A new method for designing a compliant mechanism based displacement amplifier

2016 IOP Conf. Ser.: Mater. Sci. Eng. 149 012129

(http://iopscience.iop.org/1757-899X/149/1/012129)

A new method for designing a compliant mechanism based displacement amplifier

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Abstract. Advancement of precision industries, displacement amplifying device is essential to produce precise and long range of motion for micro-actuator. Compliant mechanism based displacement amplifier (DA) is more appropriate to attain high precision motion. Compliant mechanism utilizes elastic nature of material to achieve required motion. In this research paper, compliant mechanism design is developed using topology optimization. The output of the topologically optimized design is impossible to fabricate as it is due to the presence of senseless regions. Hence, this optimized design is considered as a primary design of compliant mechanism which provides the configuration of kinematic linkages and also provides the details of the geometrical locations of the flexure hinges. Selection of appropriate geometrical parameters of the flexure hinges is another critical task in the design process and parameterization technique is used to determine flexure hinge parameters. Structural performance of mechanical amplifier confirmed using finite element method (FEM).

Index Terms: Compliant mechanism; displacement amplifier(DA); Topology optimization; Flexure hinges; FEM.

1.Introduction

High precision motion is fundamental in the MEMS and precision industries. For example, the alignment of fibre-optics and lasers, the positioning of specimens in a scanning electron- microscope, the positioning of masks in lithography, cells manipulation in microbiology, and assembly and manipulation of micro-scale components in micro-assembly applications [1]. In the micro systems, Dual motion positioning stage is more appropriate, coarse motion is achieved through motor actuated ball screw and linear slider for, and associated piezoelectric parts for fine motion require high level but controlled motion is complicated. Integration of amplifying device with Nano positioning stage provides a convenient for control [2]. Such the device assembly makes very fine resolution possible and meets accelerating nanotechnology in high-tech precision manufacturing.

Compliant mechanisms are widely used in micro systems (MEMS) applications where precision of motion, reliability, ease of fabrication, compactness and feasibility in micro-environments are essential. Compliant mechanisms are mechanisms that transmit motion, force or energy by elastic deflection of flexural members instead of movable joints [3]. Compliant mechanisms have some obvious advantages over conventional mechanisms. They do not have joints and thus most of them are available in one piece, which saves on assembly costs. Furthermore, the absence of backlash, friction and wear associated with joints in conventional mechanisms are almost negligible in compliant designs. Design of compliant mechanism is very complicated. Traditional kinematics itself is quite insufficient and it usually has to be combined with elastic deformation theory. As compliant mechanisms undergo large displacements, geometric nonlinear effects are to be included in the elastic analysis. Stress concentration effects have to be considered in thin and narrow regions. Howell and Midha [4] have presented a pseudo-rigid body model for designing a flexure hinge based compliant mechanisms. Ananthasuresh [5] have synthesized compliant mechanisms through topology optimization. Subsequent efforts have made use of geometric nonlinearity in finite elements for topology optimization to synthesize large-deflection compliant mechanisms [6].

Performance of Compliant mechanism is completely dependent on flexure hinges. Flexure hinges are slender region which act as a rotational pin joint through elastic deformation. Various flexure hinges design were implemented to improve the efficiency of the mechanism. Various contour profiles are introduced which are majorly classified as symmetrical and asymmetrical contours. In symmetrical profile, various type of con-tours such as conic sections [7], circular, elliptical, parabolic and hyperbolic [8], v shaped notches [9], quadratic rational Beziercurves [10], and polynomial contour [11] were investigated so far by the researchers. Shifting of rotational axis during operation is more in the case of symmetrical contour and hence the researchers found promising in asymmetrical contour profile [12]. and various geometrical parameters of flexure hinges are also investigated obtain the appropriate design [13-14].

This research paper attempts to develop a amplifying device for precision motion. The concept of amplifying mechanism is developed through topology optimization techniques. Flexure hinges is adapted in the slender region and parameterization technique is integrated to achieve a appropriate flexure geometry. Parameterization provides a geometrical details of flexure hinges with respect to its location. This technique improves the efficiency of the compliant mechanism design.

