VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Giedrius AUGUSTINAVIČIUS

RESEARCH OF A FLEXURE BASED MICROPOSITIONING STAGES

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
MECHANICAL ENGINEERING (09T)

VGTU LEIDYKLA

Vilnius TECHNIKA 2014

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The summary of the doctoral dissertation was distributed on 18 December 2014.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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MIKROPOZICIONAVIMO SISTEMŲ TAIKANT LANKSČIAS JUNGTIS TYRIMAI

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
MECHANIKOS INŽINERIJA (09T)

Vilnius LEIDYKLA TECHNIKA 2014

Disertacija rengta 2008–2014 metais Vilniaus Gedimino technikos universitete.

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Disertacija bus ginama viešame Mechanikos inžinerijos mokslo krypties tarybos posėdyje 2015 m. sausio 19 d. 14 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.

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Disertacijos santrauka išsiuntinėta 2014 m. gruodžio 18 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

VGTU leidyklos „Technika“ 2304-M mokslo literatūros knyga.

Introduction

Problem formulation

Various precise positioning stages have been developed using conventional technologies. A key element of translational or rotational motions are bearing structure. However, the bearing structure encounter problems such as friction, wear, backlash and lubrication, which struggle to achieve high positioning accuracy. Some of practical, precise positioning systems utilize flexure-based structures, such as flexure mechanisms as a result can have many advantages: negligible backlash and stick-slip friction; smooth and continuous displacement; adequate for magnifying or reduce the output displacement of actuation and inherently infinite resolution. A monolithic structure of mechanism required to eliminate assembly errors. Many flexure based precise positioning stages proposed by scientists have a single directional output motion. Two single directional output motion stages are required to couple in perpendicular one onto another in order to get planar dual axis directional motion. For this reason, the Abbe's errors increase and assembly errors appear, which struggle to achieve positioning accuracy. If two single directional output motion stages have been coupled into a monolithic structure in the same plane perpendicular, then the geometrical parameters of the stage would increase a lot. Actuating 3RRR (revolution/revolution/revolution) precise positioning stages, which are proposed, by three piezoelectric actuators is more expensive. Besides, the positioning of the stage in the directions of the x and y axes is not identical due to not perpendicular directions of actuations. As a result, positioning becomes more complicated. Precise positioning stages based on the lever or SR (Scott-Russell) lever compliant mechanisms do not eliminate cross-axis coupling errors. Furthermore, modelling algorithm of compensation is difficult.

This present work focuses in the development and researches of a flexure based micropositioning stages for calibration of the rotary encoder raster's or code's scales on a rotational platform with limited geometrical parameters.

The relevance of the thesis

Science and technology research in micro- and nano- technologies promise breakthroughs in such areas as micro-, nano- manufacturing, biotechnology, nano electronics, information technology, fabrication of nanosystems and provides the impetus to the development and research of positioning in micro-, nanoscale.

Research object

A dual axis flexure based micropositioning stages with mechanical and piezo-electric actuation.

Aim of the thesis

The aim of the work is to propose a methodology for micropositioning rotary encoder raster or code scales on the rotating platform; to create physical models using proposed methodology and to establish an analytical approach and experimental researches for obtaining accuracy parameters and dynamical characteristics of the stages.

Objectives of the thesis

In order to achieve the aim of the work, the following objectives must be completed:

1. Overview and analysis of scientific literature about precise positioning stages.
2. To propose a methodology for micropositioning of the rotary encoder raster or code scales.
3. The analytical approach and finite element method analyses for obtaining accuracy parameters and dynamical characteristics of the micropositioning stages, developed on the basis of the proposed methodology establish.
4. To create physical models of the micropositioning stages with mechanical and piezoelectric actuation and to perform the experimental research for obtaining accuracy parameters and dynamical characteristics of stages.
5. To establish the inverse hysteresis model for a proposed micropositioning stage with piezoelectric actuation for increase positioning accuracy.

Methodology of research

In this work, theoretical calculations have been carried out based on the principles of theoretical mechanics, vibration theory, theory of measurements using the analytical and finite element analysis methods with Matlab/Simulink, SolidWorks, Ansys, Origin, PI MicroMove, PC-DMIS EMS, Labview software package.

