Design of Compliant Mechanism Based Microgripper with Three Finger Using Topology Optimization

R. Bharanidaran and B. T. Ramesh

***Abstract*—**High precision in motion is required to manipulate the micro objects in precision industries for micro assembly, cell manipulation etc. Precision manipulation is achieved based on the appropriate mechanism design of micro devices such as microgrippers. Design of a compliant based mechanism is the better option to achieve a highly precised and controlled motion. This research article highlights the method of designing a compliant based three fingered microgripper suitable for holding asymmetric objects. Topological optimization technique, a systematic method is implemented in this research work to arrive a topologically optimized design of the mechanism needed to perform the required micro motion of the gripper. Optimization technique has a drawback of generating senseless regions such as node to node connectivity and staircase effect at the boundaries. Hence, it is required to have post processing of the design to make it manufacturable. To reduce the effect of post processing stage and to preserve the edges of the image, a cubic spline interpolation technique is introduced in the MATLAB program. Structural performance of the topologically developed mechanism design is tested using finite element method (FEM) software. Further the microgripper structure is examined to find its fatigue life and vibration characteristics.

***Keywords*—**Compliant mechanism, Cubic spline interpolation, FEM, Topology optimization.

I. Introduction

HIGHLY controlled and precised motion of manipulating devices is required in precision industries. Microgripper is a key part for manipulating the micro objects [1]. The design and development of microgripper has drawn more attention in micro manipulation research. Microgripper design should be included the physical nature of the micro sized objects to be handled such as shapes, fragile natured biological cells and bacteria [2], and changes in physics of micro sized components [3]. Therefore, the design of gripping devices and its mechanism at micro level has a potential research area attracted many academic as well as industrial researchers. Incorporating the conventional joints in the mechanism at micro level of microgripper leads to inaccuracy in motion due to backlash, wear, manufacturing error, assembly error and friction between the assembled parts. Drawbacks found in the conventional joints at precision and micron level motion suggests the designer to develop an alternate design methodology such as monolithic compliant mechanism. Compliant mechanism based design has a slender region called flexure hinges which allows a limited rotation between two rigid parts during bending. The control over precision motion of microgripper design is extremely depends on the kind of slender regions and their design [4]. Monolithic compliant mechanism design has been developed by adopting various approaches such as Mechanism synthesis [5], [6], pseudo rigid body model [7], optimization technique [8], inverse methods [9] and intuitively [10]. Among various methods highlighted in this research paper, optimization technique has proven that it is more general and efficient.

Topological optimization is a mathematical approach of developing a conceptual design of compliant mechanism [11]. It is solved effectively by using Solid Isotropic Material with Penalization (SIMP). Bendsoe and Sigmund [8] implemented SIMP or Power law interpolation approach alternate to a homogenization based method. In this technique, the material property is assumed as constant in all the elements of the discretized initial design domain. Element relative density is assumed as variable and raised to some power times. The heuristic optimization algorithm has been used to optimize the relative density of the element based on the objectives and constraints considered. For the distribution of density of the material over the domain, displacement is computed based on the Finite Element technique. Therefore, discretization of the continuous domain in to finite number of elements resulting few drawbacks that is known as senseless region which is impossible to manufacture. Senseless regions have stair case effects at the boundaries and node to node connectivity. Hence, it is required to perform post processing [12] to uproot the senseless regions. Other than mechanism design another important segment of the microgripper is jaws, which should be versatile to handle the asymmetric, spherical and cylindrical micro objects. Handling asymmetrical objects is complicated to use the device during surgery [13].

In this research work, many design aspects are considered to design a microgripper to handle the asymmetrical object. Compliant mechanism is designed through modified topological optimization technique and the functional design of gripper is made with three fingers, two as common holding finger and third one is to support from slipping of the object. The structural behavior of the microgripper is investigated through FE technique. Displacement, Stress, Strain developed

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in the device is studied and the fatigue life of the component is evaluated. Dynamic characteristics study is also carried out to find the natural frequency of the microgripper.

