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Parametric Modeling and Analysis of XY Flexural Mechanism using FEA

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Abstract- Present article discuss about parametric modeling of XY flexural mechanism which uses Double Parallelogram Manipulator (DFM) as building blocks. DFM offers a zero parasitic error motion with small amount of rotation of motion stage. DFM is used as building block for design of XY flexural mechanism. Parametric model of DFM and XY mechanism is developed using Design Modeler ANSYS. FEA analysis is carried out to determine stiffness, parasitic motion and rotation of motion stage. Effect of parametric variation is studied and regression model is developed. Developed model is further used for optimization of XY mechanism. Present paper analyses the performance characteristics of the two proposed designs (using DFM) of XY mechanism, using ANSYS as FEA tool. It is observed that the latter design provides higher accuracy due to its symmetric constraint layout.

Keywords- Flexural Mechanism, FEA, ANSYS

I. INTRODUCTION

Compact XY flexure stages that provide large range of motion are desirable in several applications such as semiconductor mask and wafer alignments, scanning interferometry and atomic force microscopy, micromanipulation and micro assembly, high-density memory storage, and MEMS sensors and actuators [1]. A micropositioning stage generally refers to a system which can automatically move an end-effector with certain degrees-of-freedom (DOF) in its work space, and maintain a submicron positioning resolution. For micropositioning stages, it is desirable to have large work space, high resolution, high bandwidth, and compact size. During the past several decades, a good deal of effort has focused on improving the performance of such devices [2].

A flexure mechanism stage driven by a piezoelectric actuator is a good example of a precise scanner, and its resolution is small enough to be used in a precision microscope. However, the working range of this scanner is limited to several tens of micrometers, thus limiting the measurement range of any microscope employing it. It is difficult to find commercially available compact scanners that satisfy the requirements of both high resolution and extensive working range [3].Micropositioning mechanism is a key and essential technology in many fields, such as scanning electron microscopy (SEM), X-ray lithography, mask alignment, and micromachining. Recently, there have been quite a number of studies on the analysis and design of micro-positioning mechanisms with flexure hinges [5],[6] Presented a Dual-Axis Long-Traveling Nano-Positioning Stage (DALTNPS). In order to extend the traveling and increase the accuracy, the two sorts of stages, a traditional ball-screw stage and a three-degrees-of-freedom (3-DOF) piezo-stage, were composed. The traditional ball-screw stage which is composed of two guide-ways and a ball-screw at each axis is a long-travel stage, and the 3-DOF piezo-stage, which is composed of three piezoelectric actuators and four translation–rotation mechanisms, is a high precision stage.

Paper [9] describes and discuss the most used smart material used for actuation in micro mechanisms: thermo mechanical actuators (shape memory alloy, thermal dilatation of solids, thermal expansion of gas), magneto mechanical actuators (Magnetostriction, magnetic fluids, shape memory alloy magnetic), electromechanical actuators (piezo electric, electro active polymers, fluid electric, electrostatic), fluid mechanical actuators, and also those that use multiple principles at the same instant. The paper [11] presents the design and control of a single-axis positioning stage with a total travel of 50mm.The single-axis stage is comprised of a long-range slide way, running on ultra-high molecular weight polyethylene (UHMWPE) bearings, and a short-range positioning stage, comprised of a PZT driven flexure. Recently, piezoelectric (PZT) actuators have been largely used in ultra precision positioning devices, with applications found in optical devices; semiconductor related manufacturing facilities, ultra precision machining tools, and various nanotechnology microscopes. Compared with traditional servo-motors or linear motors, the PZT actuators are superior with regard to their fast response, small sizes, and cost-effectiveness [12].

Thus compliant mechanism with several advantages like frictionless motion, absence of backlash and wear, clean mechanism without any need for lubrication, reduced noise, smooth geometry changes and a lighter design provides wide range of motion. Flexural mechanism basically consists of hinges and flexure beams. Shorya Awatar in his paper [1] has presented the design of planar mechanisms using different basic building blocks such as single beam flexure, parallelogram flexure and double parallelogram flexure unit.

This paper presents the design of XY flexural mechanism using double flexural manipulator (DFM). Parametric analysis of XY mechanism is carried out to obtain optimized dimensions of DFM used with respect to length, width and thickness to obtain the desirable working range of displacement 10 mm to 15mm with a force up to 45N (due to VCM actuator specifications). This design can be successfully used to precision scanning motion mechanism.