The experiments have been carried out in the Laboratories of the Department of Mechanical Engineering of Vilnius Gediminas Technical University is using Lion Precision, Physik Instrumente, National Instruments, Hexagon metrology hardware.

Scientific novelty

1. Methodology of raster and code scale micropositioning has been proposed and researched, the application of which increase or decrease input motion, but also decrease motion trajectory linearity errors due to these characteristics:
   - Flexure hinges applied for the increase of positioning accuracy and forming planar monolithic structures with positioning mechanisms;
   - Decoupled positioning in the directions of the *x* and *y* axes;
   - Power acting in a symmetric way, which cause platforms' translation movements in the directions of *x* and *y* axes.
2. Dynamic models of micropositioning systems have been proposed in order to determine dynamic characteristics, while assuming that flexure hinge is as if elastic element, which has three degrees of freedom.

Practical value of research findings

The application of the proposed stages is the positioning of rotary encoder raster or code scales for calibration operation; besides can be used for planar positioning in such areas as micro-, nanomanufacturing, biotechnology, nanoelectronics, information technology, fabrication of Nanosystems and other.

Defended statements

1. According to the motion trajectory linearity errors proposed micropositioning stages have been implemented 44% with mechanical actuation and 17% with piezoelectrical actuation, comparison to tradicional micropositioning stages.
2. Application of an inverse hysteresis model of the micropositioning stage control with piezostack actuators results in significantly increased positioning accuracy, even 94%.

Structure of the thesis

The scientific work consists of the general characteristic of the dissertation, three chapters, conclusions, list of literature, list of publications and addenda. The total scope of the dissertation is 114 pages, 58 pictures, 14 tables, 119 numbered formulas and 10 addenda. A total of 75 scientific literature sources has been studied.

1. Review and analysis of a flexure hinges and their application in micropositioning stages

High accuracy positioning is critically important for many modern technologies, especially in the fields of micro- and nanotechnologies. Various precise positioning stages were developed using conventional technologies based on stepper-, servo motors, ball screws, and rigid linkages, pneumo-, hydro-, micro actuators. A key element of translational or rotational motion is bearing structure. However, these conventional technologies encounter problems such as friction, wear, backlash and lubrication, which struggle to achieve high positioning accuracy. Some of precise positioning systems utilize flexure-based mechanisms. The compliant mechanisms transform an input form of energy (mechanical, electric, thermal, magnetic, etc.) into output motion. The principle aim of compliant mechanism is to achieve low stiffness in the direction of the required motion and high stiffness in all other directions without introducing undue stress and friction (Lobontiu, 2002). Precise positioning stages utilizing the compliant mechanism can have many advantages: negligible backlash and stick-slip friction; smooth and continuous displacement; adequate for magnifying or reduce the output displacement of actuation; and inherently infinite resolution. A monolithic structure is required to eliminate assembly errors. There have been a few modelling studies for the analysis and design of the monolithic flexure hinge mechanisms (Lobontiu, 2003; Hwang *et al.* 2007; Kim *et al.* 2005; Huang *et al.* 2009; Tang *et al.* 2009; Zhang *et al.* 2012; Smith *et al.* 2005).

To meet the requirements of precise motion at sub-micro-, nanoscale and high speed, high accuracy and large load, piezoelectric actuators (PAs) are essential drive positioning mechanisms for achieving ultra precision. Therefore, PAs are highly effective actuators for flexure-based mechanisms. However, due to the non-symmetric nature of piezoelectric materials, a converse piezo effect produces hysteresis and constitutive nonlinearities at all drive levels. The hysteresis effect between the displacement and the electric field often decreases positioning precision. Its nonlinearity with local memory causes positioning errors and critically limits the operating speed and precision of PA. Nonlinear hysteresis effects can be compensated by the following three efforts: by use of electric charge control, by use of feedforward nonlinear models and by use of closed-loop control schemes, respectively. However, the charge current control may not only cause drift and saturation problems, it can also substantially reduce operating range. Another solution is to model the converse piezo effect, so that feed-forward compensation can be used correct hysteresis nonlinearity based on the inverse-hysteresis model. Mathematical models of hysteresis behavior proposed in the literature include the Preisach model, the generalized Maxwell-slip hysteresis model, Prandtl-Ishlinskii model, Duhem model, Bouc-Wen model, Dahl model and others. Predicting PEA displacement in the above models needs three or more parameters of the differential equations. The third effort is to combine the feedforward control and the feedback control.

