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PERFORMANCE ANALYSIS OF COMPLIANT MECHANISM FOR MICRO POSITIONING STAGE

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ABSTRACT

Engineering applications are judged in today's fast-paced and intensely competitive industry based on exact and accurate results. Deflection of beams in compliant mechanisms is used to meet the growing needs for precision motion. Compliant mechanisms are referred to as a type of mechanism that is based on the mobility and rigidity of a component, allowing for increased precision without necessarily reducing its accuracy. Motion is achieved via molecular deformation combined with beam bending in the elastic zone. Compliant mechanisms are utilized in modern techniques for precision scanning, such as micro-nano processing microscopes and biological scanners. Major failures of compliant mechanisms are caused by repetitive in-plane and out-of-plane movement of compliant beams. This work presents an experimental and numerical analysis of a compliant mechanism utilized in biomedical scanners for linear motion in the XY direction. This study paper delves into the performance analysis of compliant mechanisms for various beam constraint positions and materials. The elastic deformation of the beam within the elastic zone of the material is totally responsible for the range of the motion and movement of the compliant mechanism in the XY direction. The maximum range of motion, stress, and stiffness values of XY Mechanism are used to determine the performance of a compliant mechanism. For various beam combinations, the compliant mechanism is examined.

1. INTRODUCTION

Compliant mechanisms achieve their mobility by converting the input force or the energy in a movement in which the structures undergo an elastic deformation. Compliant Mechanism consists of Beams and joints for motion transmission, Actuators to provide actuating force, Optical Encoder to detect displacements. Compliance mechanisms are important ingredients in various fields of research such as robotics, micro-electromechanical systems, biomechanics, precision engineering etc. Compliant mechanism made up beams and hinges. Circular hinge provides more deformation as compared to rectangular hinge (Frank Dirksen, R. Lammering, 2011). Generalized Model for Commonly Used Flexure Hinges represents compliance values (Guimin Chen, 2011). 3D Profile scanner with Nanometer resolution developed by H Shino using parallel beams (H Shino, 2010). Parallel actuated exoskeleton is more effective than serial actuated exoskeleton (Justin Hunt, 2018). Lucas develop efficient design of compliant metamaterials (Lucas, 2019).

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Mingxiang Ling work on piezoactuated compliant mechanism which provide concurrent large workspace and high dynamic frequency for precision positioning (Mingxiang Ling, 2018). Matt Culin determines planar compliance values by experimental method (Matt Cullin, 2014). Qingson Xu developed New Flexure Parallel-Kinematic Micropositioning System With Large Workspace (Qingsong Xu, 2012).

1.1 Translational positioning mechanism

A translational positioning mechanism is usually required to provide the translational motion in the two-dimensional plane or three-dimensional space. To generate the translational positioning in more than one direction serial - parallel kinematic chain is used. It provides high load capacity, low inertia and high resonant frequency.

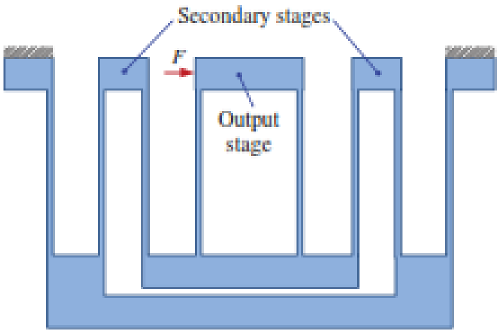

Figure 1. Translational positioning System (Zeyi Wu,Qingsong Xu 2018)

As shown in Figure 1 In Translational positioning system one directional output motion is obtained without disturbing other axis motion (Qingsong Xu, 2018).

1.2 Rotational positioning mechanism

Rotational Movement in compliant mechanism can be achieved with the combination of beam and hinges as shown in Figure 2. The rotational stage is guided by radial flexures with fixed–guided constraint The circle-like output platform can rotate around the centre of the stage However, its rotational range is less due to the mechanism stress stiffening effect and over constraint (Qingsong Xu, 2018).