2. Design of Amplifying mechanism

Design of amplifying mechanism is a challenging task. Hence, compliant mechanism is adapted to provide high precision motion device. A primary or conceptual mechanism design has been developed using topology optimization technique. An open source for mechanism design developed in MATLAB [15] is modified according to the requirement of the present design. MATALB output provides the concept of the mechanism. In general, any mechanism consists of links and joints. Number of links, number of joints and fairly accurate length of the links required for formulating the mechanism are found through the MATLAB output. The primary mechanism is then post processed from the manufacturing perspective to obtain the final design [16]. In the post processing stage, flexure hinges are introduced at the hinge locations. Flexure hinges play a vital role in achieving controlled and precise motion of microgripper. The selection of suitable parameter of the flexure requires high attention. Parameterization is implemented to obtain the geometrical parameters through a finite element software package ANSYS Workbench. Parameterization on flexure hinges are done based on the output displacement and equivalent stress.

2.1 Topology optimization

Topology optimization is an efficient and logical method to achieve the conceptual design of compliant mechanism. The initial design domain is prepared based on the requirement such as input and output. Required design domain is shown in Figure 1. Finite element analysis is carried out in the initial design domain subjected to the boundary and loading conditions. Finite element model of the initial design domain is developed by discretizing the domain into 120 numbers of elements horizontally and 60 numbers of elements vertically. Dark shaded regions in the rectangular domain are considered to be solid regions by assigning the element relative density value is equal to a higher value. Solutions of the initial design domain for the given boundary conditions are obtained from the finite element method. Solid Isotropic Material with Penalization (SIMP) approach is used (15) to solve the optimization problem. In SIMP method, young's modulus 'E0' is assumed as '1' and uses penalization 'p' to make intermediate densities 'ρ'.

$$E_i = \rho_i^p E_0 \tag{1}$$

In this research work, the percentage of material volume reduction is considered as 50% of material from the initial volume. A mesh independent filter is used with filtering radius of 1.2 to remove the numerical instabilities such as a checkerboard pattern in the final solution, mesh dependency and local minima.

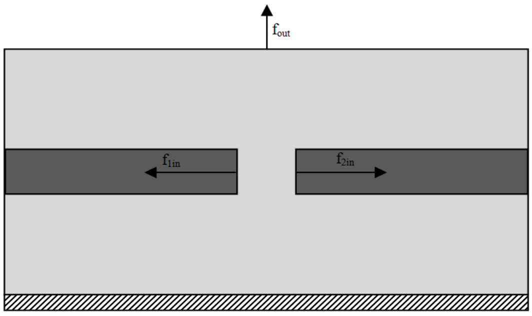

Figure 1. Initial design domain

The objective function of the topology optimization problem is formulated as given in equation (2).

Maximize:

$$-MPE = U_1^T K\ U_2 = \sum_{e=1}^{N} (x_e)^p \left(u_{eo2}^{\ T} k_0 u_{ei1}^{\ T} - u_{eo2}^{\ T} k_0 u_{ei2}^{\ T}\right) \qquad (2)$$

Subject to : $V(x)/V_0 = f$
: $KU = F$
: $0 < x_{min} \leq x \leq 1$

f1in and f2in are forces at input port, fout is a force acting at output port, uei1, uei2 are global displacement vectors at input port and ueo2 is a global displacement vector at output port, K is the global stiffness matrix, F is the global force vector, Ke- elemental stiffness matrices, xe - relative density of the element materials, Ko is the local stiffness matrix, p - penalization, ρ - density of the material, Eo - constant young's modulus and Ei is the penalized young's modulus

Topology optimization code is executed in MATLAB software, result after 253 iterations are illustrated in the following Figure 2.

