \rho_i^p E_0 \qquad (1)$$

In this work, another key input parameter considered by the author is the percentage of material volume reduction and in his work he has permitted to reduce 60% of material from the initial volume. The initial design domain considered in this research work is shown in Figure 2. The design domain is treated as two regions, lengthy jaws in right side and actuation mechanism in the left side. This design gives handiness in changing the geometrical parameter of the jaws. That is, length and shape of the jaw can be modified according to the requirement. Jaws of the gripper exert force f_{1out} and f_{2out} when f_{in} is applied at the input port. Applied forces (input) are amplified in to ten times.

Topology optimization problem is formulated as per the given equation (2).

Maximize:

$$-MPE = U_1^T K U_2 = \sum_{e=1}^{N} (x_e)^p (u_{e2}^T k_0 u_{e1} - u_{e3}^T k_0 u_{e1}) \qquad (2)$$

Subject to : $V(x)/V_0 = f$

: $KU = F$

: $0 < x_{min} \le x \le 1$

Where

U - Global displacement vectors

F - Global force vectors

K - Global stiffness matrix

u_{e1} - element displacement vector due to input port

k_e - Stiffness matrix of the element

u_{e2} - element displacement vector due to $f1_{out}$ output port

u_{e3} - element displacement vector due to $f2_{out}$ output port

x - Vector of design variables,

x_{min} - minimum relative densities (In the MATLAB program, non-zero value has been assumed to avoid singularity)

N - Number of elements

P - Penalization power (typically p = 3)

V(x) - material volume

V_0 - design domain volume

F (volfrac) - volume fraction

The heuristic updating scheme for the design variables x is done by the algorithm as follows [9]:

$$x_e^{new} =$$

$\max(x_{min}, x_e - m)$

If $x_e B_e^{\eta} \le \max(x_{min}, x_e - m)$,

$x_e B_e^{\eta}$

If $\max(x_{min}, x_e - m) < x_e B_e^{\eta} < \min(1, x_e + m)$,

$\min(1, x_e + m)$

If $\min(1, x_e + m) \le x_e B_e^{\eta}$

Where

m (move) - positive move-limit

η (= 1/2) - Numerical damping coefficient and

Be is found from the optimality condition as

$$B_e = \frac{-\dfrac{\partial c}{\partial x_e}}{\lambda \dfrac{\partial V}{x_e}}$$

λ is the lagrangian multiplier that can be found using bi-sectioning algorithm.

The sensitivity of objective function can now be found as;

$$\frac{\partial u_{out}}{\partial x_e} = -p\,(x^e)^{p-1}(u_{e2}^T k_0 u_{e1}) + p\,(x^e)^{p-1}(u_{e3}^T k_0 u_{e1}) \qquad (3)$$

The mesh-independency filter works by modifying the element sensitivities as given in equation 4:

$$\frac{\hat{\partial c}}{\partial x_e} = \frac{1}{x_e \sum_{f=1}^{N} \hat{H}_f} \sum_{f=1}^{N} \hat{H}_f x_f \frac{\partial c}{\partial x_f} \qquad (4)$$

The convolution operator (weight factor) $\hat{H}_f$ is written as

$$\hat{H}_f = r_{min} - \mathrm{dist}(e,f),$$

$$\{f \in N \mid \mathrm{dist}(e,f) \le r_{min}\},\ e = 1, \ldots, N$$

Where

dist (e, f) - the distance between centre of element e and

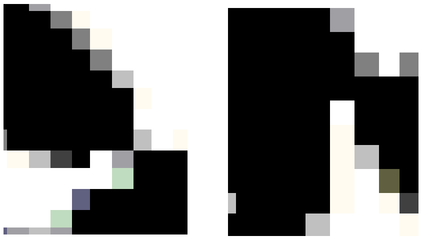

(a) (b)

Fig.3 Senseless regions developed from MATLAB program

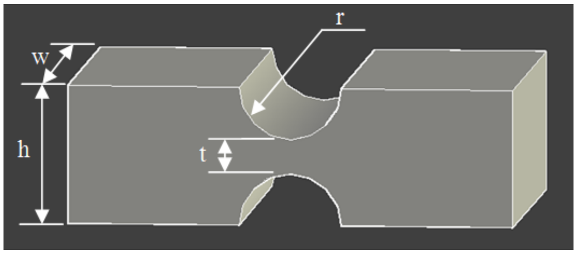


Fig.4 Circular flexure hinges

centre of element f.