II. Design of Microgripper

A. Topology Optimization

Logical and conceptually simple method for designing a compliant mechanism is a topology optimization technique and it is performed by means of SIMP approach. In this approach, the material property such as young's modulus of the domain is assumed as constant for each element of the discretized design domain. Optimization variable considered in this research work is the element relative density. The discretization of the continuous domain results a senseless region in the optimized image. Hence, Bi-cubic spline Interpolation function is introduced in the MATALB code to minimize the effect of senseless regions. The design variable 'x' is interpolated using in-built cubic interpolation function in the MATLAB. These interpolation functions are smoothen the edges as a curve or straight lines and the node-to-node connectivity is replaced as small segment as shown in Fig. 3. MATLAB program for topology optimization developed by Sigmund, et.al [8] is modified according to the initial design domain, the necessary boundary conditions and the necessary interpolation function is introduced.

The initial design domain is planned according to the design requirement of the microgripper. Fig. 1 shows the initial design domain, input force $f1_{in}$ is introduced at left end of the domain and three output forces $f1_{out}$, $f2_{out}$ and $f3_{out}$ are demanded on the other end. Forces $f1_{out}$, $f2_{out}$ and $f3_{out}$ will be used to move the microgripper jaws. Hence, there are four forces acting on the domain and causes four displacements $u1_{in}$, $u1_{out}$, $u2_{out}$, and $u3_{out}$ in the design domain.

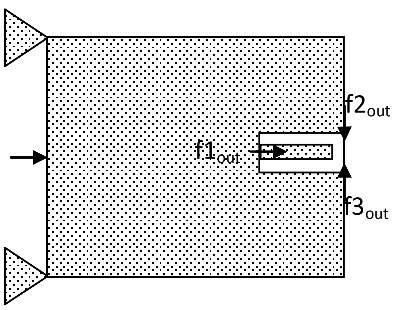


Fig. 1 Initial Design Domain

Hence, the Output displacement u_{out} is computed as

$$f_{o1}^T u_1 + f_{o2}^T u_1 - f_{o3}^T u_1 \quad (1)$$

The objective function of the Topology optimization problem is formulated as:

$$-u_{out}(x) = -f_{o1}^T u_1 - f_{o2}^T u_1 + f_{o3}^T u_1 \quad (2)$$

$$= \sum_{e=1}^{N} (x_e)^p \left(-u_{1oe}^T k_0 u_{1e} - u_{2oe}^T k_0 u_{1e} + u_{3oe}^T k_0 u_{1e}\right) \quad (3)$$

Subject to : $\frac{V(x)}{V_o} \le f$,

: KU = F,

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

U, K, and F - global displacement, stiffness matrix and force vectors,
x - Design variable,
p - The penalization power,
N - Number of elements used to discretize,
V and V0 - Material volume and design domain volume,
f - Volume fraction.

Input for the MATLAB program such as number of elements (70 x 60), the percentage of volume reduction (60%) and penalization power (3) are considered. After the completion of 156 iterations, the MATLAB Program generates a graphical solution as shown in Fig. 2, where few pairs of elements conflicts each other about their existence in the resulting image. This shows that there is no existence of converged results. Hence, this state is assumed as the optimized shape of the gripping mechanism and is considered as final solution.

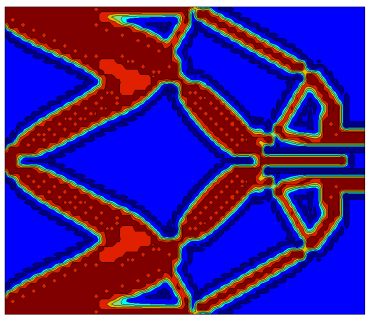


Fig. 2 Topologically optimized three fingered microgripper

B. Structural Analysis

Structural analysis is required to predict the performance of the designed microgripper. Static analysis is conducted to evaluate the stress raised in the hinge like regions, displacement of the three fingers are observed to find the maximum movement, and the required input force is calculated from the reaction force occurring in the input port. The fatigue analysis is performed to find the life span of the microgripper component. Vibrational analysis is also performed to evaluate dynamic nature of the microgripper design.