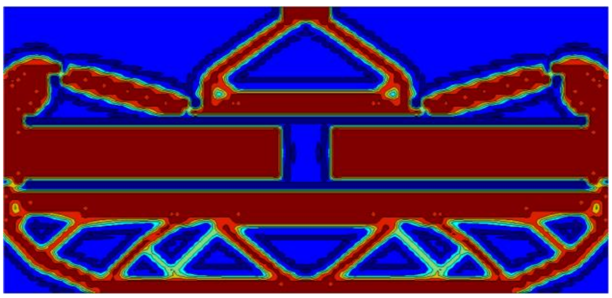

Figure 2. Topologically optimized design

2.2 Post processing using parameterization

Optimized result provides the kinematic configuration for amplifying mechanism. It means, the conceptual design provides information about the flexure hinge location and length of the linkages. Based on the configuration the MATLAB model is converted as a solid CAD model using AutoCAD software shown in Figure 3. Flexure hinges location is identified and circular profile flexure hinges are designed. A flexure hinge is a mechanical element that provides the relative rotation between adjacent rigid members through material flexibility (bending) instead of a conventional rotational joint. Each individual flexure hinge is accompanied by a complete set of compliances (or conversely, stiffness) that define its mechanical response to quasi-static loading. The benefits gained from flexure joints are at the cost of overcoming several disadvantages such as limited relative motion and a cause for stress concentration must be taken into account while designing. To overcome these drawbacks and to develop better flexures, a set of criterion such as the range of motion, the amount of axis drift, the ratio of off-axis stiffness to axial stiffness, and stress concentration effects are to be considered in the design process.

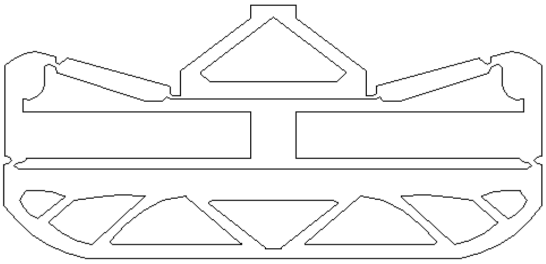

Figure 3. Solid model of amplifying mechanism

In the Figure 3, radius of the circular profiled flexure hinges is in the range of 9 to 11 mm. Radius is approximated based on the intensity of the color and shape of the hinge observed form the optimization result.

2.2.1 Numerical investigation

In this research work, Finite Element Method (FEM) has been used to design and evaluate the structural performance of amplifier. The compliant mechanism based amplifier is analyzed to predict the output displacement for the given input displacement and stress, strain developed. The developed FE model is opened in mechanical modeler to perform the structural analysis. Material property of the stainless steel is assigned to the amplifier model. The necessary loading and boundary conditions are introduced in the FE model. Boundary conditions for this structural analysis problem are; constraining all the degrees of freedom of bottom portion of the amplifier, load is applied as an input displacement at the input ports of the amplifier model. Directional deformation at x and y (mm), Equivalent stress (MPa) at input displacement are the requested parameters/output from the structural analysis. This static structural problem is solved through default solver in the ANSYS workbench.

Direction displacement along x and Y axis is shown in Figure 4 (a) and (b) which clearly shows the output goes in straight line for the given input. Displacement along X axis is 6.6775E-5 mm and output displacement along Y axis direction is 6.026E-4 mm. The geometrical advantage (GA) which is the ratio of output to input for the design is about 10. Hence the design is at satisfactory from the GA perspective. Stress also noted very minimum as 0.34 MPa, hence it can be loaded further to attain more output displacement if required.

