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Modeling of a 4DOF precise positioning stage by finite element method

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1. Introduction

Positioning with nanometre level resolution and accuracy is critically important for many modern technologies, especially in the fields of micro and nanotechnology. Micro/nano positioning systems are widely used in various applications, such as optical alignment [1, 2], scanning probe microscope [3, 4] and micro/nano manufacturing [5, 6]. Various micromotion stages were developed using conventional technologies based on servomotors, ball screws and rigid linkages [7]. However, these conventional technologies encounter problems such as friction, wear, backlash and lubrication, which struggle to achieve high positioning accuracy. The majority of practical precision positioning systems utilize flexure-based structures, such as compliant mechanisms and notch-flexure-based mechanisms. Micromotion stages utilizing the flexure hinge mechanism can have many advantages: negligible backlash and stick-slip friction; smooth and continuous displacement; adequate for magnifying the output displacement of actuation; and inherently infinite resolution.

Fundamentally, a flexure hinge mechanism is designed to either amplify or reduce the output displacement or force.

There have been a few modelling studies for the analysis and design of the monolithic flexure hinge mechanisms. Paros' model [8] was developed to calculate spring rates of a single-axis flexure hinge mechanism. However its application was limited to one hinge itself not to a system. There have also been researches on design formulae [9], and methodology [10] of the monolithic flexure hinge mechanism. Their applications were very specific. A more generalized model to estimate the elasticity, natural frequency, and dynamic characteristics of an assembly of flexure hinges was developed by Tanaka [11]. Furthermore, a finite element method (FEM) was also used for the design and analysis of the flexure hinge mechanism. A computer based method that automatically generates equations of motion for the flexure hinge mechanism was recently presented. The method also solves the generated equations numerically to predict the static characteristics of the hinge flexure mechanism.

This paper proposes a novel 4 DOF precise positioning stage on the rotational platform for calibration of the rotary encoder's raster scales. The stage is featured with flexure-based joints and mechanical actuation. The flexure-based joints for required motion were optimised and their performances in terms of workspace, maximum stress, resonant frequency have been evaluated by finite element analysis approach, using SolidWorks Simulation software package.

2. Mechanical structure

The proposed stage consists of the external ring (base), internal ring and target plate, which are joined with compliant mechanisms – flexure hinges. Centring/tilting adjustment elements are equipped in the same plane, in the two, one other perpendicular axes, as shown in Fig. 1.

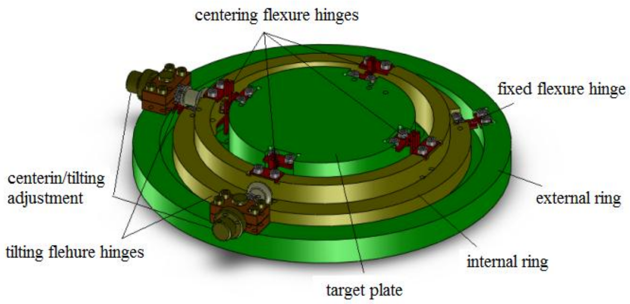

Fig. 1 4 DOF precise positioning stage

External ring is mounted on the spindle platform of the angle comparator. Internal ring with external ring are joined with two tilting flexure hinges and one fixing flexure hinge. Two tilting flexure hinges are mounted in the two one other perpendicular axes and one flexure hinge is mounted in the symmetry axis between these flexure hinges. Internal ring and the target plate are joined with four centring flexure hinges, which are located in the two, one other perpendicular axes, as shown in Figs. 1 and 2.

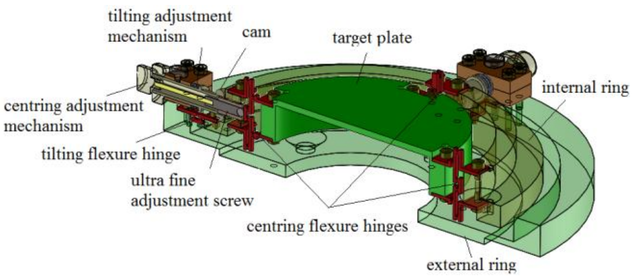

Fig. 2 Stage cross-section

While there are many types of commercially available actuators, that can achieve nanometre level precision, most are more expensive than manual actuators and require for expensive control system. In order, to make positioning system as inexpensive as possible, it uses manual adjusters, to provide motion. These high precision adjusters avoid all of the complications associated with hydraulic, pneumatic drivers or electronic actuators. It is also complicated to install electric, pneumatic or hydraulic source into the positioning system, because it is fit on the rotational platform.