The Static behavior of the microgripper is studied using Finite element analysis software package, ANSYS WORKBENCH. The solid model of the microgripper is developed in AutoCAD (Fig. 3) by tracing the cloud points of topologically optimized domain through MATLAB. The behavior of the material of the microgripper is considered as isotropic in nature and the mechanical properties of SS 316 are given in Table I. The common exchange format of the CAD model (.sat) is imported in to ANSYS Workbench software to carry out the structural analysis. The Solid model is meshed with triangular elements to study the output precisely as shown in Fig. 4 (a). For analysis, the conditions considered are two handles are fixed and the displacement of 10μm is applied at input port (Fig. 4 (b)).

TABLE I
MECHANICAL PROPERTIES OF STAINLESS STEEL TYPE316

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

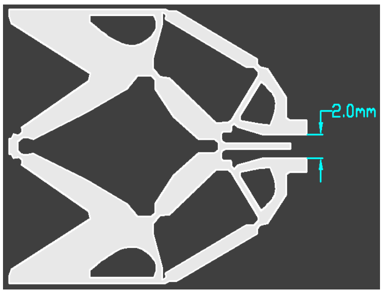


Fig. 3 Solid Model of the topologically optimized Microgripper

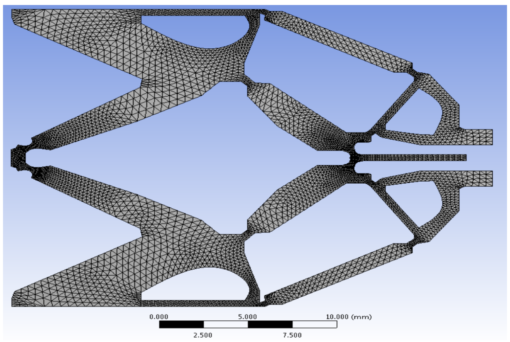


Fig. 4 (a) FE Model of the microgripper

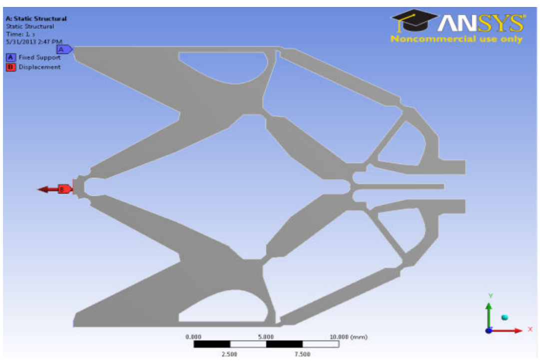


Fig. 4 (b) Loading and Boundary Conditions

FE model with loading and boundary conditions is solved using Ansys Workbench. Displacement of the microgripper jaws is found to be 5.8μm for the supporting jaw and 4.1μm for the other two holding jaws. From the vector flow pattern observed in Fig. 5 reveals that only a small region undergoes deformation and others behaves as rigid link.