II. DESIGN OF FLEXURAL MECHANISM

Flexural mechanism gives precision motion by having relative motion between fixed support and motion stage. Relative motion is generated by interface element. An interface element such as ball bearings, sliders, and liquid / air films used in conventional mechanisms generate friction, backlash and do not offer high precision and high order of repeatability. If these interface elements are replaced with flexible elements such as hinges, flexible beams eliminates friction, backlash and offers high precision scanning with high order of repeatability. Based on this basic principle XY, XYθ, etc. flexural mechanisms are developed. Investigation of these building blocks of flexural mechanism is carried out in article [15]. It is clearly mentioned DFM offers better performance in terms of parasitic motion and rotation of motion stage. Hence present paper uses DFM as building block for planar mechanism.

2.1 Double Parallelogram Flexure:

The double parallelogram flexure unit is used as the building block for two-axis planar flexural mechanisms (Fig.1) which is also called Double Flexural Mechanism (DFM).

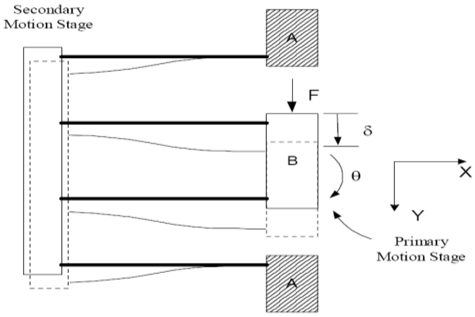


Fig 1: Double Parallelogram Beam Flexure

Deflection, Angular rotation and parasitic error motion is calculated by

$$\delta = \frac{FL^3}{12\,EI} \qquad \theta \approx t^2\left(\frac{1}{b_1^2}+\frac{1}{b_2^2}\right)\frac{\delta}{L} \qquad \varepsilon = 0$$

This flexure allows relative Y translation between bodies A and B, but is stiff in relative X displacement and rotation, although not as stiff as the parallelogram flexure. The parasitic error ε, along X direction, is considerably smaller because any length contraction due to beam deformation is absorbed by a secondary motion stage.

Double parallelogram flexure offers large range, good rotational stiffness, no purely kinematic parasitic errors, and excellent thermal stability. The standard double parallelogram flexure module is used as a building-block and various XY planar flexural mechanisms are developed by Awatar [1].

The primary objective of the design is to achieve large ranges of motion along the X and Y. In design it is the need to maintain high stiffness and small error motions in the out-of-plane directions. The mechanism is so designed such that the rotation of the motion stage, being a parasitic error motion, is inherently constrained.