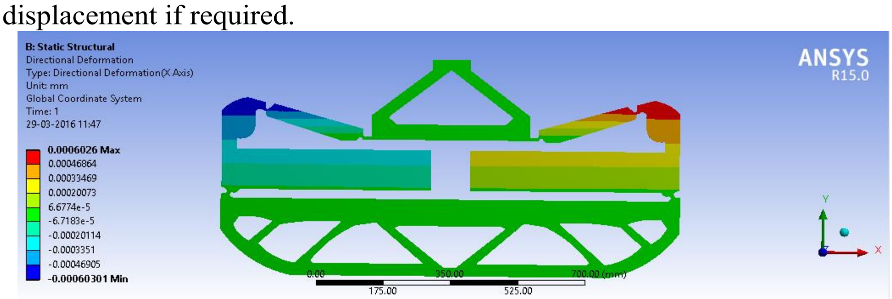

Figure 4(a). X- Directional deformation

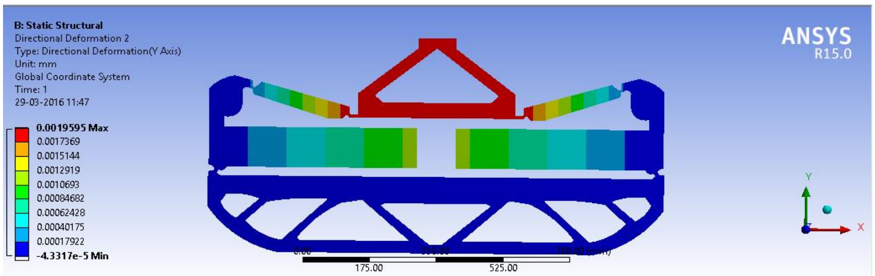

Figure 4(b). Y- Directional deformation

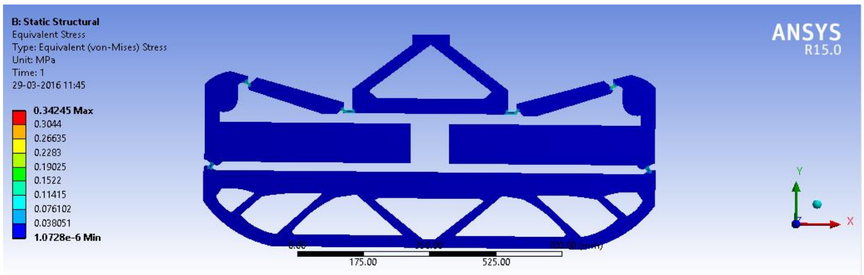

Figure 5. Contour plot of Equivalent stress

2.2.2 Parameterization

In this design process, further improvement in design is carried out by parameterization technique using ANSYS Workbench. The developed CAD model with flexure hinge radius parameter is illustrated in Figure 6.

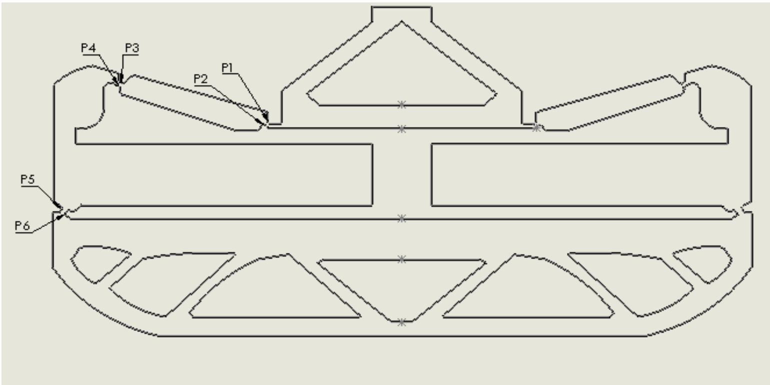

Figure 6. Parameterised model

Parameterization is carried out as a multi objective problem using screening algorithm in Ansys Workbench. Objectives are maximization of the output displacement and minimization of stress developed in the hinge region. Parameterization is carried on the radius of the circular flexure hinges as named P1 to P6. Three candidate points are obtained as listed in table. 1.

Table.1. shows the optimal variation for this range of radius. Stress and deformation are not equable in all 3 candidate points. Hence we can select candidate point 1 for the final design. At the same time, for the higher loads, variation in the flexure parameters may be obtained.

Table 1. Parameterization results with three candidate points

	Candidate 1	Candidate 2	Candidate 3
P1	9.499	10.499	10.099
P2	9.6	10.85	10.35
P3	10.433	10.211	10.655
P4	9.9	9.98	9.18
P5	9.671	9.1408	10.528
P6	9.4636	10.3727	10.009
Deformation (mm)	0.0018883	0.001847	0.001791
Stress (MPa)	0.33267	0.33809	0.3299

The analysis considered only a small range for radius which can be increased to attain better result. Considering other geometrical parameters of flexure hinges and various other contours, better results may be obtained.

3.Conclusion

A new complaint mechanism amplifier is designed and tested for its performance. A systematic methodology is developed for the design of a compliant mechanism and its functional characteristics are thoroughly investigated numerically. Conceptual mechanism design for the required application is generated using topology optimization technique. Location of flexure hinges in the compliant mechanism were identified and integrated. Circular flexure hinges are considered based on high accuracy motion. The radius of flexure hinge parameters is considered in the range of 9 to 11 mm. Parameterization is carried out to determine the appropriate geometry of the flexure hinges based on the output displacement and stresses. Hence, this research paper provides an explicit methodology to design and determine appropriate flexure geometry to ameliorate the ease of manufacturability of compliant mechanism.

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