Displacement and Stress Analysis of Elliptical Arc Notch Type Hinge Using FEA Tool

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Abstract:
Current technologies of micro-nano equipment manufacturing, stereo-lithography, etc. use precision scanning mechanisms. Flexure-based compliant mechanisms are being designed for efficient and precise positional control of objects in scanning systems. These mechanisms leverage the material flexibility/elasticity to enable motion that is free from friction and backlash. Efficiency of these mechanisms depend on performance of flexural hinge used for deflection. This paper presents displacement and stress analysis of notch type "Elliptical Arc Hinge" using 'ANSYS Workbench'. The analysis examines deformation, maximum induced stresses and joint stiffness based on various geometric parameters, including the length, thickness and radius of the hinge. Hinge Geometry is modelled in 'ANSYS Workbench' and iterations are run for various geometric parameters using parametric analysis tool. Results are plotted in terms of graphs. The graphs indicate that the motion direction displacement is inversely related to the thickness of joint and is in direct proportion to the length of the joint. Further such graphs can be used to predict the performance of elliptical arc flexural hinge before selection for use in compliant mechanism.

Keywords: Compliant mechanisms, Precision Scanning mechanism, Flexural hinges

1. Introduction

Applications like micro-nano instruments, Lithography, scanning tunnel microscope, micro-manufacturing etc. requires high positioning accuracy and resolution. Compliant mechanisms employing flexures hinges are commonly used in such applications for precise scanning. These mechanisms eliminate friction, backlash unlike conventional joints. Compliant mechanisms are manufactured as monolithic structures using wire EDM (Electric Discharge Machining), water jet machining or laser cutting process [1,2]. Linear displacement relation between input and output motion is provided by flexure. Flexures have smooth and continuous displacement. Due to the absence of friction lubrication is not needed in flexural joints. Flexural joints produce motion or displacement through elastic deformations of its material. Due to inherent elastic limit of such materials mechanism employing flexures have limited range of motion which restricts their use in applications requiring good accuracy for small range of travel. When flexures are a part of compliant mechanisms its dynamic as well as static characteristics are influenced by flexure stiffness [3]. Designing CM (Compliant Mechanism) is complicated and non-intuitive task because of complex inbuilt deformations of its elements. Flexural joints have been analyzed by different authors previously for investigating various mechanical properties like displacement, maximum stress and stiffness, drift of center of rotation, maximum elastic deformation and frequencies. Analytical equations are derived and experimental data is used to validate the results yield by analytical equations [4].

Characterized by a slender, curved profile a flexure joins two rigid components providing a precise and controlled rotation when stimulated by an actuating force. It plays a critical role in lumped compliant mechanisms. Profile of joint can be circular, elliptical, hyperbolic or any other common shape. Topology optimization method can be effectively used to synthesize the hinge profile geometry. Closed form compliance equations can be solved using Castigliano's second theorem. Further before experimental validation closed form compliance equations can be verified using Finite Element Analysis method [5].

To develop an efficient compliant mechanism for precision scanning applications, it's essential to select the appropriate geometric parameters for the joint and to simulate and enhance the behavior of flexural hinge [2]. This work attempts to characterize an elliptical arc notch type hinge based on performance parameters like displacement, stress and motion direction stiffness against various geometrical parameters. First chapter covers the introduction to complaint mechanisms and flexural joints. A brief history of previous work on compliant mechanisms is presented in literature review. Selection of geometric parameters and performance parameters for analysis, FEA (Finite Element Analysis) using 'ANSYS Workbench" are represented in subsequent chapters followed by discussion on results and future scope of the work. Figure 1 shows compliant Scott Russell mechanism designed by YanlingTian [2].