$\widehat{H}_f$ - Convolution operator f is zero outside the filter area. The convolution operator decays linearly with the distance from element f.

In a general form, filtering is known as applying a mathematical operator to some value like the density, the gradient of the objective function or any other variable [23]. For a smoothened the spatial variation of the design variable in the topological optimization, an operator that prevents fast variations of the filtered variable should be applied.

B. Post optimization process

Topologically optimized design is developed using MATLAB. It is clearly understood from the output results of the MATLAB code that the design is highly impossible to manufacture it directly due to the senseless regions developed as a part of MATLAB output as illustrated in Figures 3(a) and 3(b).

The optimization algorithm assigns design variable value to elements. The single finite element has the value of design variable between 0 and 1. Hence, optimized designs with senseless regions are unavoidable in this technique. There are two possible senseless region developed in the output of the algorithm. A staircase effect that can be suitably replaced using smooth edges and Node to node contact occurs in the output as shown in Figure 3(a). Node to node contact arises in this mechanism design technique where two links need to be connected by means of pin joint. This can be replaced by providing suitable flexure hinges.

Flexure hinges are slender region where adjoining members in the component are connected and permits a limited relative rotation. Rectangular contour [5], Conic section contour [14] and polynomial contour [15] are the various flexure hinge contours that could be used to replace the senseless regions during post processing stage. In this research work, circular contours are introduced explicitly at the locations where senseless regions were developed in the MATLAB output of the design to make it convenient to be manufactured. Precision of the circular flexure hinges is higher than that of the other flexure hinge contours. Shift of center of rotation axis in the circular hinges are lesser than other contour flexure hinges [16]. The material flexibility at the sensible regions of the microgripper and its behavior are analyzed by varying the radius of the circular hinges from 1.5 to 3.0 mm in steps of 0.5mm.

This paper investigate by varying radius parameter circular flexure hinges as shown in Figure 4 considering other parameters width (w), height (h) and thickness of web (t) as constant. Rotation or bending of the flexure hinges are mainly depends on radius of the flexure hinges. Hence, Radius parameter of the circular hinges is varied from 1.5, 2.0, 2.5, and 3.0.

Stiffness parameter (K) of the circular flexure hinges could be calculated using equation 5 [22];

$$K = \frac{9\pi r^{(\frac{1}{2})}}{2Etw^{(\frac{5}{2})}} \tag{5}$$

Where,

E – Young’s modulus of the material
t – Width of the notch
b – Thickness
r – Radius of circular notch

Gripping force required to be measured precisely. Hence this work introduces the cantilever behavior in one of the microgripper jaw. Deformation is measured through FEM, calibrated and processed to calculate the gripping forces. For better sensitivity, flexure hinges are introduced in the cantilever jaw instead of uniform cantilever beam [13]. Right circular flexure hinge is designed in the beginning of gripping jaw to attain maximum precision in the deflection. Cantilever jaw deflects more than the other jaw. And the deflection of the cantilever jaw is proportional to the gripping force act on the micro object. For various input displacements the gripping forces were measured at the cantilever jaw.