2.2 FEA Analysis Current XY Flexure Mechanism:

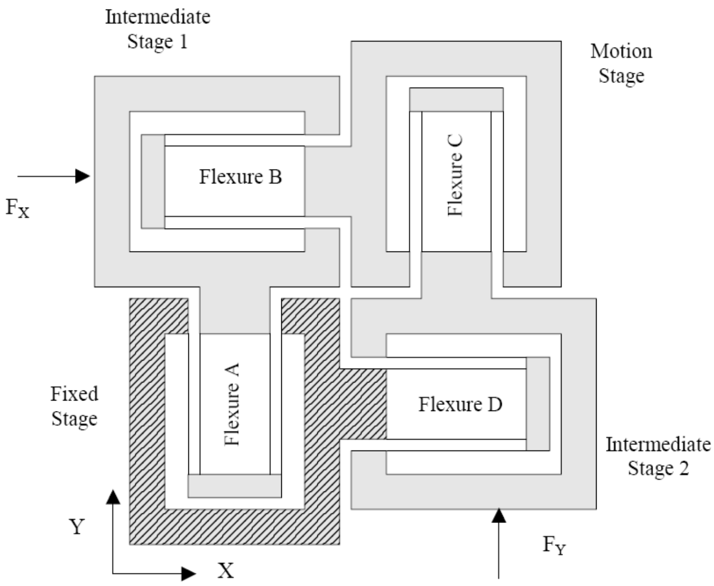


Fig 2: XY Flexural Mechanism 1

The above mechanism shown in Figure2 achieves all the desirable attributes required in XY mechanism. The constraint arrangement includes four basic rigid stages: Ground, Motion Stage, and intermediate Stages 1 and 2. Stage 1 is connected to ground by means of flexure module A, which only allows relative X translation; the Motion Stage is connected to Stage 1 via flexure module B, which only allows relative Y translation; the Motion Stage is connected to Stage 2 via flexure module C, which only allows a relative X translation; and finally, Stage 2 is connected to Ground by means of flexure module D, which only allows relative Y translation. Thus, in any deformed configuration of the mechanism, Stage 1 will always have only an X displacement with respect to Ground while Stage 2 will have only a Y displacement. Furthermore, the Motion Stage inherits the X displacement of Stage 1 and the Y displacement of Stage 2, thus acquiring two translational degrees of freedom that are mutually independent. Since the Y and X displacements of the Motion Stage do not influence Stage 1 and Stage 2, respectively, these are ideal locations for applying the actuation loads.

The mechanism was modeled on Pro-E, and Analysis was carried out using ANSYS. The model is symmetric and provides constraints in both the directions. Aim of FEA analysis to determine the stiffness, deflection, stresses, and parasitic error motion. Material used is stainless steel (Young's Modulus: 2.1 X 10^5 N/m2, Poisson's ratio: 0.33). Figure 3(a) shows boundary conditions applied to CAD model, Figure 3(b) shows deformation of motion stage in X-direction under force of 35 N, Figure 3(c) shows Parasitic motion (i.e. motion in Y-direction) for 35N force, and Figure 3(d) shows Equivalent stresses generated. Stresses (187 N/mm2) generated in both directions are less than the yield stresses of stainless steel (250 N/mm2). Hence, a deformation in the entire mechanism is within elastic limit and it will be restored by removing applied load of 35 N. Further, Mechanism shows a deformation of 8.556 mm in X direction, Stiffness in X-direction comes to 4.43837 N/mm which is having close agreement with theoretical calculations presented in previous section. Figure 3(c) shows a parasitic error motion, FEA Analysis shows a very negligible amount of deformation in Y direction when motion stage moves in X-direction. Similar, FEA analysis is carried in Y-direction and results of FEA analysis is shown in Figure 4 (a), (b), (c) & (d). Experimental setup is developed and experimental results are discussed.

2.3 Experimental Setup:

XY flexural mechanism is manufactured using standard Wire EDM (Electrical Discharge Machining) process. In this process work piece is cut to produce finished part of the desired shape by using electric spark as a cutting tool. This electric spark produces heat with temperatures from 8000 to 12000 degrees Celsius, melting almost anything. Pulsating electric charge at high frequency current is applied to the work piece through the electrode. The wire cut EDM is a discharge machine which uses a continuous travelling vertical wire under tension as the electrode. Its path is controlled by the computer programme to produce the required shape. The spark is very carefully controlled and localized so that it only affects the surface of the material. The EDM process usually does not affect the heat treat below the surface. With wire EDM the spark always takes place in the dielectric of deionized water that makes an excellent environment for EDM process. The water acts as a coolant and flushes always the debris and thus helps to maintain surface quality. Figure 5 shows a manufactured XY Flexural mechanism. Thickness of each flexural beam is limited to 1 mm because of manufacturing constraints.

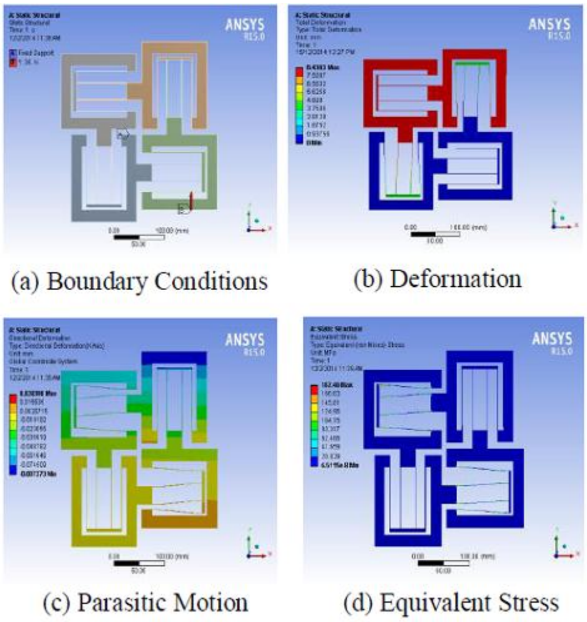


Fig 3: Analysis of XY Flexural Mechanism (X-Motion)