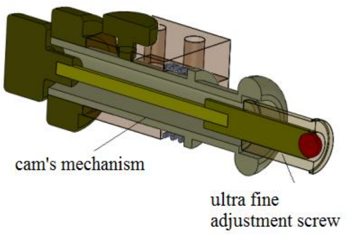

Fig. 3 Centring/tilting adjustment mechanism

Cam's mechanism was chosen to operate tilting adjustment, as shown in Fig. 3. The travel range is 55 μm. The handy dimensions of the knobs are optimally chosen to feel rotation as little as 0.5°-1°. This enables to achieve resolution of 0.3 μm. Two cams are mounted on the external ring in the two perpendicular axes of the same plane. The cam follows the plane surface of the internal ring, as a result, the tilting flexure hinges are deformed and the target plate rotates about the axis between the tilting flexure hinge and fixed tilting flexure hinge.

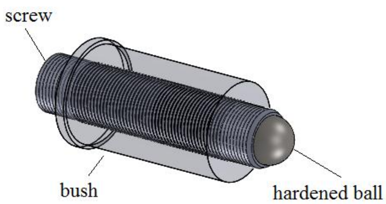

Fig. 4 Ultra fine adjustment screw

Ultra fine adjustment screw was chosen to operate centring adjustment, as shown in Fig. 3 and 4. Ultra fine adjustment screws are compact and provide extremely high resolution. Special design of stainless steel screw with a high precision brass collar provides smooth and repeatable action by mating a high precision, 0.20 mm pitch. The screws have a hardened steel ball on the tip. The handy dimensions of the knobs are optimally chosen to feel rotation as little as 0.5°-1°. This enables to achieve resolution of 0.5 μm. Axial load capacity noted by manufacturer is 40 N. Ultra fine adjustment screw equipped in the internal ring pushes the centring flexure hinge, as a result, the target plate moves to the same direction.

3. Fabrication

The flexure hinges can be machined using an electro-discharge machining (EDM) technique to ensure the machining precision of the stage.

In general, the hinge thickness should be small to increase the displacement reduction ratio, while avoiding the melting of the material during the EDM process. The minimum thickness of the hinge has to be larger than 0.3 mm. EDM can be used only for electrically conductive materials, and its performance is not substantially affected by mechanical physical and metallurgical properties of work piece material. It can perform various kinds of operations such as drilling, cutting, 3D shaping and sizing (wire EDM) and spark-assisted grinding (EDDG). It gives good repeatability and accuracy of the order of 25-125 μm. The tolerances that can be achieved are ±2.5 μm. Under normal conditions, the volumetric material removal rate is in the range of 0.1-10 mm^3/min. The surface finish produced during EDM is usually in the range of 0.8-3 μm, depending upon the machining conditions used.

4. Optimal design

The flexure hinge is used in precision positioning stage. Functionally, the ideal flexure hinge permits limited relative rotation of the rigid adjoining members while prohibiting any other types of motion. The typical flexure hinge consists of one or two cutouts that are machined in a blank material. A physical bending point is generated at a maximum stress point. The flexure hinge has the highest accuracy, when the bending point is located in the centre of the hinge. The optimal design problem considers the stress at the hinge point, the output displacement of the system and the system size. A symmetric circular flexure hinge has the bending point in the centre of the hinge. Flexure hinges are affected in two directions therefore a symmetric two-axis circular flexure hinge is suitable for ultra precision positioning system, as shown in Fig. 5.