C. Structural Analysis

Static behavior of the post processed model is evaluated through ANSYS Workbench at the time of gripping a micro object. Gripping force is measured for various radiuses of circular flexure hinges by grasping a spherical micro object between the jaws with the size of 2.5 mm radius. Image of the MATLAB output is imported into AutoCAD to make solid model by tracing a point cloud in the optimized design. Developed solid model is imported in to ANSYS Workbench to perform the structural analysis during gripping. The solid model is meshed with 4 node tetrahedron elements and the material chosen for the microgripper is stainless steel type 316 which is biocompatible in nature. Mechanical properties of SS 316 are given in Table I.

Spherical micro objects to be hold between the jaws of the microgripper are assumed as a rigid body in the analysis [17]. Suitable contact pair has been created between the jaws and micro object. To reduce the computation time, half of the model is considered by defining the required symmetric boundary conditions. Input load has been applied as a displacement of 10µm. Stress, Strain, Strain energy and Reaction forces are calculated for all the flexure hinges. Contact pressure is calculated between microgripper jaw and micro spherical object are calculated. This contact pressure is equal to the gripping force of the microgripper. For the entire flexure hinge radius gripping forces are calculated.

After finding the suitable flexure hinges, cantilever jaw is introduced by making circular hinge at the mechanism end. Deflection of this cantilever can also be measured using suitable vision based system and the gripping force is measured with respect to deflection.

Table I Material Property of SS 316

Material Properties

Density (kg/mm^3)	8.0x10^{-6}
Poisson's Ratio	0.30
Elastic Modulus (MPa)	193x10^3
Yield Strength (MPa)	205

D. *Modal Analysis of Micro Gripper*

Microgripper is experiencing a vibration during release of the object from the jaw. Hence, microgripper design is required to be investigated to find the first natural frequency [18]. In this research work, free vibration condition is assumed.

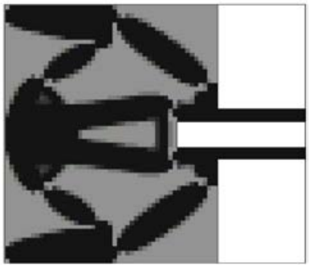


Fig.5 Optimized design domain through MATLAB

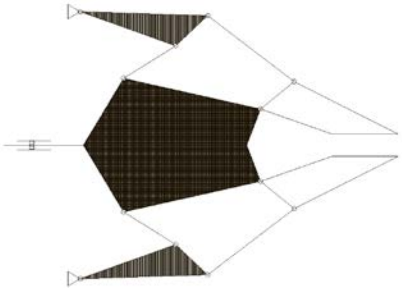


Fig.6 Equivalent kinematic model of the microgripper

Modal analysis is performed through Ansys finite element package to evaluate natural frequencies and mode shape of the microgripper. Finalized solid model of the microgripper is meshed using 10 noded tetrahedral elements which are commonly used for complex shapes. And the gripper is supported at handle and no load condition is considered. The mass and stiffness of the structure is used to find the natural frequency where it is naturally resonate. In this research work, Block Lanczos method used to extract first 10 Natural frequencies between 0 to 1MHz.

E. *Self-Weight Analysis of Micro Gripper*

Out of plane sagging due to its self weight of micro structure needs to be investigated through FEM. Because self weight leads to out of plane sagging, this affects precise motion of the gripper. Hence, Self weight study is also a significant factor in the design of microgripper [21]. Only gravitational acceleration is defined as input condition.

III. RESULT AND DISCUSSION

Topological optimization in MATLAB program was performed to optimize in the initial design domain subjected to the applied constraints. Output of the program provides the primary design of mechanism as shown in Figure 5. Materials are distributed according to the constraints and boundary conditions. Gray scale value shows the existence of the material in the output. In the Figure 5, Black color element exist where the design variable (x) is valued maximum and dilution of black color exist depends on the design variable (x) is valued minimum. Voids or no material existence is shown as a white color element.