Many flexure based precise positioning stages, proposed by scientists have single directional output motion. Two single directional output motion stages are required to couple in perpendicular one onto another, forgetting planar dual axis directional motion. For this reason, the Abbe's errors increases and assembly errors appears which struggle to achieve positioning accuracy. If two single directional output motion stages to couple into a monolithic structure in same plane perpendicular, the geometrical parameters of the stage increased a lot. Proposed 3RRR micropositioning stages actuated by three piezoelectric actuators make it more expensive. Besides, the positioning of the stage in the directions of the *x* and *y* axes is not identical due to not perpendicular directions of actuations and it makes positioning complicated. Micropositioning stages based on the lever or Scott Russell lever compliant mechanisms not eliminate cross-axis coupling errors and modelling algorithm of compensation make it difficult.

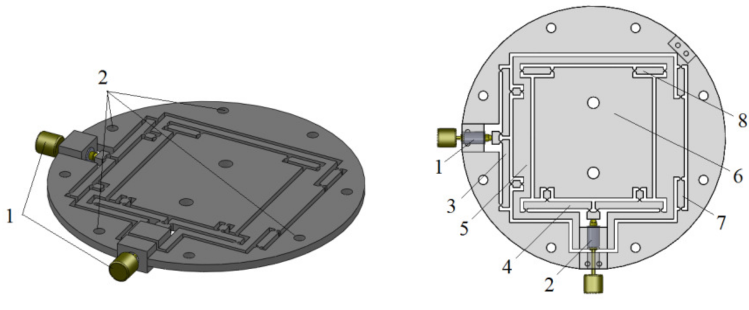
For this reason have been developed novel micropositioning stages for calibration of the rotary encoder raster or code scales on a rotational platform with limited geometrical parameters.

2. Theoretical studies of a micropositioning stages

This chapter focuses on theoretical modelling of a dual axis flexure-based micropositioning stages on the rotating platform for the calibration of the rotary encoder's raster scales. The function of a stage is to constrain motion to a desired direction. For a linear stage, the desired motion is along an ideal straight line. Any motion in a constrained direction will contribute to deviation from the ideal trajectory. Two physical models, – with mechanical and piezoelectric actuation, have been proposed.

The first design concept of a dual axis flexure-based micropositioning stage consists of a monolithic structure and two manual adjusters, similar to micrometers to provide motion, as shown in Figure 1a and Figure 1b. Adjustment screws have been mounted into the monolithic structure rigidly. Each *x* and *y* platforms consist of the input motion reduction mechanism and a guide mechanism of motion. The *y* axis platform has the same structure except that it is inside the *x* platform. The motion in the directions of the *x* and *y* axes is decoupled. Generally, a decoupled stage implies that one adjuster produces only one directional output motion without affecting the motions in the directions of other axes. The major objective for the design of a stage with decoupled output motion is to eliminate the cross-axis coupling errors between the *x* and *y* directions translations and parasitic rotation errors around the axes. The symmetric lever mechanism structure reduces input displacement, straightness deviation and makes the stage robust to variation of temperatures.

The second design concept of a dual axis flexure based micropositioning stage consists of a monolithic structure and two piezostack actuators to provide motion, as shown in Figure 2a and Figure 2b. Piezostack actuators, named PICMA P-887 and produced by Physik Instrumente (PI) GmbH & Co, have been adopted to drive dual axis micropositioning stage and possess maximal stroke of 38 µm. Each *x* and *y* stage consists of the input displacement amplifying mechanism and a guide mechanism of motion. The *y* axis stage has the same structure except that it is inside the *x* stage. The motion in the directions of the *x* and *y* axes is decoupled, as a result, reduces cross-axis coupling errors, such as referred previously. Symmetric lever mechanism structure amplifies input displacement, reduces straightness deviation and makes the stage robust to variation of temperatures.



