Design and Experimental Investigation of Compliant Gripper

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***Abstract*— In daily developing world micro level operation required precise motion and movements at nano and micro level operations there is certainly a need of alternative mechanism. This need is fulfilled by the use of compliant mechanisms rather than conventional mechanisms. This is a very fast growing field in which the device makes use of its compliance to achieve force and motion transmission. As space has become a new constraint the mechanisms providing accuracy and precision are supposed to be made compact. Compliant mechanisms are developed from a single plate which does not have any joints and are elastic continua. These mechanisms consider very simple design and manufacturing techniques. Circular hinges are optimized for displacement with variation of all the parameters using PRBM equation. In this paper the comparative consideration of circular, elliptical hinges. It also discussed the experimental validation with finite element analysis. The Geometrical Advantage (GA) is the parameter used for validation of FEA and experimental results. In the case of semi-circular hinges GA achieved is 4.49 and for elliptical hinges GA is approximately 4.**

***Index Terms* — FEA (Finite Element Analysis), PRBM (Pseudo Rigid Body Method), Geometrical Advantage(GA).**

I INTRODUCTION

Traditional mechanisms consists of movable joints and are capable of transforming the linear motion force and turning moment. The increase in demand of the precision and accuracy in every field has forced designers to develop mechanisms which will overcome the backlash and friction associated with the traditional mechanisms preventing the movements from being accurate [1] . Compliant mechanisms provide us the increase in accuracy with light weight and less space [2]. The main criterion of such a design is elasticity, stiffness and in many cases strength. The structures are designed to avoid deflection under a measured quantity of load[3]. The benefits of using compliant mechanisms is ease of manufacture (zero stress machining techniques), reduced assembly expenditure, no friction, wear, nosie and ability of accommodating unconventional actuations creates upper hand in the use of compliant mechanism.

The stiffest structure has been considered optimal. In many cases the structural optimization, minimization of compliance of the structure is kept as an objective function. However, it is doable that higher performances are often obtained with a flexible structure rather than the stiffest structure if flexibility is with efficiency enforced within the structure. Furthermore it is a proven fact that flexible components will provide more mechanical advantage to the structure. Thus the above mentioned fact is proved in compliant mechanisms. The compliant mechanisms use the deformation as source of motion. It is a new class of joint less mechanism solely designed from the flexibility point of view. Compliant mechanisms have fewer parts and no joints as compare its counter parts providing less friction and overcomes the backlash than the rigid body mechanisms. Thus design of compliant mechanisms prove how the flexible structures provide higher accuracy than the stiff counter parts[4].

These mechanisms are used widely for various applications depending upon the requirement of precision in a focused field. The widest applications of precision instruments in a biomedical research thus there precision range is down to nanometers from millimeters, the main application is cell handling.

M.R.Arvind, A.Senthil & Bhat [5] developed a micro-gripper by considering the 2D- Flexure hinge parameters of circular and elliptical hinges. The finished the results of parameters and position of hinge on the stiffness and output displacement of gripper. Using PRBM approach, a micro-gripper was planned by Lin and Shih [8] and counter-link lengths were optimized. Krishnan and Saggere [6] explained micro category gripper for manipulation of complicated shaped-small sized objects for any position and projected rotational flexures idea with obtained a most geometrical advantage of 11.56. Zubir & Shirimzadeh [7] developed a high precision parallel jaw motion micro-gripper by cantilever beam approach and using PRBM approach and attended maximum jaw displacement of 100 micron and amplification factor of 2.85 and compared results using FEM, they have additionally done optimization of rigid links. Flexural hinges design depends on capability of rotation, precision of rotation, stress levels, energy consumption and energy storage that is incredibly important. Nah & Zhong [8] designed and invented a micro-gripper tested using piezoelectric actuator for wire and gear of varied displacement modes, with 170 microns stoke and amplification factor 3 mm.

Paros & Weisbord firstly introduced the right circular flexure hinges [9]. They formulated simplified design equations to find compliance of flexure hinges. Many other research groups had derived compliance equations for circular hinge & FEA results to develop empirical formula [10]. Using Casigliano's 2nd theorem for symmetric conic structure, Lobontiu derived closed form compliance equations [11].