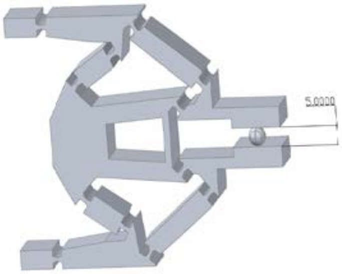


Fig.7 Solid model of the post processed microgripper

Figure 6 illustrate equivalent kinematic model of the topologically optimized mechanism design. The degree of freedom of the planar rigid body mechanism can be determined using Gruebler’s mobility equation as shown below;

$$M = 3(n-1)-2j-3g \tag{6}$$

Where

M – Degree of freedom or mobility of mechanism
n – Number of links
j – Number of lower pairs
g – Number of higher pairs

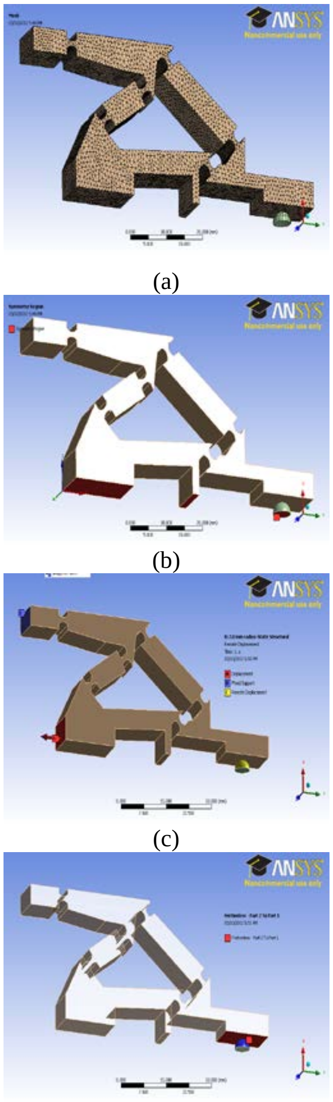
Degrees of freedom of the kinematic model shown in Figure 5 calculated as 2.

This optimized design domain consists of senseless regions. These senseless regions are developed due to lesser number of elements and shape of the element. Increasing the number elements and using other shape of elements may minimize this issue but cannot be uprooted. These senseless regions are replaced with right circular flexure hinges. From the kinematic model the position of flexure hinges easily identified as shown in Figure 6.

A. *Structural Analysis*

Structural analysis is performed in the post processed model as shown in Figure 7. Finite element model with all input conditions are shown in Figure 8. Figure 8(a) shows finite element model discretized with tetrahedron element, 8(b) shows the applied symmetric boundary conditions in red color, Figure 8(c) shows input conditions such as displacement, fixed support and remote displacement. Figure 8(d) shows the contact region (contact element). Remote displacement is applied to micro object as zero in rotation and translation.

Figure 9 shows the structural behavior of the microgripper with various radiuses of circular flexure hinges. Figure 9(a) shows that for the increasing radius of flexure, the equivalent von-misses stress reduced linearly due to the fact that the shift of center of rotation of axis in flexure hinges is relatively increasing with increasing radius.