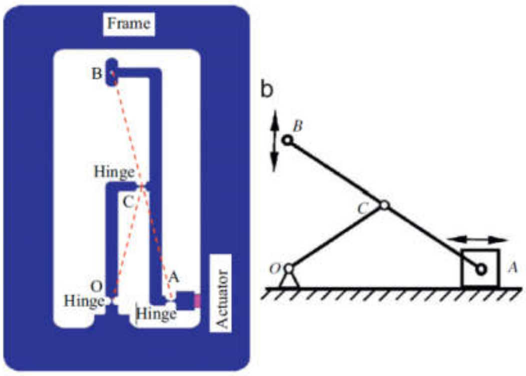


Fig. 1 Compliant Scott Russell Mechanism [2]

2. Literature Review

Min Liu, Xianmin Zhang, et al. (2016), using topology optimization method designed a new quasi V-shaped flexural hinge featuring two convex shape sides with a straight middle segment. The dimensionless compliance equations for hinge were formulated with Castigliano's theorem. The formulations for rotation accuracy, maximum stresses, and in-plane compliance were validated using FEA and experimental methods, yielding results with an uncertainty of 8% compared to simulations and 9% compared to experimental data. In comparison to filleted V-shaped hinges, QVFHs demonstrate superior accuracy of rotation. Additionally, it enhances rotational axis control and minimizes flexibility.

D.M. Brouwer, J.P. Meijaard, et al. (2013), New analytical formulas for three-dimensional stiffness have been introduced accounting for shear flexibility, limited warping and parallel stiffness of the drive. Anticlastic curving effects were modeled using shell elements in ANSYS. The results from the analytical formulas align well with the FEA results, even at large deflections.

Dongwoo Kang, Daegab Gweon (2013), Analytical equations for six degrees of freedom to calculate stiffness were derived using flexure system Ryu's method of modeling. The cartwheel type of flexure joint was assessed based on its rotational range of motion, stiffness properties and ratio of stiffness in two directions. The accuracy of the derived equations was confirmed by a comparative analysis with finite element simulations and experimental results, demonstrating a prediction accuracy within 10% error. Compared with the circular flexural hinge cartwheel type hinge confirmed the large displacement using less thickness and more radius for hinge profile geometry.

F. Dirksen and R. Lammering (2011), studied planar flexural joints in context of their use in designing of mechanisms incorporating compliance. Using topology optimization methods the occurrence of one-node hinge as an artificial artifact was addressed. Analytical equations were derived to know the mechanical related properties of the hinge, including displacement, rotation angle, stress and stiffness, center of rotation, elastic deformation and natural frequency. While deriving the equations using Timoshenko's beam theory shear deformation of flexure hinge was taken into account. Results of analytical equations were validated numerically and experimentally confirming the reliability of using equations in synthesis of joints.

Y. Tian, B. Shirinzadeh, et al. (2010), Closed form compliance formulas for both in plane and out plane compliances of filleted V-shaped flexures were derived using Castigliano's theorem. Additionally, midpoint compliance was calculated for effective parameters of geometry design. The effects of geometry variables R and θ on joint properties were assessed. Filleted V-shaped hinges exhibited different stiffness levels compared to circular hinges. Equations for linear compliance over the y and z axes as well as compliance related to rotational motion about the y and z axes, were established. To validate the compliance equations, finite element analysis was performed using ANSYS.

YanlingTian, Bijan Shirinzadeh et al. (2009), to enhance the static and dynamic performance for the precise manipulation of nanoscale objects a specialized Scott Russell mechanism has been developed leveraging the high resolution capabilities of piezoelectric actuation. Analytical solutions for this mechanism were derived using the well existing approach and the Laplace transform method. The study predicted how the cycloidal command signal can enhance the dynamic performance of the Scott Russell mechanism employing flexures. Additionally Finite Element Analysis (FEA) was used to monolithically construct the Scott Russell mechanism aiming to achieve better accuracy of positioning and also repeatability.

3. Objective and Research Methodology

The Objective of this study is Parametric Modeling of an elliptical arc notch type flexure hinge to analyze the effect of geometry parameters on the major characteristics like range of motion, stress concentration, stiffness and motion accuracy that affects the functional effectiveness.

Following methodology was implemented: Defining and selecting geometric parameters of an elliptical arc notch type hinge from extensive literature survey is the first step in study. Also literature survey will help in deciding performance parameters of the hinge to be use (displacement, maximum stress and motion direction stiffness) in the hinge analysis. After the selection of geometric parameters and performance parameters of the hinge simulations are carried for parametric modeling in 'ANSYS Workbench'. Analysis predicted the effect of various geometric parameters on performance of the hinge. These predictions are then presented in the form of graphs or charts. Steps in Research are depicted in figure 2.