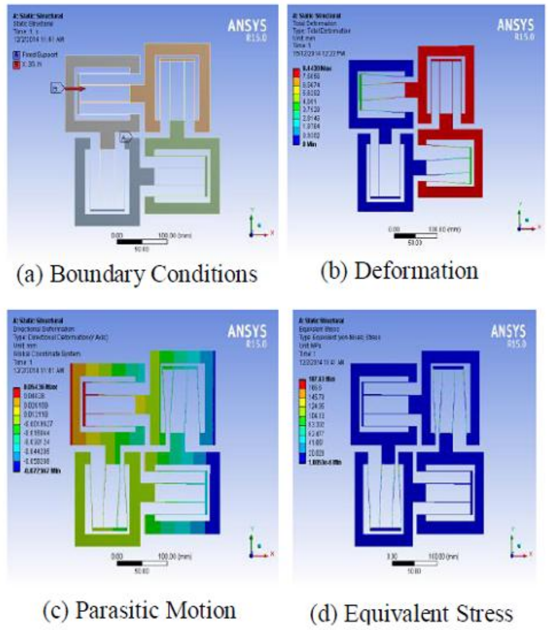


Fig 4: Static Analysis of XY Flexural Mechanism (Y-Motion)

Fig 5: Manufactured XY Flexural Mechanism 1

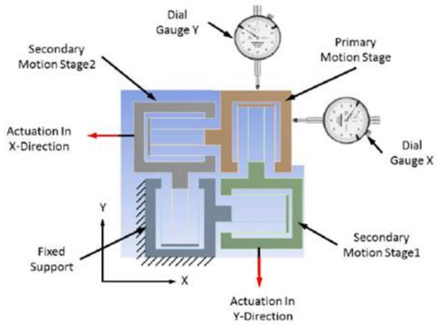


Fig 6: Experimental Setup for Measurement of X & Y Direction motion and parasitic motion

Figure 6 shows an arrangement of mounting of XY flexural mechanism on optical table and alignment of dial gauges for recording X and Y direction motions. Figure 7 shows an experimental setup which consists of two dial gauges which measures displacement of motion stage in X & Y directions respectively. These dial gauges have a resolution of 10 m and range of measurement is 25 mm maximum. Red color flexible wires are tied at actuator location to provide an appropriate actuation in X & Y directions. Load is applied using weight pan with an increment of 50 grams. For each increment of load deflection of motion stage is recorded. Load in weight pan (maximum 35 N) is given such that maximum of 7.5 mm displacement is achieved. Figure 8 shows a comparison between experimental and FEA results for X-direction motion.

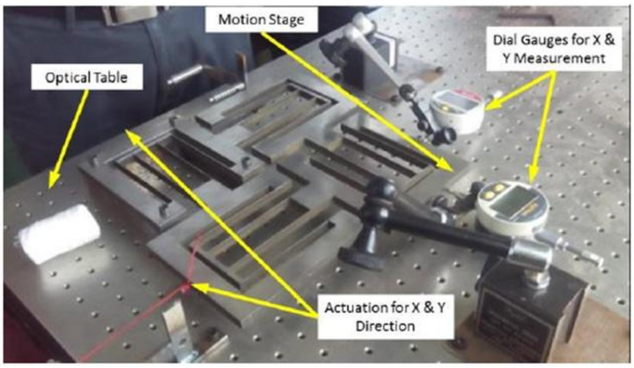


Fig 7: Experimental Setup for Measurement of X & Y Direction motion and parasitic motion

Comparison shows a close match between experimental and FEA results. Further, other dial gauge continuously records displacements in Y-directions. Results of deflection in Y-directions are shown in Figure 9. It shows max deflection of 25 m, and variation observed is due to surface irregularities only. Hence it is concluded that there is zero parasitic motion occurs in Y-direction when stage is moving in X-direction.