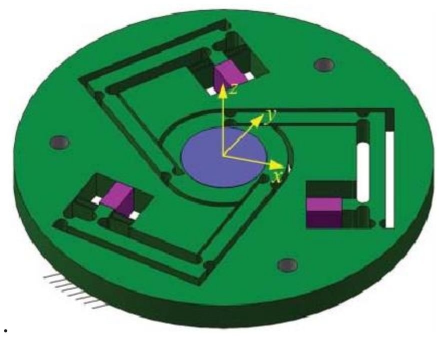

Figure 2. Rotational positioning System (Zeyi Wu, Qingsong Xu, 2018)

Radial flexure need to be developed with a larger length, larger outer radius and smaller thickness to achieve a large rotational range. However, in practise, the compactness restriction, manufacturing tolerance, and minimum stiffness criterion limit these physical parameters.

1.3 Developments and challenges in compliant mechanism

Developments in Compliant Mechanisms are based upon accuracy, precision and available space for different combinations beams. Current research is going on evaluation of displacement with piezoelectric actuator, Electromagnetic actuator and pneumatic actuator. Researchers are using combinations of beams and joints to get micro and Nano range of motion with compliant mechanism.

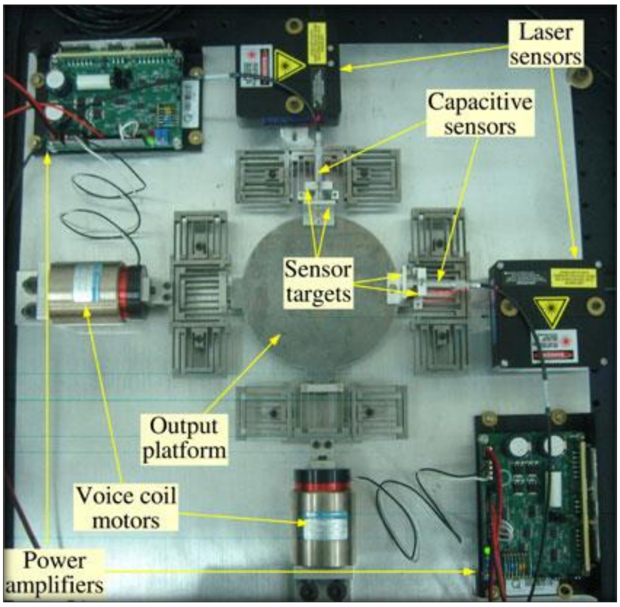

Figure 3. XY micropositioning stage (Qingsong Xu, 2012)

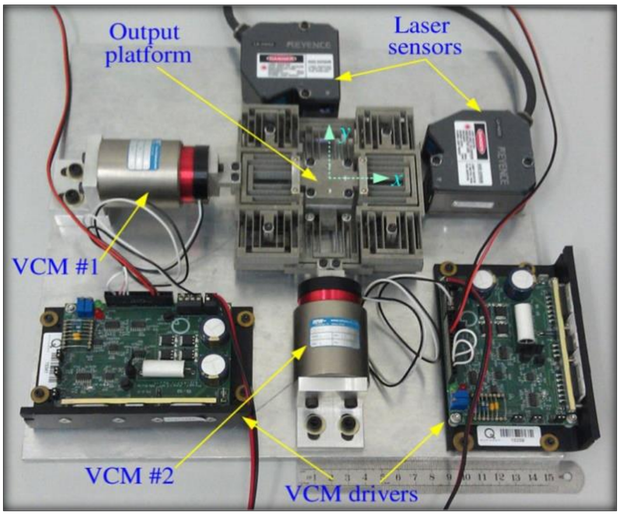

Figure 4. A prototype of XY micro stage (Zeyi Wu, Qingsong Xu, 2018)

Qingsong Xu developed Micropositioning System With Large Workspace using Parallel-Kinematic flexure. In this research work Multistage parallelogram flexure mechanism is used to achieve travel range of 10mm. It produces workspace of 105 x105 mm^2 (Qingsong, 2018). Qingsong presented XY Precision Positioning System with Compact Flexure arrangement of beams Maximum workspace is 20 X $20mm^2$ is achieved with the help of beam positions. Electromagnetic actuators are used to minimize nonlinearities and hysteresis effect (Qingsong, 2012).