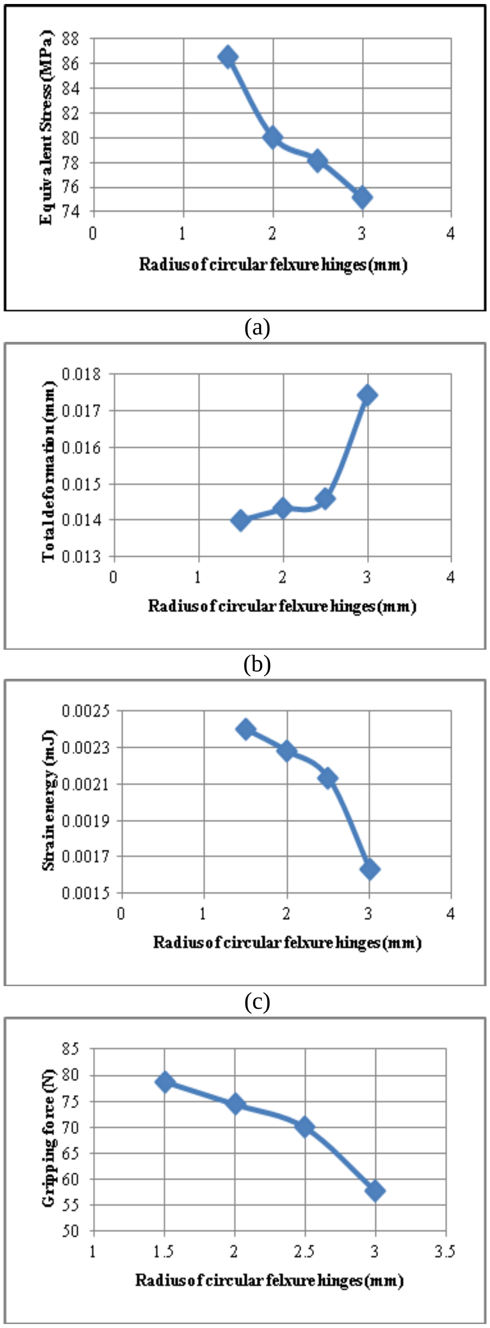
(a)

(b)

(c)

(d)

Fig.8 Finite element model with all input conditions (a) FE model (b) Symmetric region (c) input displacement and fixed support and remote displacement (d) contact between jaw and micro object



(a)

(b)

(c)

(d)

Fig.9 Structural behavior of microgripper with varying radius parameter of circular flexure hinges

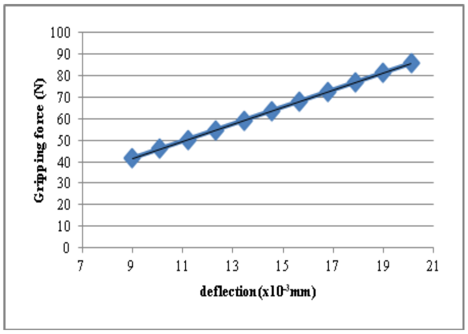
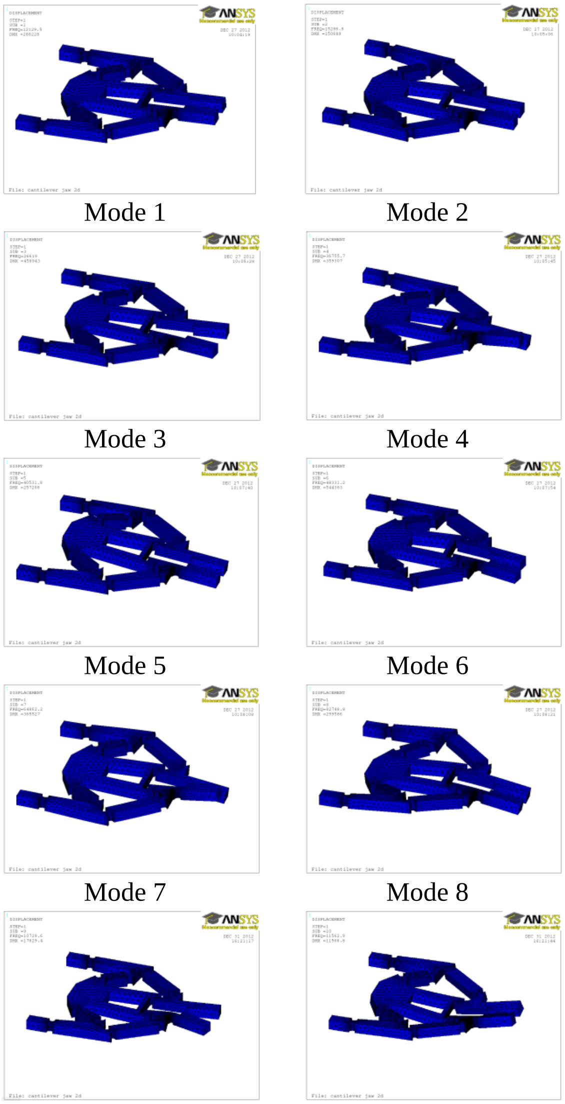