Abbreviations and Acronyms

b= thickness of mechanism
r= radius of flexure
t= neck thickness of flexure

II METHODOLOGY AND GEOMETRIC MODELLING

A. Introduction to PRBM

The PRBM (Pseudo Rigid Body Model) is a method which is used to simplify the analysis & design of compliant mechanisms. Though there are various methods available to design a compliant micro-gripper, PRBM approach is used to design a micro-gripper. In PRBM method, flexible links are replaced by rigid links and rotational springs corresponding to the bending of these links. The PRBM is a bridge that connects rigid-body mechanism theory and compliant mechanism theory [12].

There are various types of hinges those can be used in compliant mechanism. The main types of them are rectangular hinge, semi-circular hinge, elliptical hinge. The type of hinge selection depends upon the application for which the mechanism is designed. In this paper, semi-circular hinge is selected.

Using a single, monolithic piece of a metal, the gripper is designed using semi-circular flexure hinges as shown in Fig.1. This monolithic design helps to overcome the disadvantages of conventional linkages & assembly. These semi-circular hinges offer desired motion to the gripping arms. The overall motion is transferred by elastic deformation of semi-circular hinges.

For micro-gripper design, dimensional constraints considered are (70 x 90 mm). The distance between 2 tips of gripping arms is kept 1 mm. Initially, other dimensions (Fig.2.) are considered as follows –

Hinge radius (r) = 2.5 mm, overall thickness (b) = 2 mm, web thickness (t) = 1 mm, input link (h) = 20 mm.

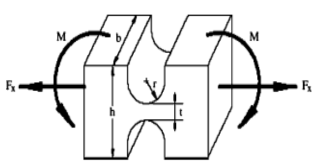


Fig.1. The generalized semi-circular hinge

B. Design of Hinges:

Hinge design is the most critical part in the compliant gripper design. The design is mostly intuition base and the success depends upon the experience of the designer.

The fact very important fact taken into consideration is the changing the Second moment of inertia which defines the strength and rigidity of the hinges and this rigidity of hinges define the exact movement of the gripper the applied force and the deflection associated with the same. Depending upon the movements desired the various types of hinges are designed and those are discussed in the following articles. The types of hinges discussed along with the results of experimentation. The different shapes of the hinges discussed in this article are semi-circular, Elliptical and constant rectangle hinges. Figure 1 shows the generalized semi-circular hinge. Similarly the elliptical hinges and constant rectangle but filleted hinges are also investigated for the effect of change in design. As shown in the following fig 3.

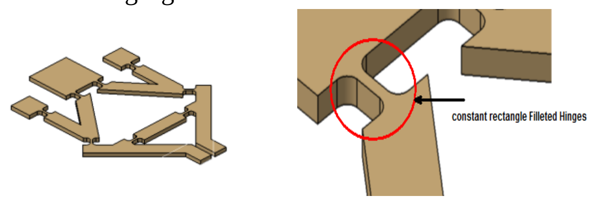


Fig. 2 Filleted constant rectangle hinges.

The figure 2 shows the hinge shape for the constant rectangle filleted hinge. As seen in the figure above the geometry is kept constant and only the shape of the hinges are changed and highlighted.

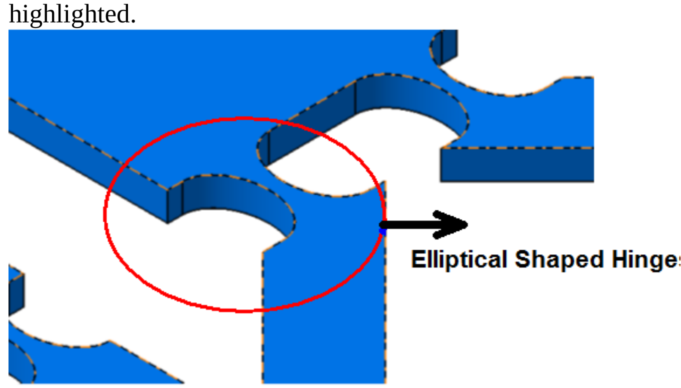


Fig 3 The elliptical shape of the hinges

The rest of the geometry has been kept the same but the variation in the hinge design has facilitated the comparison of the hinge efficiency based on the geometric advantage achieved.