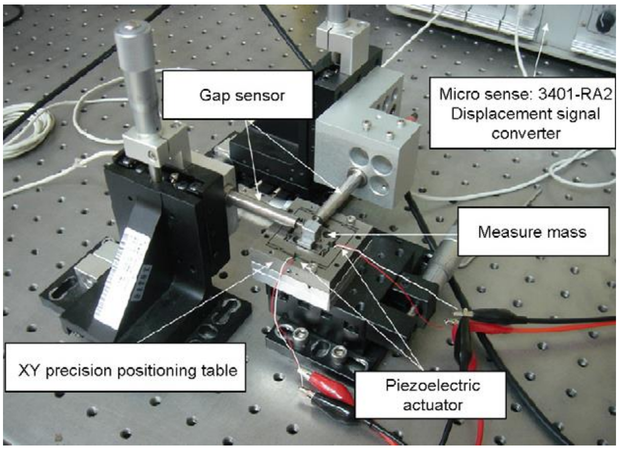

Figure 5. XY Precision positioning table(Rongfong, 2009)

Rong fong worked on precision positioning table using dual-stage XY. In this work fine and coarse positioning are performed with piezoelectric actuator and Permanent magnet motor. Maximum displacement achieved with the help of hinges and beams is 1.6mm (Rongfong, 2009). Ryson explain the effect of flexural hinges in the design of 2 DOF compliant Microgripper (Royson, 2017). Sebastian Linb had derived General design equations for the rotational stiffness, angular deflection and rotational precision of various notch flexure (Sebastian Linb, 2017).

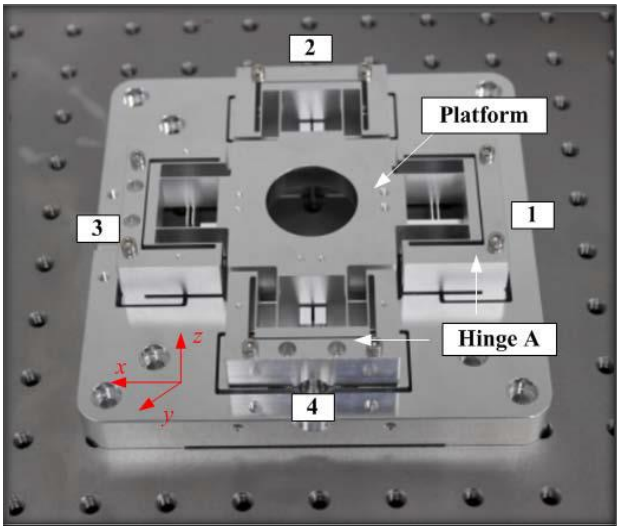

Figure 6. Flexure-based XY stage (Xiantao Sun, 2013)

Jiangkung Shang had presented 2-degrees of freedom flexure-based micropositioning stage with a flexible decoupling mechanism (Jiangkung Shang, 2015). Sicong wan develop large stroke XY Compliant mechanism with working range of 12mm (Sicong wan 2016). Sicong wan develop large stroke XY Compliant mechanism with working range of 12mm (Sicong Wan, 2016). Sandesh Solepatil works on displacement analysis of linear compliant mechanism (Sandesh Solepatil, 2019). Sandesh Solepatil presented Behaviour of linear compliant mechanism by Numerical and experimental method (Sandesh Solepatil 2021). Xiantao Sun worked on XY nano positioning stage with Parallel beam positioning method is used to achieve translational motions. X and Y beam positions are stack together to get bidirectional movement. This system is used upto frequency range of 134Hz (Xiantao Sun, 2013).

YTian presented Closed-form compliance equations of filleted V-shaped flexure hinges for compliant mechanism (Yanling Tian, 2010). Yangmin worked on Modeling and performance evaluation of a flexure-based XY parallel micromanipulator (Yangmin Li, 2009). Zhiwei Zhu works on Optimum design of a piezo-actuated tri-axial compliant mechanism for nano-cutting (Zhiwei Zhu, 2018).