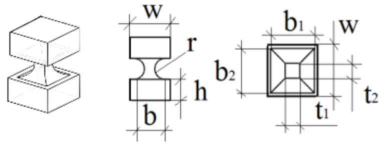

Fig. 5 Two-axis circular flexure hinge

FEM analyses were performed to optimize the geometry of flexure hinge design that must to have appropriate stiffness, experience appropriate stresses during the operation, using "SolidWorks Simulation 2011" software package. The variables considered in the finite element analyses were the width of the flexure in the direction parallel to the hinge, the thickness of the flexure hinge and the circle radius.

The principal design parameters for tilting flexure hinge, as shown in Fig. 6, are: $l = 2.5$ mm; $r = 0.5$ mm, $h = 1.0$ mm, $t = 0.5$ mm.

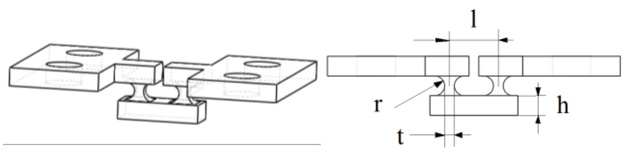

Fig. 6 Tilting flexure hinge

The principal design parameters for centring flexure hinge, as shown in Fig. 7, are: $l_1 = 1.5$ mm, $l_2 = 4.5$ mm, $l_3 = 3.0$ mm, $r = 0.5$ mm, $h = 1.0$ mm, $t = 0.5$ mm.

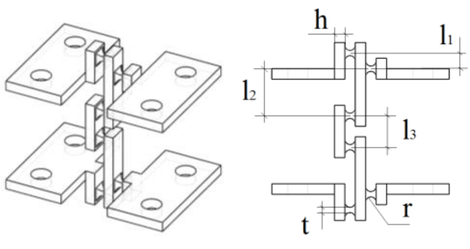

Fig. 7 Centring flexure hinge

5. Finite element analysis

The finite element analyses of the stage were performed. Main design factors of the hinge mechanism are the geometric structure and material properties. The hinge mechanism uses elastic deformation of the material. If the deformation of the hinge is over the limit of elastic deformation, the plastic deformation occurs and the lifetime of the hinge reduces significantly.

The following invariable boundary conditions were assumed in the simulation studies:

- the cam mechanism and ultra fine adjustment screw are rigid bodies, therefore their deformations not are taken into account;
- bottom plane of the external ring is fixed rigidly;
- unalloyed steel C35 is chosen for the external ring, internal ring and the target plate;
- aluminium alloy Al 7075-T6 is chosen for the flexure hinges due to their properties: small elastic modulus and high yield strength, as shown in Table;
- all parts are connected with bonded contact (no clearance);
- gravity force is applied normal to plane 9.81 N/m^2.

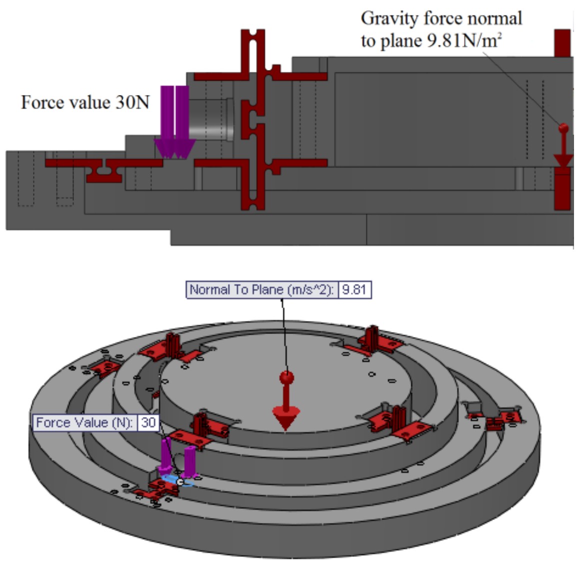

Fig. 8 Boundary conditions of tilting simulation study

The FEM analysis test of the stage was carried out in five steps.

In step 1, the maximum output displacement of the tilting positioning was simulated. An input displacement of 55 μm was applied at the horizontal plane of the internal ring, as shown in Fig. 8.