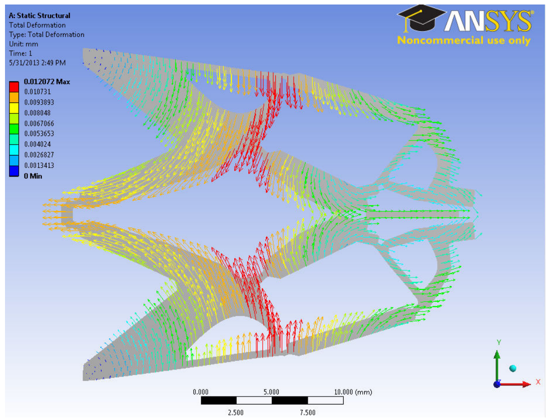


Fig. 5 Vector plot of Total displacement

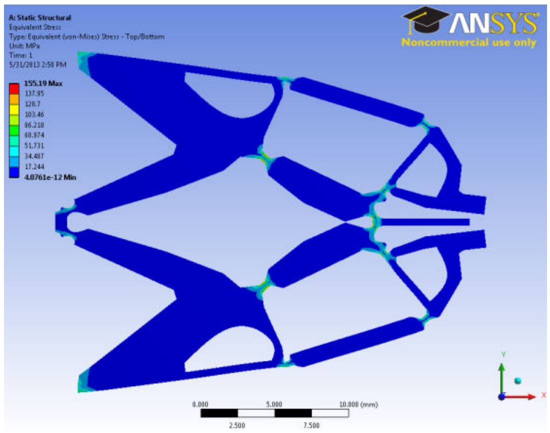


Fig. 6 (a) Equivalent stress

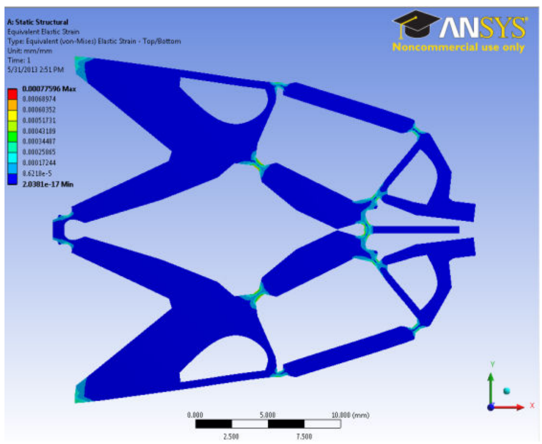


Fig. 6 (b) Equivalent stress contour plot

Contour plots of the Equivalent stress and Equivalent strain are shown in Fig. 6 (a), (b). From this figure it is observed that the hinge like regions is developed with high strains and stresses. The maximum stress developed at the hinge regions is 155MPa, which is well within the yield limit. Hence, the design is considered to be a safer one.

Another important criteria for validating the design of a micro component is its fatigue life. The fatigue life of the gripper is calculated through FEM technique to evaluate the performance and find the maximum working span of the microgripper. Stress-life method is considered since the material is ductile in nature. Zero based loading condition is considered for performing the fatigue analysis of the gripper (Fig. 7). Gerber theory is used to calculate the fatigue life since the line representing the Gerber theory has a better chance of passing through the central portion of the failure points and should be a better predictor and it is commonly used for ductile material. This theory is also called the Gerber parabolic relation because the equation is given in (4) and curve shown in Fig. 8.

$$S_{ca} = \frac{S_a}{1 - \left(\frac{S_{mean}}{S_u}\right)^2} \qquad (4)$$

S_{ca} = the corrected alternating stress (based on zero mean)
S_y = yield stress
S_u = ultimate strength
S_a = alternating stress = $(S_{max} - S_{min})/2$
S_{mean} = mean stress = $(S_{max} + S_{min})/2$

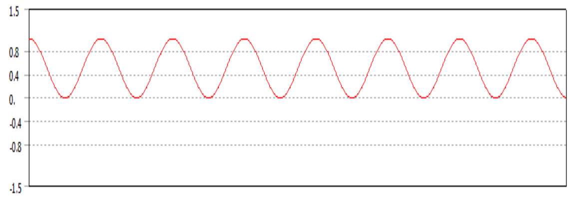


Fig. 7 Constant amplitude load Zero-Based

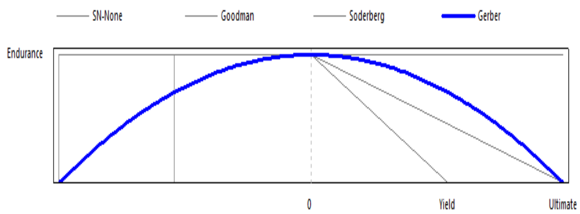


Fig. 8 Mean stress correction theory

The Fatigue life of the gripper is computed for the input displacement of 10µm, and it is found to be more than 1 million cycles as illustrated in Fig. 9, is an important evident for the quality of the design.

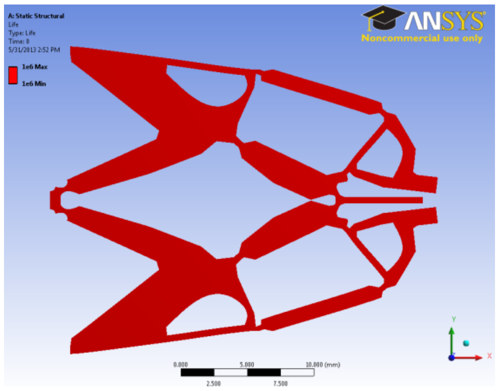
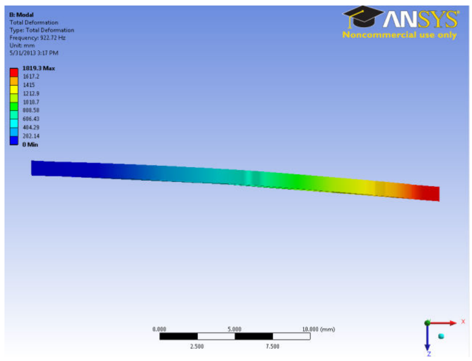