1.4 Challenges in compliant mechanism

In spite of all the benefits of implementing mechanisms, they have certain problems compared to ordinary mechanisms:

1.4.1 Limited range of motion

As the relative movement between rigid objects is accomplished through material deformation, compliant structures are not able to move continuously and can provide a restricted range of movement.

1.4.2 Parasitic motions

The relative motion produced by complying mechanisms is not pure motion, and the dynamic deformation action of these mechanisms often creates secondary unwanted motion. Parasite motions are called secondary undesirable motions.

1.4.3 Nonlinear motions

Other compliant mechanisms require major strains where linear beam equations are not true anymore. The nonlinear equations which are responsible for large-scale geometric nonlinearity should be used. This can hinder their conception and study. It’s very complicated to derive mathematical model for large deflection of compliant mechanism.

1.4.4 Fatigue failures

Many compatible systems must be packed and worked under pressure conditions that make them vulnerable to failures. For large range of motion and repetitive loading its challenging to define fatigue life of compliant mechanism as its showing non-linear behaviour for large deflection.

1.4.5 Coupling elastomechanical and kinematic behaviors

It's very essential to get exact value of actuation force for particular range of motion with elastic deformation of beams. Its Challenging to Evaluate instant output response of compliant mechanism for small range of motion.

1.4.6 Serial-parallel configurations

Parallel and serial configuration are required to design stroke range, output stiffness and mechanical bandwidth Over constraint Compliant mechanism is having complexity for kinetostatic analysis. (Sandesh Solepatil, Narendra Deore, 2019).

2. METHODOLOGY

Performance of Compliant Mechanism is evaluated using Displacement and stress analysis of Mechanism. Compliant Mechanism is design and develop for linear range of motion. Performance of Mechanism is verified by Numerical and Experimental method.

2.1 Experimental setup

3D Printed XY Compliant mechanism with Polylactic acid (PLA) is developed with parallel beams positions. XY Compliant mechanism is developed for biomedical application with required range of 5mm in X and Y Direction Range of motion is evaluated by providing actuating force from 0.1 to 1N to motion stage.

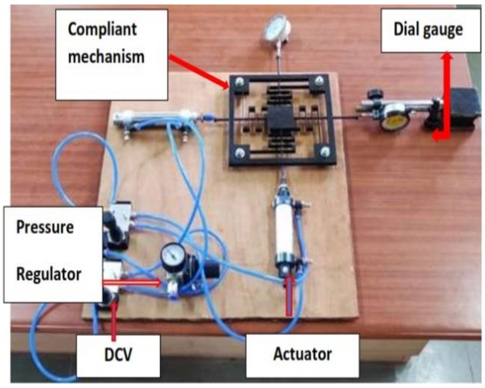

Figure7. Experimental setup Linear Compliant Mechanism

Initial Pressure of 0.1bar is set with the help of Pressure regulator to apply Pneumatic force on motion stage and displacement of motion stage is measured with the help of dial gauge indicator which is 0.3mm Maximum force of 1N is applied with the help of Pneumatic actuator on XY Stage for which PLA Material shows 5.1mm range of motion in X and Y direction.

2.2 Numerical analysis of XY compliant mechanism

2.2.1 Deflection analysis of XY mechanisms

Numerical analysis of XY Compliant mechanism is performed to evaluate displacement of motion stage in X and Y direction. Geometric modeling of mechanism is created with beam length of 50mm and cross section of $50mm.^2$ Outer part of mechanism is fixed and actuation is given to scanning platform. To Evaluate Displacement of compliant mechanism with parallel beam position Beam length of 50mm, width of 10mm and thickness 1mm aluminium alloy material with Elasticity =70 GPA are used to evaluate displacement by Numerical method. Force is applied at motion stage as shown in Figure 8 For various positions of beam at Motion stage three different mechanism are compared based on stress and displacement for Aluminium alloy material.