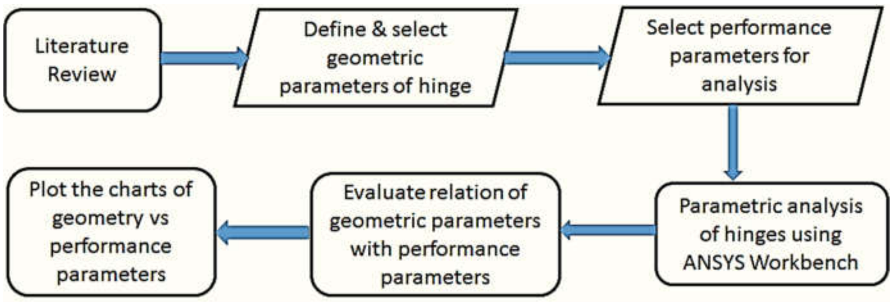


Fig. 2 Research Methodology

4. Geometry Selection

Various types of flexures are been synthesized and analyzed by different authors previously. Some common flexures employed in building lumped compliant mechanisms are circular arc, right circular, V-notch, leaf spring, Prismatic joint, elliptical hinge etc. This study is focused on analysis of an elliptical arc flexure hinge. To study the effect of geometric parameters on the behavior of hinge it becomes critical to select the type of geometric parameters of the hinge. Literature survey suggested some parameters largely influencing the hinge performance. Hinge length and thickness having are chosen as the primary parameters and major radius and minor radius of an elliptical arc are taken as secondary parameters.

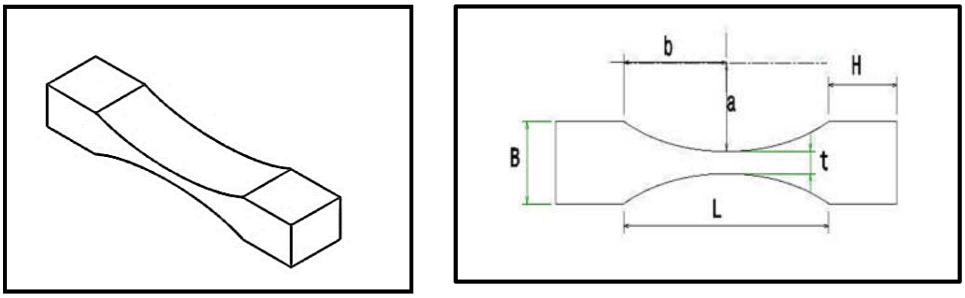


Fig. 3 Elliptical arc hinge

Primary Parameters:
a) Hinge Length: L
b) Hinge Thickness: t

Secondary Parameters:
a) Axis a
b) Axis b

5. Finite Element Analysis

In this study an elliptical arc hinge is considered as a planar single axis hinge which derives the motion along desired axes by rotation about the axis which passes through the center of flexure. Single axis flexures are ideally having less stiffness in bending direction and are to be rigid in other directions. We consider only planar motion and so planar loading conditions for hinge as shown in figure 4.