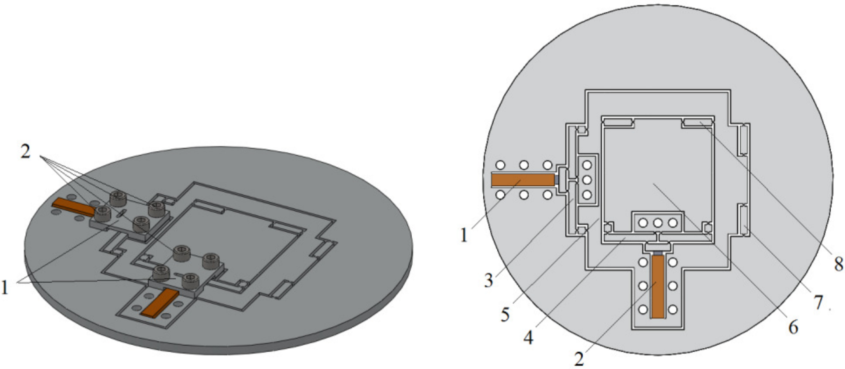
a) b)

Fig. 1. Dual axis micropositioning stage with mechanical actuation: a) micropositioning stage: 1 – knob, 2 – fixing holes; b) top view of the stage (transparent): 1, 2 – ultra fine adjustment screws, 3, 4 – motion reduction mechanisms, 5 – *x* – axis moving platform, 6 – *y* – axis moving platform, 7, 8 – support mechanisms

The positioning of specimens or equipment to very high accuracies often involves feedback and sometimes requires the use of fine servo controls. Their speed of response will be limited by the natural frequencies of the flexure. The sensitivity of a mechanism to vibration also tends to be dependent on its natural frequencies. Flexure mechanisms are inherently spring-mass systems and so it is particularly important to characterize their general dynamic behavior.

On the basis of multibody dynamics by replacing each flexure hinge with a revolution and translation joint with a linear and torsion spring while considering the remaining elements as rigid bodies, the dynamic models of dual axis micropositioning stages have been established. Two translations in the directions of the x and y axes and one rotation about the sensitive axis of the hinge φ are generally possible. The dynamics of flexure-based mechanisms have been approached by means of Lagrange's equations based on the scalar quantities of kinetic energy, potential energy, and dissipation energy.

Using MATLAB/Simulink software package have been developed the program which carried out the following actions: develop the analytic expressions of the functions of kinetic, potential and dissipation energies; differentiate them according to generalized coordinates, according their derivatives and time; transform them into the operator form and solve in respect of the generalized coordinates, generate the matrices with all the data required to form the structural diagram and Simulink-model of the stage.



a) b)

Fig. 2. Dual axis micropositioning stage with piezoelectric actuation:
a) micropositioning stage: 1 – fixing plates, 2 – fixing bolts; b) stage's view without fixing plates: 1, 2 – piezostack actuators, 3, 4 – motion amplification mechanisms, 5 – x – axis moving platform, 6 – y – axis moving platform, 7, 8 – a guide mechanisms

In order to examine the static and dynamic characteristics of the stage with mechanical actuation, the simulation of Simulink model has been carried out and the results have been obtained. When input displacements of 350 µm have been applied in the directions of the x and y axis, then the output platforms translate by displacements of 116.5 µm and the maximum stresses occur at

454.5 MN/m^2, which is 90% of the yield strength of the aluminium alloy 7075-T6.

Moreover, the reduction ratio of the stage is about 0.33 and the resolution – 0.162 µm. The natural frequencies, obtained by dynamic model are 501 Hz and 709 Hz in the directions of the x and y axes, respectively, as shown in Figure 3.

In order to examine the static and dynamic characteristics of the stage with piezoelectric actuation, the simulation of Simulink model has been carried out and the results shows, when maximal input displacements of 38 µm have been applied in the directions of the x and y axes, the output platforms translate by displacement of 65.0 µm. Moreover, the amplification ratio of the stage is about 1.7 and the resonant frequencies obtained by dynamic model are 339 Hz and 533 Hz in the directions of the x and y axes, respectively, as shown in Figure 4.

To compare the results of analytical model FEA simulations of the proposed stages, using Ansys software package, have been performed. Static and modal analyses have been conducted for obtaining the elastic properties and resonant frequencies of the micropositioning stages.