In step 2, the minimum output displacement of the tilting positioning was simulated. An input displacement of 0.3 μm was applied at the horizontal plane of the internal ring, as shown in Fig. 8.

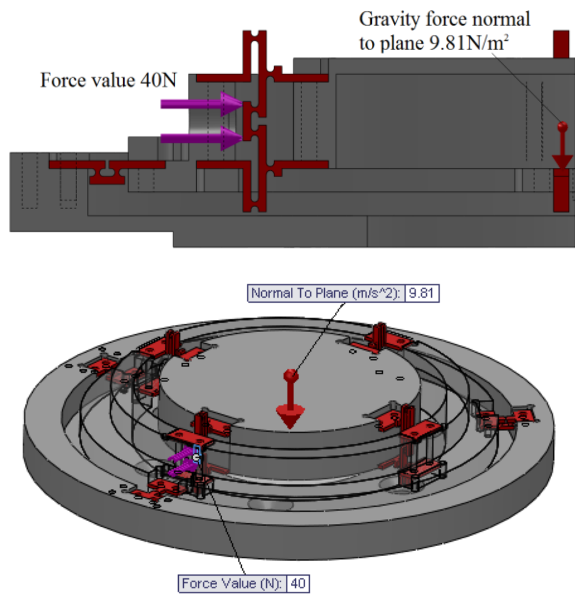

Fig. 9 Boundary conditions of centring simulation study

In step 3, the maximum output displacement of the centring positioning was simulated. Horizontal input force of 40 N was applied at the vertical plane of the centring flexure hinge, as shown in Fig. 9.

In step 4, the minimum output displacement of the centring positioning was simulated. The minimum input displacement of 0.5 μm was applied at the vertical plane of the centring flexure, as shown in Fig. 9.

In step 5, the modal analysis was simulated. The bottom surface of the external ring was fixed to immobilize the mechanism.

Table

Material properties Al 7075-T6

Property	Value	Units
Elastic modulus	7.19999992e+010	N/m^2
Poisson's ratio	0.33	N/A
Yield strength	505000003.1	N/m^2
Thermal expansion coefficient	2.4e-005	K
Mass density	2810	Kg/m^3

6. Results

In step 1, when maximum input displacement of 55 μm was applied at the horizontal plane of the internal ring, was observed, that the maximum output displacement of the target plate is in the node 1, which value is 51.08 μm and the minimum output displacement is in the node 11, which value is 26.33 μm, as shown in Fig. 10. The target plate rotates the maximum angle of 0.6336° about axis betwen tilting flexure hinge and fixed tilting flexure hinge.

In step 2, when minimum input displacement of 0.3 μm was applied at the horizontal plane of the internal ring, was observed, that the maximum output displacement of the target plate is 0.2787 μm and the minimum output displacement is 0.1455 μm. The target plate rotates the minimum angle of 0.000347° about axis betwen tilting flexure hinge and fixed tilting flexure hinge.

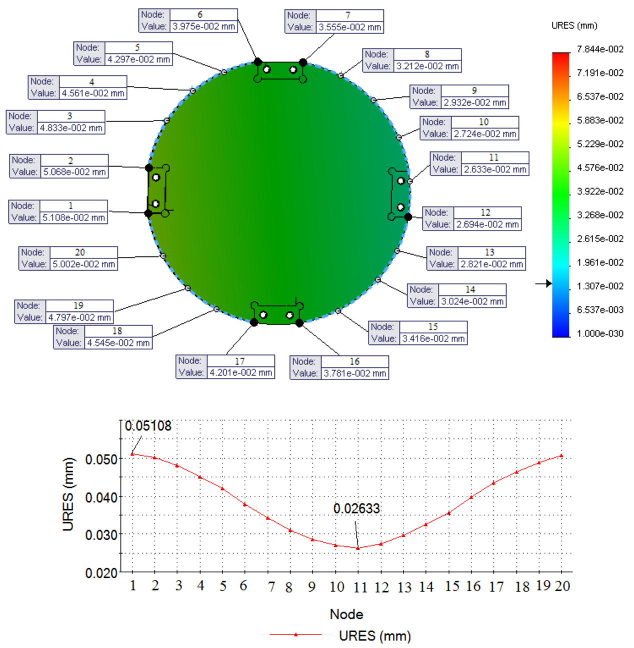

Fig. 10 Tilting displacement simulation results when maximum input displacement was applied

The stress distribution in the tilting flexure hinge is shown in Fig. 11. The maximum von Mises stress in the tilting flexure hinge occurs in the node 4. The maximum value is 450.3 MN/m^2, which is 89% of the yield strength of the aluminium alloy 7075 T-6.