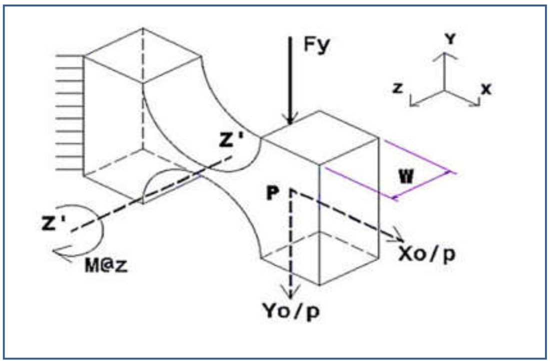


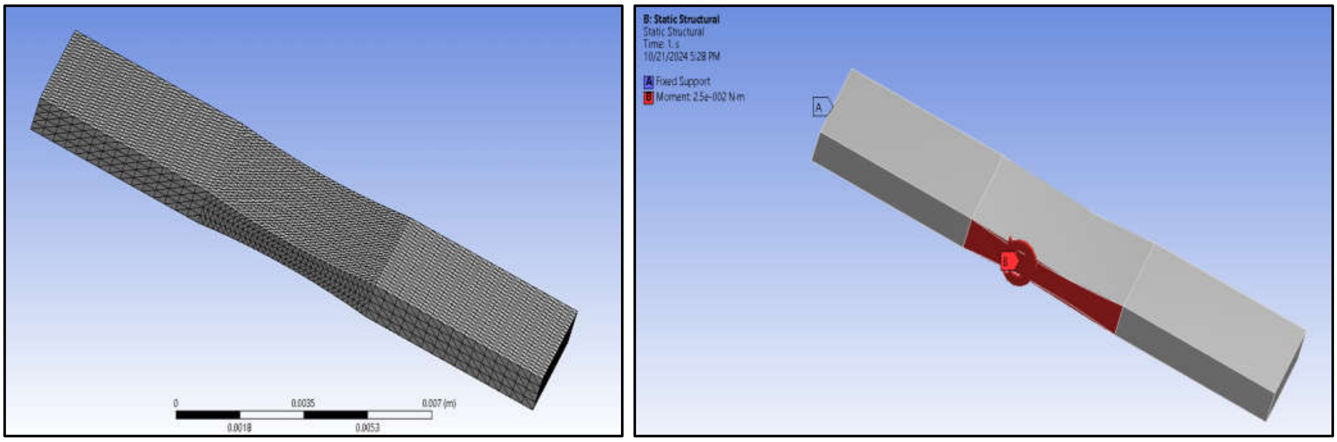
Fig. 4 General loading conditions

Considering one end of joint fixed and the force of 10N in Y direction applied at the right edge of hinge corresponding moment is applied about Z axis for each parametric model. Geometrical Data selected for parametric modeling is presented in Table 1. Here axis radius are kept constant at a = 10 mm and b = 4 mm respectively. While we vary the hinge length ‘L’ in steps of 5mm, 10mm and 15mm respectively. For each hinge length hinge thickness ‘t’ is varied in steps of 0.5mm, 0.75mm, 1.0mm and 1.25mm respectively. In total 12 parametric models were designed for simulations in ‘ANSYS Workbench’.

Table 1. Geometric data for hinge modeling

<table>
<tr><td rowspan="13">a= 10mm</td><td rowspan="13">b=4mm</td><th>L (mm)</th><th>t (mm)</th></tr>
<tr><td rowspan="4">5</td><td>0.5</td></tr>
<tr><td>0.75</td></tr>
<tr><td>1</td></tr>
<tr><td>1.25</td></tr>
<tr><td rowspan="4">10</td><td>0.5</td></tr>
<tr><td>0.75</td></tr>
<tr><td>1</td></tr>
<tr><td>1.25</td></tr>
<tr><td rowspan="4">15</td><td>0.5</td></tr>
<tr><td>0.75</td></tr>
<tr><td>1</td></tr>
<tr><td>1.25</td></tr>
</table>

In the FEA analysis, the hinge model is meshed using 10-node tetrahedral elements, resulting in a total of 20,063 elements and 33,912 nodes. A material with a Young's Modulus of 200 GPa and a Poisson's ratio of 0.3 was considered for the hinge analysis. Figure 5 depicts meshed model and analysis settings used.



(a) Meshing (b) Analysis Settings

Fig. 5 FEA Modeling

6. Results and Discussions

Each model was analyzed for determining the effect of change in hinge length and hinge thickness on joint displacement in motion direction and maximum stress. It is observed that in all the cases maximum stress occurs in that part of the hinge where the thickness of the hinge is minimal which is at the center portion of hinge. Motion direction displacement of midpoint of right face of hinge length indicated by point ‘P’ in figure 4 was analyzed for each design model. Maximum stress location is depicted in figure 6 and output results for point ‘P’ are plotted as displacement vs. hinge thickness and maximum stresses induced vs. hinge thickness for selected hinge lengths in the form of graphs. From result graphs it is observed that for selected hinge configuration maximum displacements of 0.12mm, 0.06mm and 0.04mm for hinge lengths of 15mm, 10mm and 5mm occur at minimum hinge thickness of 0.5mm. While minimum displacements lies between 0.004mm to 0.014mm for hinge length of 15mm, 10mm and 5mm. The deviation in displacement for three hinge lengths goes on increasing with decrease in hinge thickness.