C. PRBM Analysis:

Above model shown Figure.1 is analyzed by using following equation (Eqn.1) to obtain displacement at the tip of the gripping arms [13].

$$X = \frac{1}{N} F h^2 \frac{9\pi r^{2.5}}{2Ebt^{0.5}} \qquad \textbf{(1)}$$

Input Force (F), Number of hinges (N) = 8, Elasticity (E) = 200 GPa, Poisson's ratio = 0.3, Mass density = 7,850 kg/m^3.

By varying different parameters like hinge radius (r), web thickness (t), overall thickness (b) and number of hinges used (N), 4 models were designed & compared. All the designs are analyzed by PRBM method as well as FEA (ANSYS). Both the results are compared.

III. FINITE ELEMENT ANALYSIS (FEA)

A. Modeling and Analysis

The models are saved in the format of .igs in CATIA V5.These models for different hinge type is shown in Fig.3 and Fig.4. Those models are imported back into ANSYS WORKBENCH for the purpose of meshing and analysis. Fine type of meshing is selected for accurate results. The boundary conditions are put on modelled gripper as per requirement and after meshing, displacement parametric analysis for different input force is carried out in FEA for structural steel material. FEA displacement analysis results for rectangular and circular are shown in Fig 5 and 6 respectively.

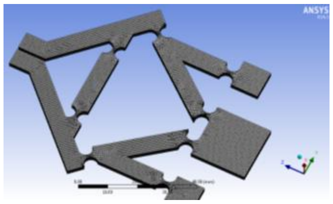


Fig.4. Meshed Model of gripper

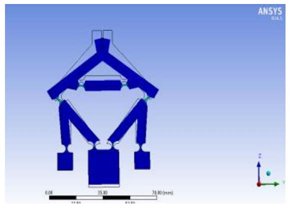


Fig 5 Deformed Shape of Gripper

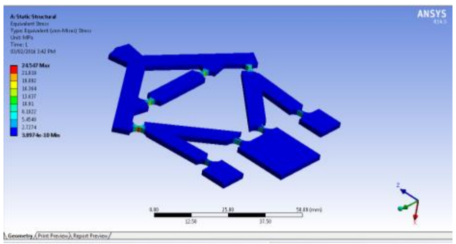


Fig.6.Von Mises stresses developed

B. Comparison of Results :

The result outcome by both analyses is compared in Table 1, Observation of results it can be concluded that FEA results are validated with PRBM analysis with 4.56% error.

TABLE I
COMPARISON OF PRBM AND FEA DISPLACEMENT RESULTS.

SR.NO	FORCE	PRBM	FEA	%Variation
1	5	0.013963	0.01335	4.56
2	10	0.027926	0.02670	4.56
3	15	0.041890	0.04006	4.56
4	20	0.055853	0.05341	4.56
5	25	0.069817	0.06677	4.56
6	30	0.083780	0.08012	4.56
7	35	0.097744	0.09348	4.56
8	40	0.111707	0.10684	4.56
9	45	0.125670	0.12019	4.56
10	50	0.139634	0.13354	4.56
11	55	0.153597	0.14690	4.56
12	60	0.167561	0.16025	4.56
13	65	0.181524	0.17361	4.56
14	70	0.195488	0.18696	4.56
15	75	0.209451	0.20032	4.56
16	80	0.223414	0.21367	4.56

IV EXPERIMENTAL SETUP

A. Experimental Procedure:

The experimentation is mainly focused on input and output displacement. Manufactured models for both type of hinges are rigorously tested for the same. Test setup is shown in fig 9 (a) and (b) . The experimentation carried out under high definition camera. The initial skeleton model and manufactured model which is mounted on setup as shown in the fig 7 and 8 respectively.