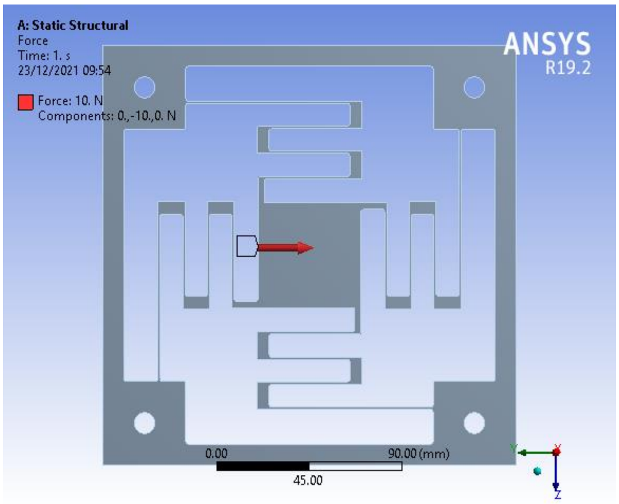

Figure 8. Force at motion stage

Figure 9 shows displacement of mechanism 1 at 10N force with aluminium alloy material Displacement value at 10N force is 2.37 mm and maximum displacement of 6.55mm is achieved at 30N.

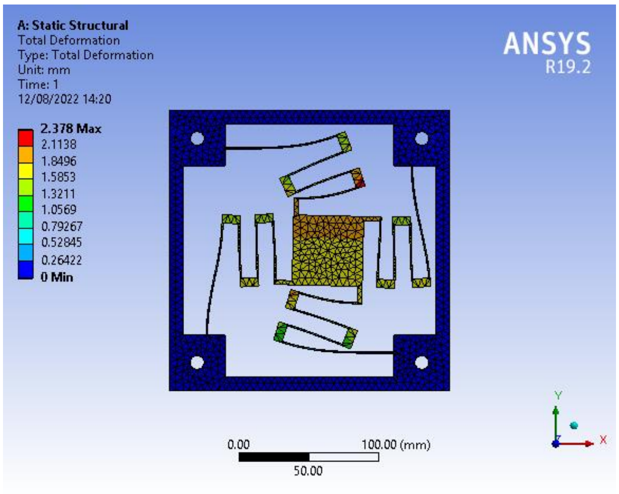

Figure 9. Displacement of Mechanism 1 at 10N force

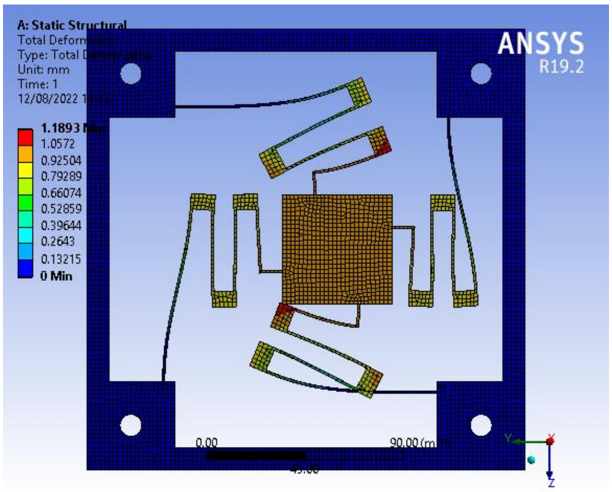

Figure 10. Displacement of Mechanism 2

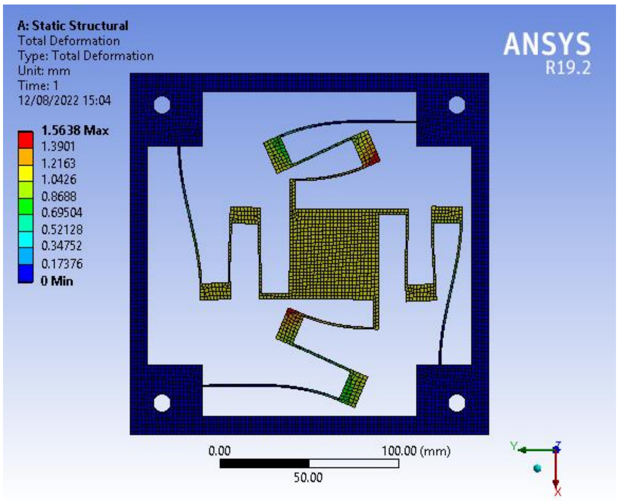

Figure 11. Displacement of Mechanism 2

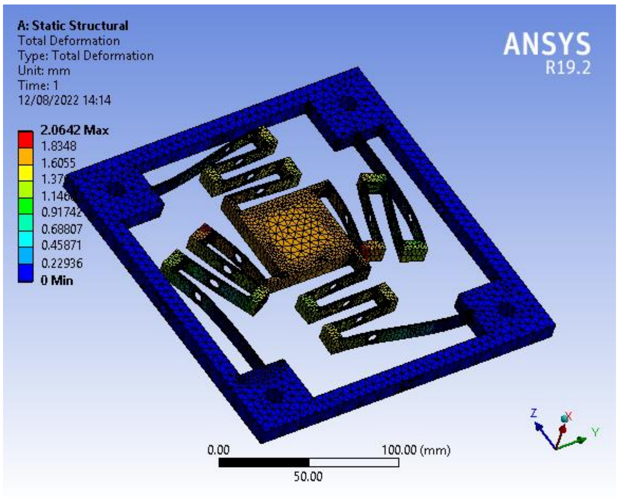

Figure 12. Displacement of Mechanism 1 with PLA Material at 02N force

Figure 10 shows displacement of mechanism 1 at 10N force with aluminium alloy material Displacement value at 10N force is 1.18 mm and maximum displacement of 2.68mm is achieved at 30N. Figure 11 shows displacement of mechanism 1 at 10N force with aluminium alloy material Displacement value at 10N force is 1.56 mm and maximum displacement of 3.44 mm is achieved at 30N.