Fig.10 Plot between Deflection of cantilever jaw and gripping force exerted in that jaw

Figure 9(b) clearly reveals that the deformation increases with increasing the flexure radius as the web thickness varying minimally from the centre in larger radius of flexure. Figure 9(c) shows that the strain energy is decreasing with increase in the radius of flexure. Flexures flexibility also increases with increasing radius and is indirectly proportional to strain energy. Figure 9(d) indicates that the gripping force decreases with increasing radius of flexure hinge.Considering gripping force, equivalent Von-mises stress, and accuracy in motion (negligible shift in center of axis rotation) 1.5mm or 2mm radius can be better performer for the micromanipulation.

One of the microgripper jaws is modified as cantilever jaw with the length 18.5 mm. From the deflection of this cantilever jaw the gripping force can be measured. For various input displacement the deflection is plotted in the Figure 10. It clearly reveals that deflection increases linearly with increasing input force.



Mode 1
Mode 2
Mode 3
Mode 4
Mode 5
Mode 6
Mode 7
Mode 8
Mode 9
Mode 10

Fig.11 mode shape of the microgripper for the first 10 natural frequencies

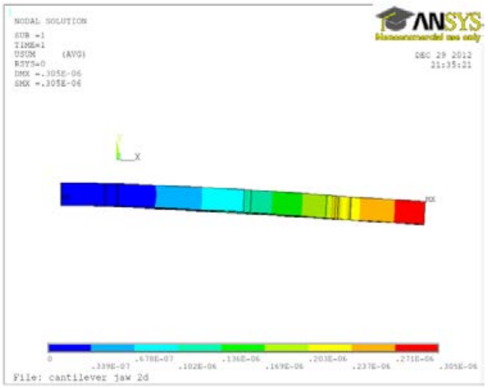


Fig.12 Deformation of the microgripper due to self weight

B. Modal analysis

Table II shows the extracted first 10 natural frequency through FEM. First natural frequency of the structure starts 1212.9 Hz. Microgripper is having high first natural frequency. This ensures the design of microgripper is dynamically acceptable. By scaled down the first natural frequency can be increased proportionally.

Figure 11 illustrate that the mode shapes of the microgripper when it subjected to free vibration.

Table II First 10 natural frequencies of the microgripper

Set	Time/Frequency (Hz)	Load step
1	1212.9	1
2	1528.7	1
3	2661.9	1
4	3675.6	1
5	4053.2	1
6	4833.1	1
7	6486.2	1
8	8274.9	1
9	10730	1
10	11563	1

C. Self weight analysis

Figure 12 shows that deformation due to self weight. The value of the deformation is $0.3\text{x}10^{-6}$. Since the structure of the microgripper is in millimeter size the deformation in out of plane can be neglected.

IV. CONCLUSION

In this work, new methodology is developed to design a microgripper. Mechanism designed systematically using topological optimization and Optimized topology is modified through post optimization technique. In post optimization technique senseless regions are replaced with flexure hinges. Due to high accuracy in motion, circular flexure hinges are used in the design of microgripper. Various radiuses of flexure hinges were investigated. Accuracy and gripping force developed are found to be high in smaller circular hinge radius. Force measuring cantilever jaw was introduced to sense the gripping force in the design. Relation between deflection and gripping force are also studied. Final design has high fundamental frequency and negligible deformation in the out of plane direction due to its self weight. Hence, this method of designing compliant based microgripper is significant and effective.

V. FUTURE WORK

Structural behavior of cantilever jaw can be analyzed for various hinges and generic form of equation can be generated. Various polynomial contours of flexure hinges can be introduced in the design to evaluate the accuracy variation.

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