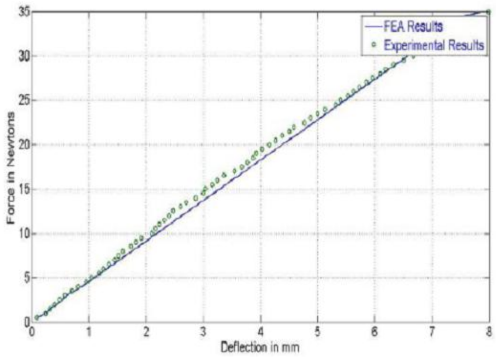


Fig 8: Comparison of experimental and FEA results for X-direction.

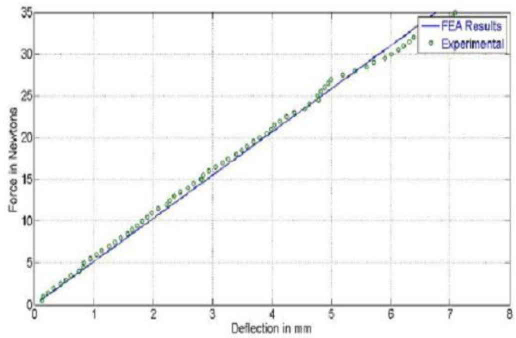


Fig 9: Comparison of Experimental and FEA results for Y-direction

Current mechanisms have following difficulties

- XY Mechanism is fixed at one end and provides a unsymmetrical constraints
- Due to unsymmetrical constraint motion stage bends in downward direction due to self-weight.
- Problem of rotation of motion stage is more and need to be addressed

Hence, symmetrically constraint mechanism is decided for further analysis. Figure 10 shows a symmetrically constrained mechanism in which support is provided from all sides and problem of bending of motion stage due to self-weight is alleviated.

III. PARAMETRIC XY FLEXURAL MECHANISM

In this section planar flexural mechanism is analyzed using FEA tool ANSYS. The feature-based parametric modeling technique (shown in Fig. 11) from ANSYS is used. Basically Flexural mechanism is built using multiple DFM flexures. Dimensions of DFM are parameterized (parameters: Length of beam, width of beam and thickness of beam) and used for generating different geometries. Following table 1shows parameters considered for analysis along with its ranges.

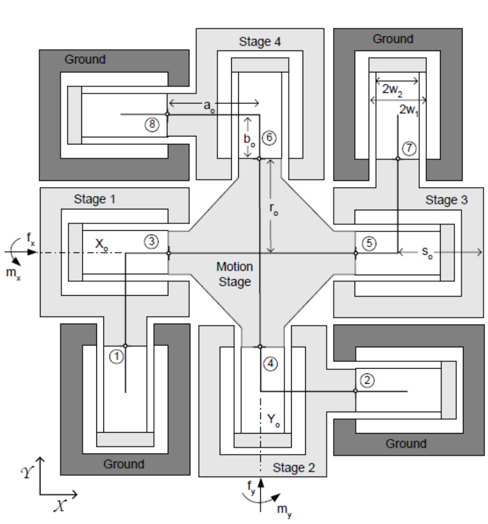


Fig 10: XY Flexural Mechanism 2

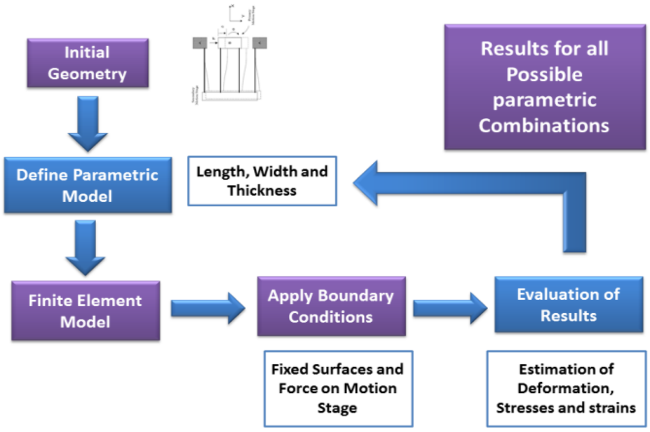


Fig 11: Parametric FEA Analysis Procedure

FEA Analysis is carried out to have a variation in length, thickness and width of flexural beam of DFM. Range of these parameters are listed in Table-1 below,

Table 1: Range of Parameters for FEA Analysis

Sr. No.	*Parameter*	*Range*
1	Length (mm)	50-75-100-125
2	Width (mm)	8-10-12-14
3	Thickness (mm)	0.75-0.8-0.9-1.0

These parameters are used for creating CAD models for XY flexural mechanism. Total 64 models are developed using CAD software Creo2.0. These models are further converted into neutral file format .iges and imported to ANSYS workbench for FEA analysis. Boundary conditions are applied on CAD model as shown in fig.