Figure 12 shows displacement of mechanism 1 at 0.2N force with PLA material Displacement value at 0.2N force is 2.064 mm and maximum displacement of 5.11mm is achieved at 1N Force.

2.2.2 Stress analysis of XY mechanisms

To get range of motion without failure of mechanism stress analysis of XY Mechanisms are performed with actuating force of 2N to 30N with aluminum alloy material

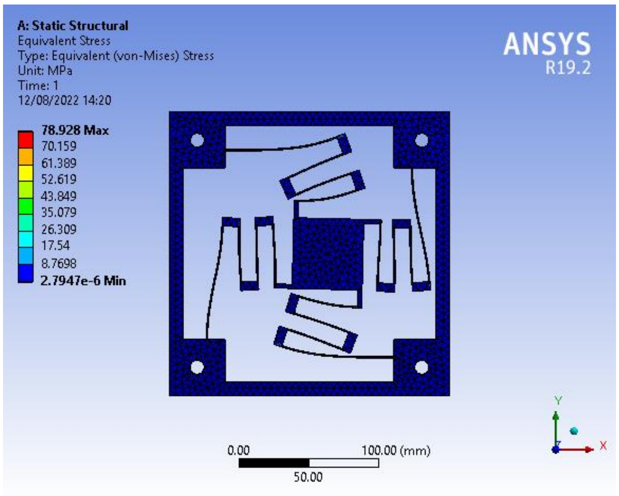

Figure13. Stress analysis of Mechanism 1

Figure 13 shows Stress analysis of mechanism 1 at 10N force with aluminium alloy material Stress value at 10N force is 78.92(Mpa) and MaximumVon-Mises Stress value of 236.76 (Mpa) is achieved at 30N actuating force. Figure 14 shows Stress analysis of mechanism 2 at 10N force with aluminium alloy material Stress value at 10N force is 52.61(Mpa) and MaximumVon-Mises Stress value of 157.83 (Mpa) is achieved at 30N actuating force.