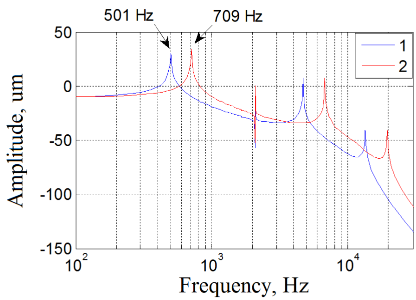


Fig. 3. Resonant frequency (Bode diagram) of a micropositioning stage with mechanical actuation: 1 – x axis positioning; 2 – y axis positioning

The simulation results of a micropositioning stage with mechanical actuation show, when the input displacement of 350 µm has been applied in the direction of the x axis, then the output platform translates by displacement of 111.53 µm and the maximum stress occurs at 467.5 MN/m^2, which is 92.57% of the yield strength of the aluminium alloy 7075 T-6. Whereas when the input displacement of 350 µm has been applied in the direction of the y axis, then the output platform translates by displacement of 113.05 µm and the maximum stress occurs at 384.4 MN/m^2, which is 76.11 % of the yield strength of the material aluminium alloy 7075 T-6. Moreover, the FEA results show that the reduction ratio of the stage is about 0.308. The resolution of the stage is 0.155 µm and 0.157 µm in the directions of the *x* and *y* axes, respectively. The resonant frequencies, obtained by FE analyses are 516.75 Hz and 728.42 Hz in the directions of the *x* and *y* axes, respectively.

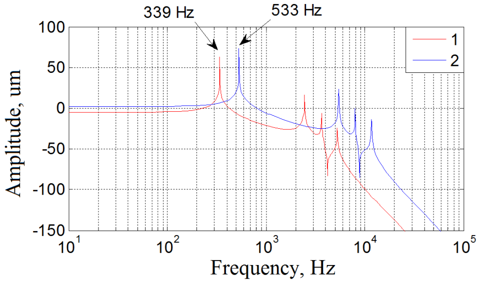


Fig. 4. Resonant frequency (Bode diagram) of a micropositioning stage with piezoelectric actuation: 1 – *x* axis positioning; 2 – *y* axis positioning

The simulation results of a micropositioning stage with piezoelectric actuation show, when the input displacement of 38 µm has been applied in the direction of the *x* axis, then the output platform translates by displacement of 64.6 µm and the maximum stress occurs at 211 MN/m^2, which is 41.2% of the yield strength of the aluminium alloy 7075 T-6. Whereas when the input displacement of 38 µm has been applied in the direction of the *y* axis, then the output platform translates by displacement of 62.71 µm and the maximum stress occurs at 165 MN/m^2, which is 32.3% of the yield strength of the material aluminium alloy 7075 T-6. Moreover, the FEA results show that the amplification ratio of the stage is about 1.7 and 1.65, in the directions of the *x* and *y* axes, respectively. The resonant frequencies of the micropositioning stage with piezoelectric actuation obtained by FE analysis are 320.92 Hz and 533.49 Hz in the directions of the *x* and *y* axes, respectively.

3. Experimental research of a micropositioning stages

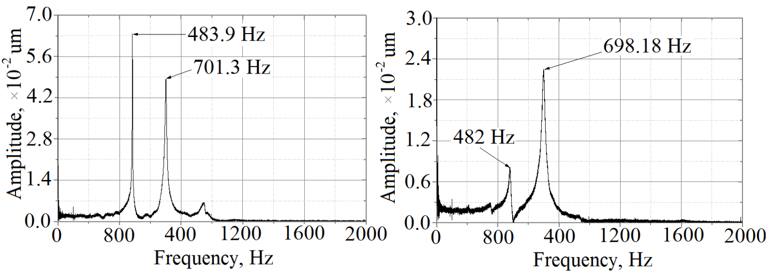
This chapter describes experimental research of the accuracy parameters and dynamical characteristics of the proposed micropositioning stages. The monolithic structures have been machined using an electro-discharge machining (EDM) technique in order to ensure the machining precision of stages.

The experimental setup of the micropositioning stage with mechanical actuation is shown in Figures 5a and 5b. The input displacement has been measured by eddy current proximity sensor. Input displacement and output displacement have been measured by coordinate measurement machine in parallel with eddy current proximity sensor.

a) b)

Fig. 5. Experimental setup of a micropositioning stage with mechanical actuation: a) experimental stand and measurement equipment; b) positions of spheres

The researches of micropositioning stage with mechanical actuation have been carried out. The aim of the research has been to measure the accuracy parameters and to obtain natural frequencies of the stage. The research has been carried out in three steps: firstly, the stroke of the stage has been measured; secondly, the resolution of the stage has been identified; finally, the natural frequencies of positioning stage have been obtained.