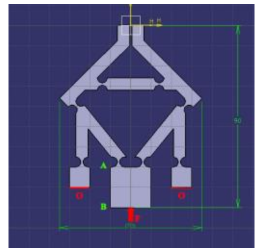


Fig.7: Skeleton of boundry condtions for gripper

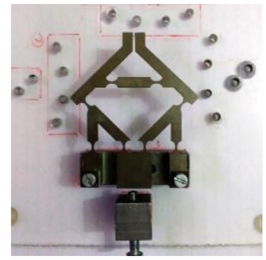
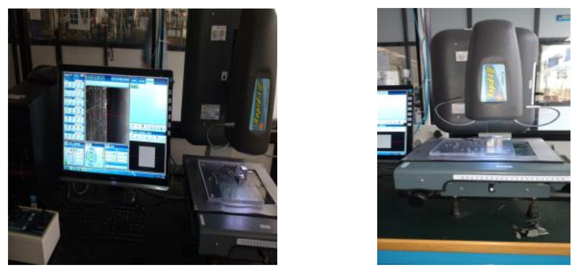


Fig.8: Manufactred model mounted on setup of boundry condtions for gripper

The model is made out of steel and fixed at the appropriate location displayed in the fig 8. The gripper is pasted on the blocks and the actuation is done using a screw, the screw is turned and the relative motion is given as a input motion to the gripper.



(a)Experimental setup (b) Vertical Camera Setup

Fig.9 Experimental Setup

The value of the input motion is seen in the fig 10. Initial and after displacement gap difference is the value of input displacement. After giving this input displacement due to the elastic properties of mechanism gripping end are also deflected from original position. The output displacement is also difference in the original and final position. The displacement change is shown in fig 11.

Input displacement: 1st result

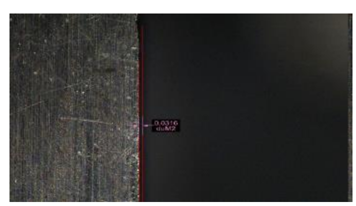


Fig.10 Input Displacement to the link.

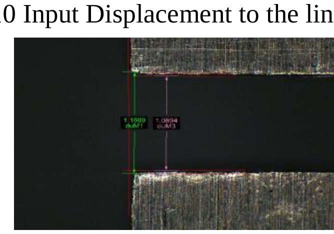


Fig.11: Output Displacement at Gripping end.

Output displacement: initial gap of gripper arm is 1.1689
1.1689-1.0894 = 79.5(micron)
As seen in the Fig 10 and Fig 11 the input displacement and the experimental setup are quite clear. Taking in to consideration the amount of the minimum input motion the use of high definition camera played a very vital role. As seen above the input displacement is in microns and cannot be predicted by the naked eye. Initial gap of 1.1689 microns was at the ideal and then 1.0894 microns and at the input of 0.031 microns input. Further results will clarify the jaw motion. The angular jaw motion with the help of Hinges can be well understood from the above article.

V. RESULTS AND DISCUSSION

A. Variation of Hinge Parameters

By varying different parameters like hinge radius (r), web thickness (t), overall thickness (b) and number of hinges used (N), 4 models were designed & compared. All the designs are analyzed by PRBM method as well as FEA (ANSYS). Both the results are compared.

By changing different parameters outcome of comparison between FEA and PRBM is represented in graphical formats. Fig 12 to Fig 15 shows variation in the hinge radius, variation in thickness, variation in web thickness and variation in number of hinges respectively.