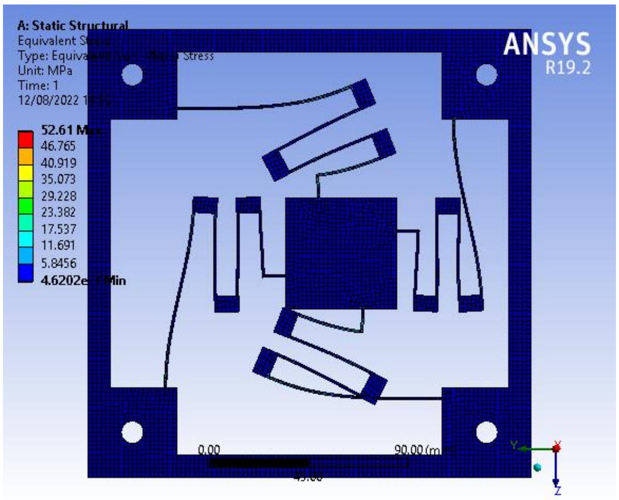

Figure14. Stress analysis of Mechanism 2

Figure 15 shows Stress analysis of mechanism 3 at 10N force with aluminium alloy material Stress value at 10N force is 48.65(Mpa) and MaximumVon-Mises Stress value of 145.95 (Mpa) is achieved at 30N actuating force.

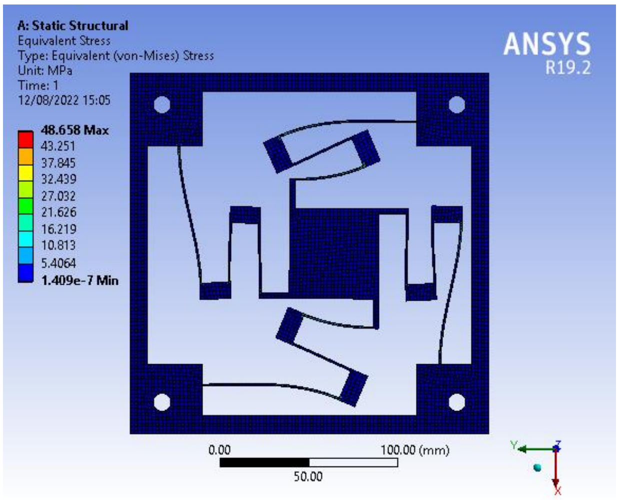

Figure 15. Stress analysis of Mechanism 3 at 10N force

Figure 16 shows Stress analysis of PLA Material is carried out to evaluate equivalent stress in mechanism at 1N Force Max stress of 10.978 (Mpa) is induced in mechanism at 1N force which in beyond yield point

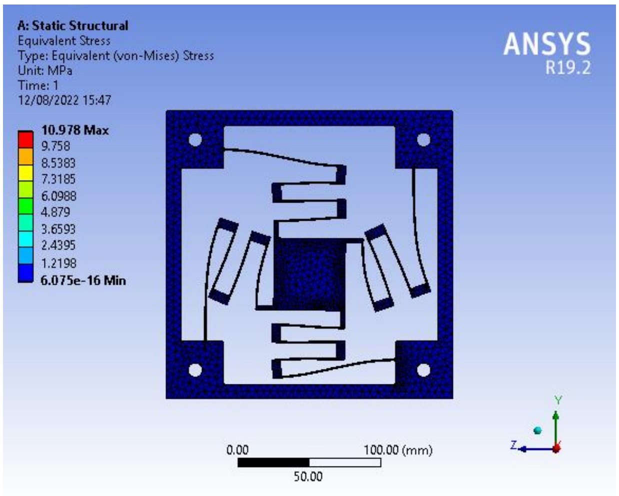

Figure 16. Stress analysis of Mechanism 1 at 1N force with PLA Material

3. RESULTS AND DISCUSSION

Compliant Mechanism is analyzed with Numerical and Experimental method to evaluate its Range of motion and stress values. Figure 17 Shows Graph of force vs Displacement. Maximum Displacement of 6.554mm is achieved with Mechanism 1, Maximum displacement of 2.68mm at 30N force with mechanism 2 and Maximum Displacement of 3.44mm at 30N force is achieved with mechanism 3 with aluminium alloy material.