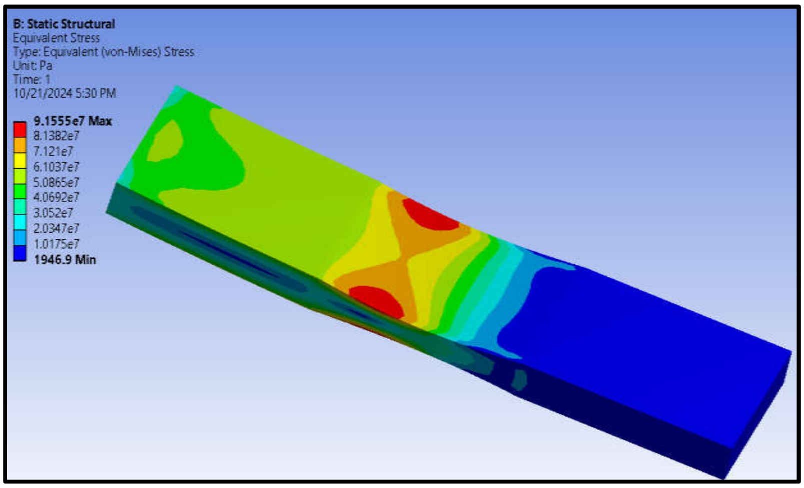
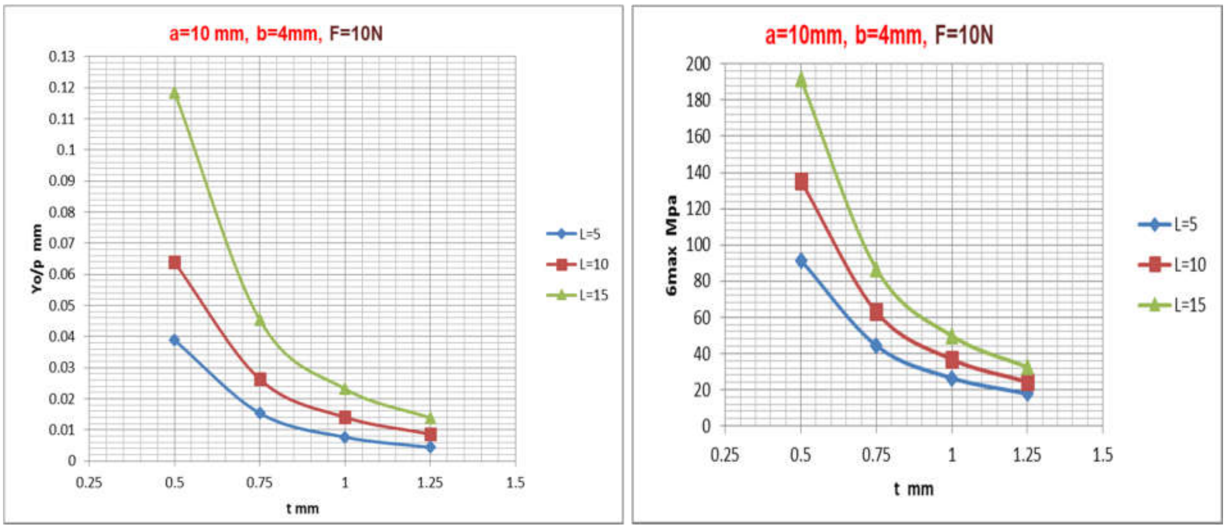