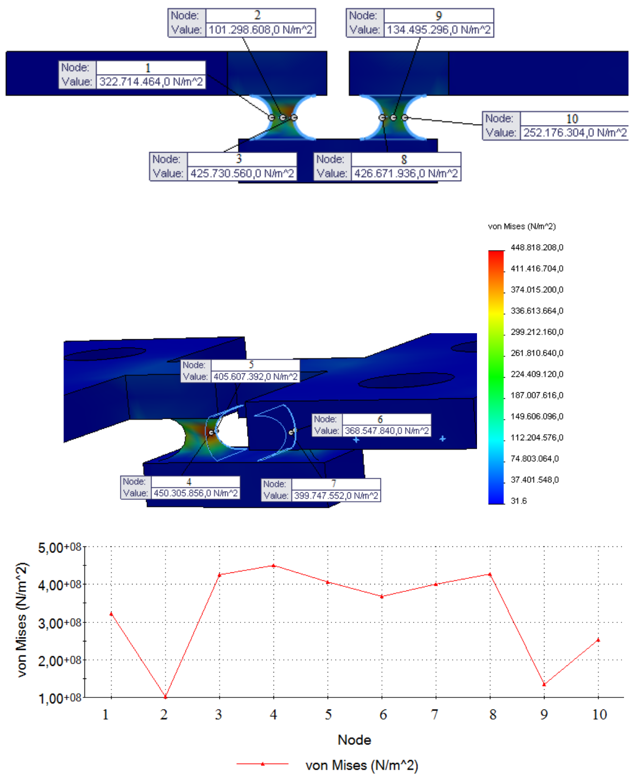

Fig. 11 Finite element analysis of the von Mises stress in the tilting flexure hinge

In step 3, when maximum input force of 40 N was applied at the vertical plane of the centring flexure hinge, was observed, that the maximum output displacement of the target plate is 55.86 µm, as shown in Fig. 12.

In step 4, when minimum input displacement of 0.5 µm was applied at the vertical plane of the centring flexure hinge, was observed, that the minimum output displacement of the target plate is 0.22 µm.

In step 5, after the modal analysis was obtained that the first modal frequency is 171.78 Hz.

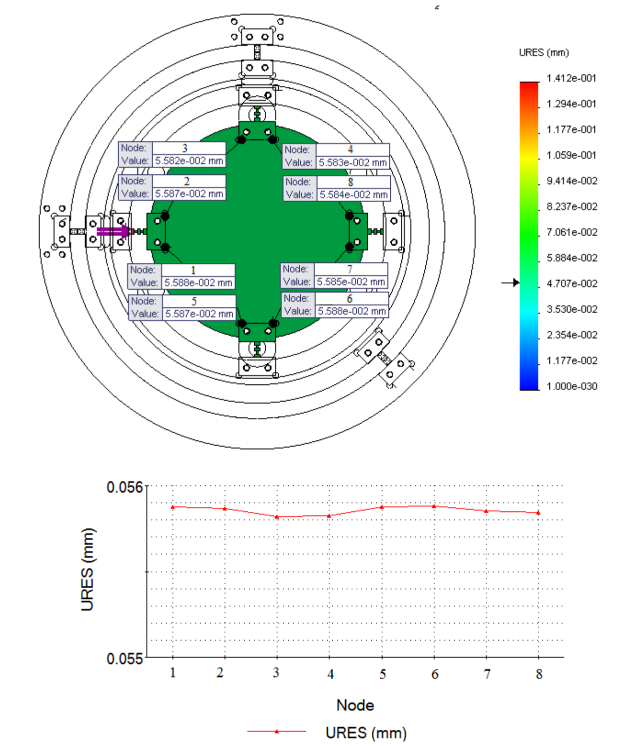

Fig. 12 Centring displacement simulation results when maximum input force was applied

The stress distribution in the centring flexure hinge is shown in Fig. 13. The maximum von Mises stress in the centring flexure hinge occurs in the node 5. The maximum value is 500.6 MN/m^2, which is 99% of the yield strength of the aluminium alloy 7075 T-6.