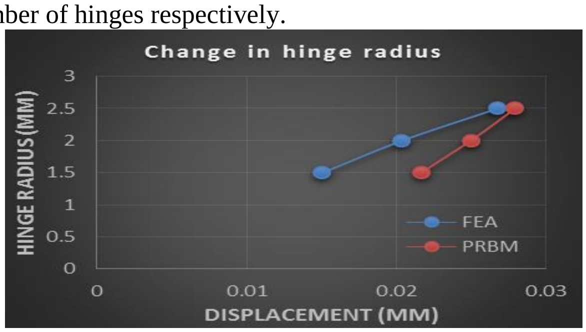


Fig.12. Change in hinges radius

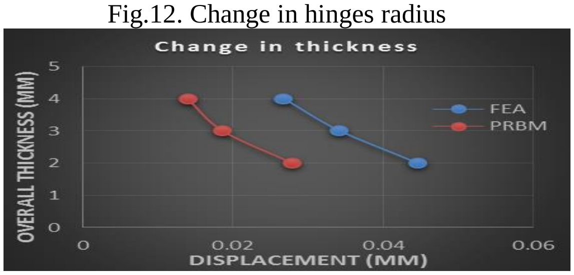


Fig.13. Change in overall thickness

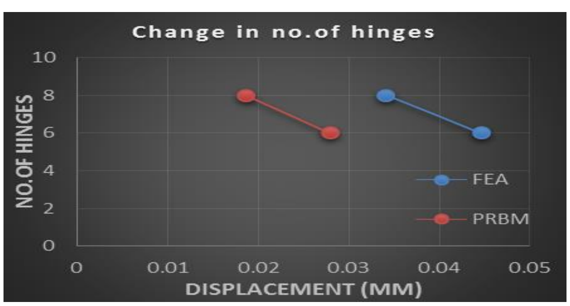


Fig.14 Change in Number of Hinges

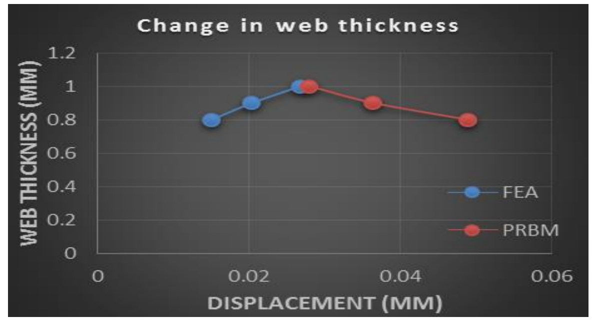


Fig.15. Change in web thickness

The analysis in FEA for both hinges is checked for safe by using Von misses stresses. Both models are considered safe with criteria as yield strength .The safe models are then manufactured with specified material conditions and tested for displacement.

The geometrical advantage thus achieved is of the order 5.47.These are the results calculated and measured for the generalized semi-circular type of hinge the these results give a fair idea of the hinge role in actual displacement occurring in the same design topology.

B. Experimental Results for Semi-circular Hinge:

Geometrical advantage is ratio of output displacement to input displacement. By observing table 2 Geometrical advantage using **FEA** is **5.47** and Avg. geometrical advantage of experimental result is **4.4975**.

TABLE II
EXPERIMENTAL RESULTS FOR CIRCULAR HINGE.

SR.NO	INPUT DISPLACEMENT (micron)	(FEA) OUTPUT DISPLACEMENT (micron)	GA of FEA	(EXPERIMENTAL) OUTPUT DISPLACEMENT(micron)	GA of EXPERIMENTAL
1	31.60	236.30	5.47	79.5	2.52
2	54.80	409.84	5.47	152.10	2.78
3	73.50	549.68	5.47	260.40	3.55
4	100.9	754.60	5.47	476.00	4.72
5	141.0	1054.500	5.47	829.70	5.89
6	169.1	1264.640	5.47	952.90	5.64
7	193.4	1446.380	5.47	1113.600	5.76
8	226.3	1697.420	5.47	1156.680	5.12

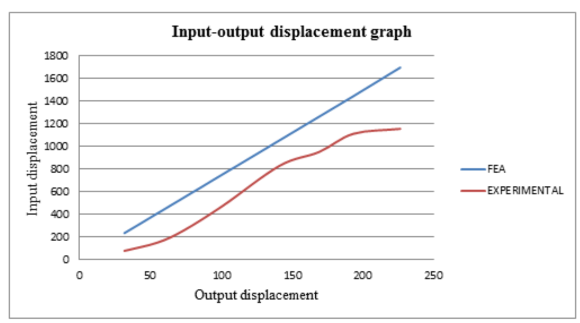


Fig.16: FEA v/s Experimental displacement results for circular hinges

The fig 16 explains depicts the Input and out put displacement graph of experimental and FEA. FEA is a linear graph and experimental is a little out of linearity due to non ideal conditions.