These different CAD models are analyzed using FEA tool ANSYS. Stiffness of each model is estimate and compared with theoretical stiffness value. Figure 12 shows a comparison between theoretical and FEA results and have close match with each other.

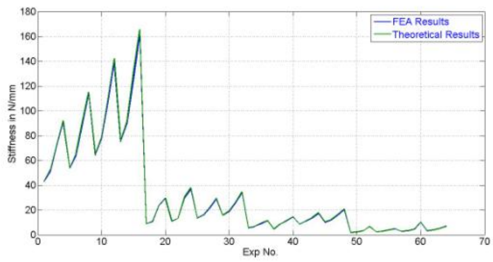


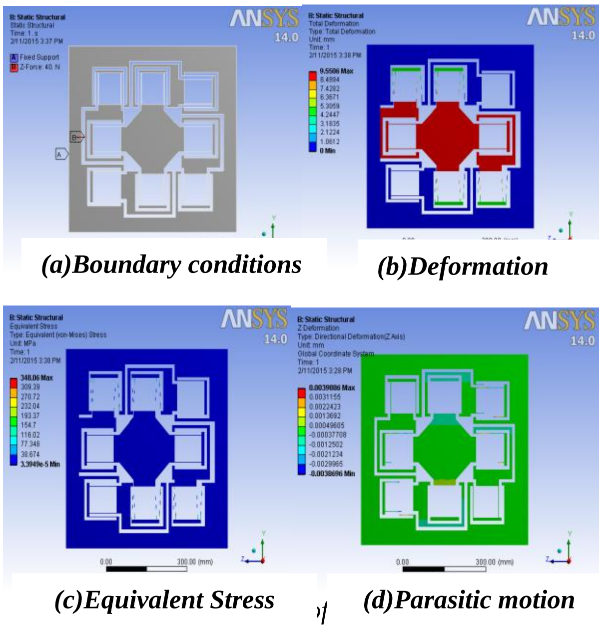
Fig 12: Comparisons of FEA and Theoretical Results

Table 2 Design requirements for mechanism

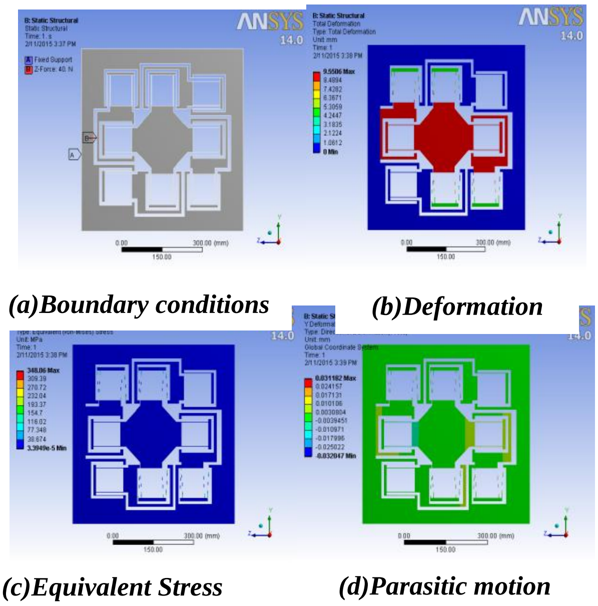
Sr. No.	*Parameter*	*Range*
1	Range of Mechanism	15-20 mm
2	Max. Allowable force (N)	40 N
2	Stresses (Maximum Allowable)	400 N/mm^2

Based on the design requirements for mechanism listed above in table 2, dimensions are decided and FEA and theoretical results shows that Parameters: Length = 100 mm, Width = 10 mm & Thickness = 0.8 mm. Figures 13& 14 shows a counter plot of deformations and stresses generated in this the model Flexural mechanisms. Figure 13 shows deformations in Y-direction, Force applied is 40 N and Figure 13(a) shows a boundary conditions (fixed and force applied) Figure 13(b) shows deformation in Y-direction and Figure 13(c) shows stresses generated and Figure 13(d) shows parasitic error motion. It is observed from all results that maximum deformation achieved is 9.5 mm, stresses are within allowable range and parasitic error motion is very less i.e. less than 0.0039 mm.