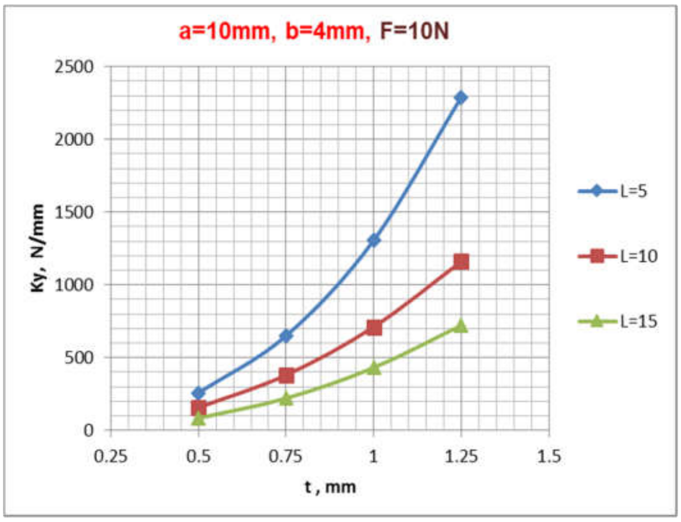
Fig. 6 Maximum Stress location

Maximum stress is found to occur at minimum hinge thickness of 0.5mm for all the hinge lengths and is 90 Mpa, 140 Mpa and 192 Mpa for hinge length of 5mm, 10mm and 15mm respectively. Motion direction stiffness is observed as 700 N/mm, 1200 N/mm and 2300 N/mm for hinge length of 15 mm, 10 mm and 5 mm respectively. Minimum stiffness for all lengths occurs at minimum hinge thickness.



(a) Displacement vs. thickness

(b) Maximum Stress vs. thickness



(c) Stiffness vs. thickness

Fig. 7 Analysis Results

In addition to stress and deformation analysis, accuracy of motion is also evaluated by measuring the amount of drift for axis of motion. Ideally the hinge rotates about an axis passing through its center indicated as ‘Z’ axis in figure 4. For pure motion direction displacement ideally the ratio of displacement of axis of rotation and that of hinge should be minimum. Displacement of axis of motion is termed as axis drift and is measured in terms of percentage with respect to hinge displacement in motion direction. More axis drift percentage indicates less motion accuracy. Figure 8 Indicates that axis drift of the hinge is more sensitive to length variation than thickness variation of the hinge. Axis drift of 40 % to 50 % is observed for all hinge thickness for hinge length of 5mm while it rises to more than 60% for hinge lengths of 10mm and 15mm respectively.

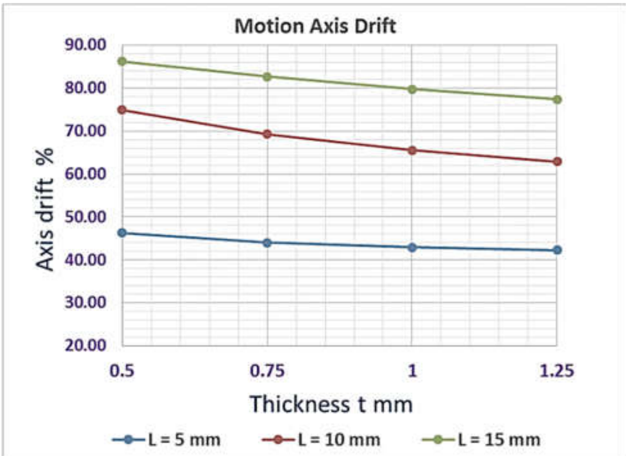
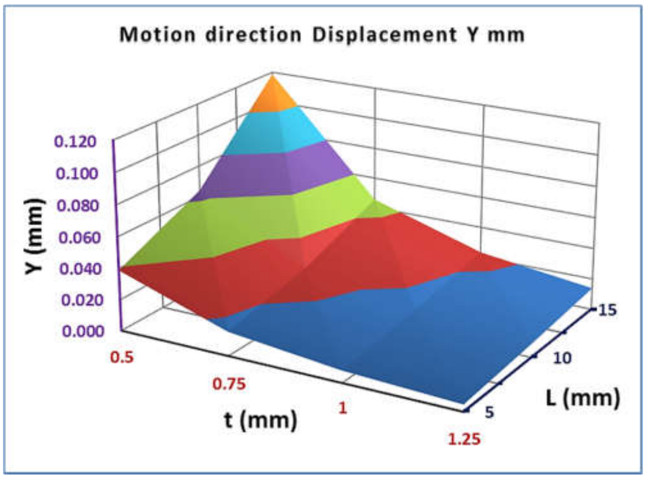
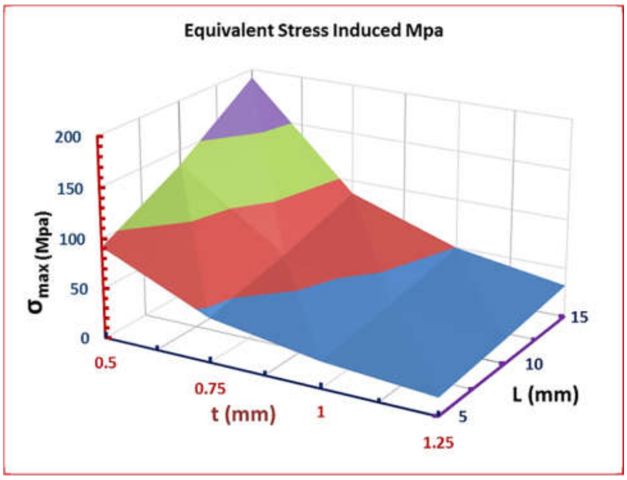