The fig 16 shows the input displacement though it is very less but the deflection achieved is substanstial. This has further enhanced the feature of the compliance. The further omparison of the other types of hinges is as follows

C. Experimental Results for the Elliptical Hinge:

The same procedure is followed for elliptical hinge model from observation of Table 3, the GA by FEA is 5.69 and by expeimental approach 3.4**.**

TABLE III

EXPERIMENTAL RESULT COMPARISON WITH FEA.

SR.NO	INPUT DISPLACEMENT (micron)	(FEA) OUTPUT DISPLACEMENT (micron)	GA of FEA	(EXPERIMENTAL) OUTPUT DISPLACEMENT(micron)	GA of EXPERIMENTAL
1	33.3	189.588	5.69	95.7	2.88
2	61.4	349.560	5.69	242.9	3.95
3	85.4	486.200	5.69	307.0	3.59
4	105.2	598.940	5.69	348.3	3.31
5	120.5	686.040	5.69	384.1	3.19
6	139.3	793.080	5.69	441.2	3.17
7	171.9	978.680	5.69	534.2	3.11
8	215.5	1226.9200	5.69	706.7	3.28
9	248.7	1415.9200	5.69	803.3	3.23
10	284.1	1617.4800	5.69	974.1	3.43

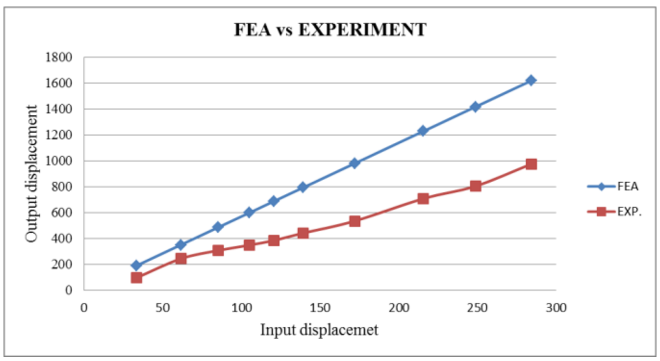


Fig.17: FEA v/s Experimental displacement results for elliptical hinges

The table 3 shows the results of the eliptical hinges input displacement in microns and FEA output and the experimental output that too in microns these readings give us the basic idea about the Geometrical advantage. The graph in fig 17 shows a bit variation in the linearity is due to the inherent material irregularities and the manufacturing process incapabilities. .

The geometric ratio will also clear the rest of the details of the hinges specifically allowing us to reach the inference about the efficiency and accuracy as well as the geometric advantage.

V. CONCLUSION

A compliant micro-gripper having semi-circular flexure hinges were designed and analyzed using PRBM method & FEA. All different configurations were analyzed and compared with each other. Some of major observations are, 1. As radius of a semi-circular hinge (r) is increased, the deformation at the tips increases. Also the increase in (r) causes increase in stresses. 2. Overall thickness (b) is inversely proportional to the displacement. But stresses reduce due to increase in material thickness. 3. If web thickness (t) is reduced, more deflection is obtained at the cost of increase in stresses. 4. Number of hinges plays vital role in design of compliant mechanism. It decides the distribution of force and stresses throughout the mechanism. If numbers of hinges are increased, the deformation reduces and stresses also get reduced.

Thus from the above comparison of the hinges we can see that the semi circular hinges gives the fast and satisfactory results. The geometric ratio will also clear the rest of the details of the hinges specifically allowing us to reach the inference about the efficiency and accuracy as well as the geometric advantage. The two types of hinges are used in the work elliptical and semicircular. If we compare these for geometrical advantage semicircular hinges are better for operation due to high GA.

The table 3 and 4 for the geometric ratio shows the FEA and Experimental results of the hinges of which is constant and a little variation is observed in the experimental results due to the variation in the virtual and actual boundary conditions.

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