Fig. 9 Fatigue life of the microgripper

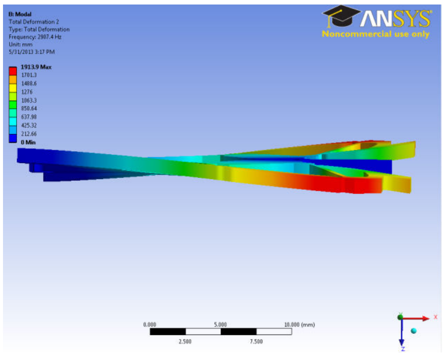
During operation of the microgripper, resonator force sensors [14] may be used in the assembly or other forces may be acting on the microgripper. This may cause vibration and may lead to resonance. Hence, predicting the natural frequency of the microgripper is an important factor to evaluate the design. With same boundary conditions, modal analysis is carried out in the ANSYS workbench environment. First five natural frequencies are calculated and listed in Table II. The mode shapes for the first five natural frequencies are shown in Fig. 10 (a)-(e).

TABLE II
LIST OF NATURAL FREQUENCY

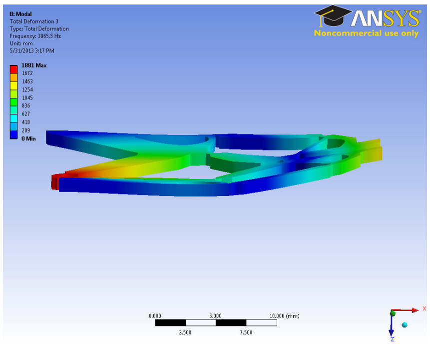
Mode	Frequency (Hertz)
1	922.7
2	2907.3
3	3965.4
4	5077.3
5	5120.4



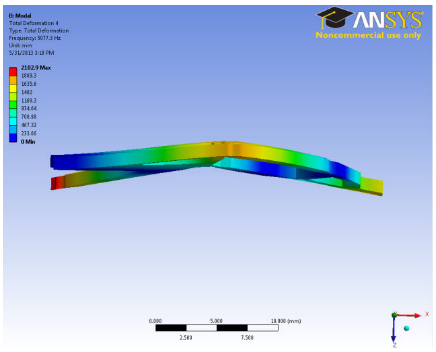
(a) Mode 1



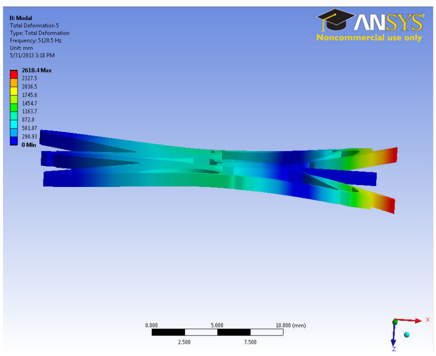
(b) Mode 2



(c) Mode 3



(d) Mode 4



(e) Mode 5

Fig. 10 Mode shape of the Microgripper For the first five fundamental frequencies

III. Conclusion

In this research work, compliant mechanism based three fingered microgripper is designed for better gripping of the asymmetric objects. Topology optimization is performed to obtain the design of microgripper mechanism and structural analysis is carried out to predict the fundamental characters of microgripper. Topology optimization is performed using MATLAB code and the resulting image is modified by means Bi-cubic spline interpolation function reduce the effect of senseless regions. Structural analysis of the microgripper is performed to evaluate the static analysis, fatigue analysis and modal analysis. Fatigue life predicted in this design shows the evident to prove the design is highly qualified that the life span of the design is more than 1 million cycles for zero based loads and another important criteria, fundamental frequencies of the micro gripper is also evaluated and the mode shapes of the device is also determined.

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