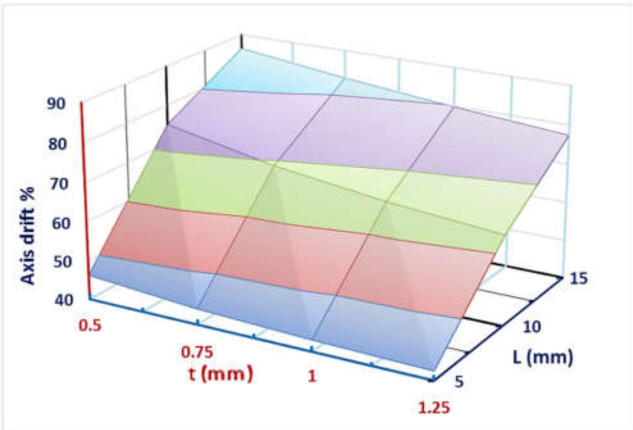
Fig. 8 Axis drift



(a) Variation of displacement



(b) Stresses induced



(c) Axis drift variation

Fig. 9 Displacement, Stress and Motion accuracy against geometry

7. Conclusion

When flexural joints are utilized in compliant mechanisms, the static as well as the dynamic characteristics of the mechanism are influenced by the properties of those flexural joints. Characterization of an elliptical arc flexural hinge is done for evaluating its performance parameters like displacement, maximum stresses induced, motion direction stiffness and motion accuracy, against geometrical parameters like joint length and thickness. Twelve parametric models of flexure were designed and analyzed in 'ANSYS Workbench' which serves as an tool which is useful for FEA analysis of various compliant mechanisms. Hinge length was varied from 15mm to 5mm in steps of 5mm and hinge thickness was varied from 0.5mm to 1.25mm in steps of 0.25mm.From analysis results it is observed that displacement in desired direction is inversely proportional to hinge thickness and maximum stress induced is also inversely proportional to hinge thickness. This trade-off between stress and displacement is critical in hinge selection for use in design of compliant mechanisms. Since the hinge behaves as a cantilever beam the displacement in motion direction is obtained by rotation of the hinge about its center axis. Axis of rotation and its deflection with displacement of hinge is critical in modeling of flexure hinge. Motion accuracy measured in terms of axis drift depicted in figure 8 implicates that the drift is more sensitive to change in hinge length. Further three dimensional charts obtained in figure 9 can serve as a beforehand guide for designers in selection of optimized parameters for an elliptical arc hinge.

Future work involves generation of dimensionless graphs, accuracy of motion and analysis for rotational stiffness of the hinge and compares the hinge with other conventional joints used in compliant mechanisms.

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