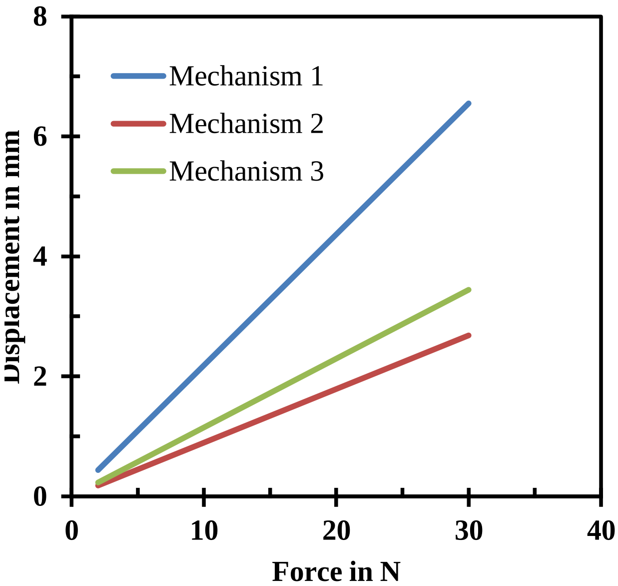

Figure 17. Graph of Force Vs Displacement

Figure 18 Shows Graph of Force Vs Displacement for Mechanism1 with PLA Material. By performing Numerical and Experimental analysis of XY Compliant mechanism with PLA Material we got maximum displacement of 5.1mm with Numerical method and 5.2mm with Experimental method for force of 1N. Stiffness of XY Compliant mechanism with PLA Material is 0.192N/mm

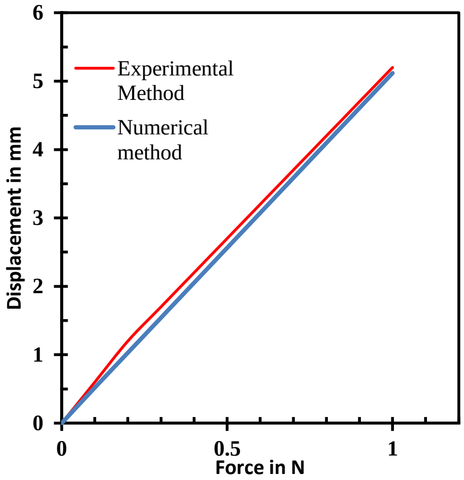

Figure 18. Graph of Force Vs Displacement for Mechanism1 with PLA Material

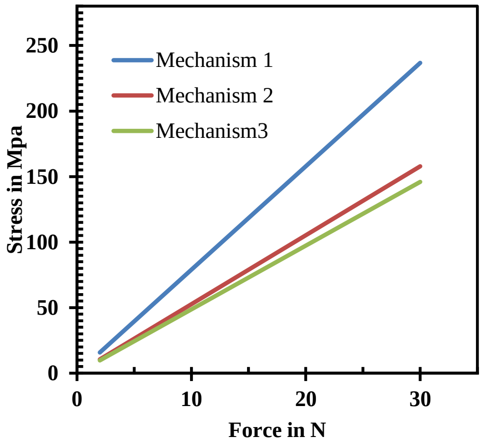

Figure 19. Graph of Force vs Stress

Figure 19 Shows Graph of force vs Stress Maximum Stress induced in Mechanism 1 is 236.76(Mpa), in mechanism 2 stress values is 157.83(Mpa) and in mechanism 3 stress values is 145.95(Mpa) at 30N Actuating force.

4. CONCLUSION

By Performing Numerical analysis using compliant mechanism1, 2 and 3 maximum range motion of 5.2403 mm is achieved in X and Y direction with Aluminium alloy material using parallel beam compliant mechanism. By performing Numerical and Experimental analysis of XY Compliant mechanism with PLA Material maximum displacement of 5.1mm with Numerical method and 5.2mm with Experimental method for force of 1N.

By Comparing stress values of Mechanism 1 with PLA Material and Aluminium alloy material maximum displacement of 5.2mm is achieved with PLA Material.

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