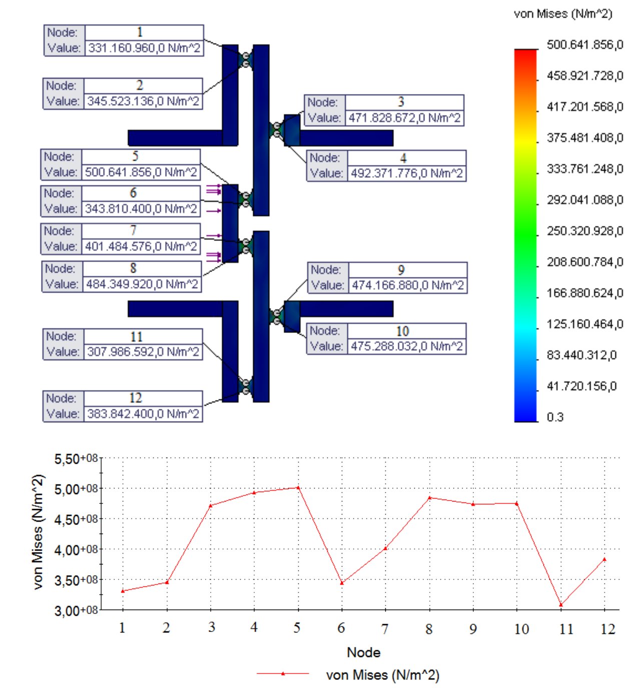

Fig. 13 Finite element analysis of the von Mises stress in the centring flexure hinge

7. Conclusions

Novel 4DOF precise positioning stage, using flexure-based joints for the require motion, was designed. Finite element analysis was used to find an optimal configuration of the flexure structure by taking into account the maximum stress. The FEA results show that the proposed positioning stage can provide motions with high precision and resolution. As the result, the resolution of 0.22 μm of centring movement and the resolution of 0.28 μm of tilting movement was achieved. Besides, the stage also possesses configurationally simplicity and compactness.

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G. Augustinavičius, A. Čereška

KETURIŲ LAISVĖS LAIPSNIŲ PRECIZINIO POZICIONAVIMO SISTEMOS MODELIAVIMAS BAIGTINIŲ ELEMENTŲ METODU

R e z i u m ė

Straipsnyje pateikta nauja keturių laisvės laipsnių precizinio pozicionavimo platforma ant besisukančio pagrindo kampo keitiklių rastrinių skalių kalibravimui. Precizinio pozicionavimo platforma pasižymi tuo, kad mechaninio vykdiklio judesys perduodamas tampriaisiais vyriais. Reikiamam pozicionavimo tikslumui pasiekti tamprieji vyriai yra optimizuoti. Baigtinių elementų metodu, naudojant SolidWorks Simulation programinį paketą, buvo ištirtos šios precizinio pozicionavimo platformos charakteristikos: veikimo zona, rezoliucija bei savųjų virpesių dažnis.

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MODELING OF A 4DOF PRECISE POSITIONING STAGE BY FINITE ELEMENT METHOD

S u m m a r y

This paper proposes a novel 4DOF precise positioning stage on the rotational platform for the calibration of the rotary encoder’s raster scales. The 4DOF precise positioning stage is featured with flexure-based joints and mechanical actuation mechanisms. The flexure-based joints for required motion were optimised. Their performances in terms of maximum and minimum output displacements, maximum stress and resonant frequency have been evaluated via finite element analysis approach, using SolidWorks Simulation software package.

Keywords: flexure hinge, precise positioning, positioning stage.

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