Similarly Figure 14 shows results for X-direction. Here also less parasitic error motion is observed. Such mechanism can be manufactured by standard EDM process and further experimental investigation is to be carried out.



(Y-Motion)



(X-Motion)

CONCLUSIONS

XY flexural mechanism is very much useful in precision applications such as laser scanning, microscopy, micro-nano fabrication systems. Flexural mechanism has an advantage of zero backlash and friction and offers better control on position. Mechanism 1 is supported at one end, which give rise to vertical motion of motion stage due to self-weight. Mechanism 2 is symmetrically supported and provided a lesser or zero vertical motion. Hence mechanism 2 gives better performance and need to be developed experimentally and tested.

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REFERENCES

[1] Shorya Awtar, Alexander H. Slocum, "Constraint-based Design of Parallel Kinematic XY Flexure Mechanisms", ASME MD-06-1015.

[2] Qing Yao, J. Dong, P.M. Ferreira, "Design, analysis, fabrication and testing of a parallel-kinematic micropositioning XY stage", International Journal of Machine Tools & Manufacture. 47 (2007) 946–961.

[3] Dongwoo Kang, Kihyun Kim, Dongmin Kim, Jongyoup Shim, Dae-Gab Gweon, JaehwaJeong, "Optimal design of high precision XY-scanner with nanometer-level resolution and millimeter-level working range", Mechatronics 19 (2009) 562–570.

[4] Deyuan Zhang, Chienliu Chang, Takahito Ono, Masayoshi Esashi, "A piezodriven XY-microstage for multi probe nano recording Sensors and Actuators", A 108 (2003) 230–233.

[5] Byung-Ju Yi, Goo Bong Chung, Heung Yeol Na, WheeKuk Kim, Il Hong Suh, "Design and experiment of a 3-DOF Parallel Micro-mechanism Utilizing Flexure Hinges", IEEE Transactions On Robotics And Automation, Vol. 19, No. 4, August 2003.
[6] Chien-Hung Liu, Wen-YuhJywe, Yeau-RenJeng, Tung-Hui Hsu, Yi-tsung Li, "Design and control of a long-traveling nano-positioning stage", Precision Engineering 34 (2010) 497–506.
[7] S. Avadhanula, R. S. Fearing, "Flexure Design Rules for Carbon FiberMicrorobotic Mechanisms".
[8] I. Santos, I. Ortiz de Zárate, G. Migliorero, "High Accuracy Flexural Hinge development".
[9] Sergio Lescano, Micky Rakotondrabe, Nicolas Andreff, "Micromechanisms for Laser Phonosurgery:A Review of Actuators and Compliants Parts", IEEE International Conference on Biomedical Robotics and Biomechatronics, BIOROB'12., Rome :Italy (2012).
[10] L.F.Campanile, M Rose, E.J.Breitbach, "Synthesis of flexible mechanisms for airfoil shape control: a modal procedure".
[11] Eric S. Buice, David Otten, Raymond H. Yang, Stuart T. Smith, Robert J. Hocken, David L Trumper, "Design evaluation of a single-axis precision controlled positioning stage", Precision Engineering 33 (2009) 418–424.
[12] Yung-Tien Liu, Bo-Jheng Li, "Precision positioning device using the combined piezo-VCM actuator with frictional constraint", Precision Engineering 34 (2010) 534–545.
[13] Won-jong Kim, Shobhit Verma, Huzefa Shakir, "Design and precision construction of novel magnetic-levitation-based multi-axis nanoscale positioning systems", Precision Engineering 31 (2007) 337–350.
[14] Chih-Liang Chu, Sheng-Hao Fan, "A novel long-travel piezoelectric-driven linear nanopositioning stage", Precision Engineering 30 (2006) 85–95.
[15] Suhas Deshmukh, Rachel Patil, Y.P. Reddy, "FE Analysis and Experimental Investigation of Building blocks for Flexural Mechanism", ICNTE 15 Paper No.30, 07/08 January '15.