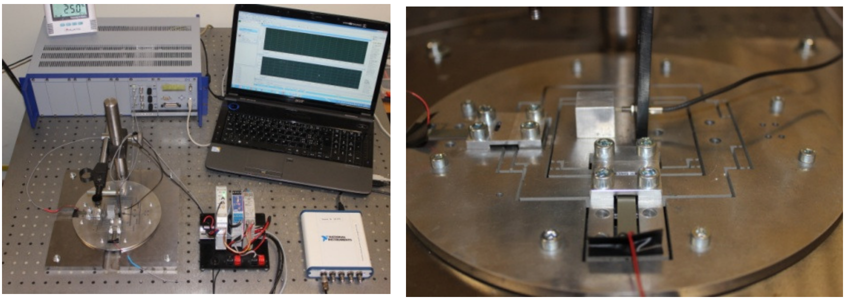


a) b)

Fig. 6. Resonant frequencies of a micropositioning stage with mechanical actuation: a) excitation in the direction of the *x* axis; b) excitation in the direction of the *y* axis

The obtained experimental results show that the micropositioning stage with mechanical actuation has a workspace zone of 110.1×111.9 μm^2. The differences between experimental and analytical results are 5.17% and 3.62% in the directions of *x* and *y* axes, respectively. The differences between experimental and FEM results are 1.28% and 1.02% in the directions of the *x* and *y* axes, respectively. Motion linearity errors over entire positioning stroke is 1.13 μm, 0.8 μm and 1.4 μm in the directions of the *x*, *y* and *z* axes, when the stage has been positioned in the direction of the *x* axis. The range of errors over entire positioning stroke is 0.83 μm, 1.12 μm and 0.92 μm in the directions of the *y*, *x* and *z* axes, when the stage has been positioned in the direction of the *y* axis. In the presented graph we can see that the natural frequencies of the stage are 483.9 Hz and 698.18 Hz, in the directions of the *x* and *y* axes, respectively, as shown in Figures 7a and 7b.

The researches of a micropositioning stage with piezoelectric actuation have been carried out. The aim of the research has been to measure the accuracy parameters and to obtain natural frequencies of the stage. The experimental setup of the micropositioning stage with piezoelectric actuation is shown in Figures 6a and 6b. The output displacement of the output platform has been measured by eddy current proximity sensor.

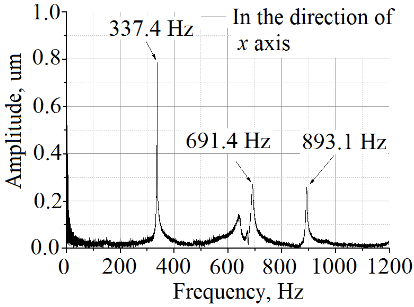


a) b)

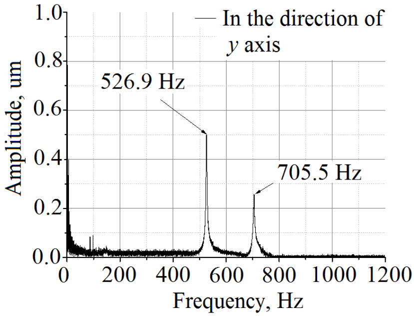
Fig. 7. Experimental setup of a micropositioning stage with piezoelectric actuation: a) experimental stand and measurement equipment; b) micropositioning stage

The obtained results show that the micropositioning stage with piezoelectric actuation has a workspace zone of 63.12×60.9 μm^2. The differences between experimental and analytical results are 2.89% and 6.3% in the directions of the *x* and *y* axes, respectively. The differences between experimental and FEM results are 2.13% and 2.87% in the directions of the *x* and *y* axes, respectively. The range of errors over entire positioning stroke is 0.11 μm and 0.09 μm in the directions of the *y* and *z* axes, when the stage is positioned in the direction of the *x* axis. The range of errors over entire positioning stroke is 0.2 μm and 0.22 μm in the directions of the *x* and *z* axes, when the stage is positioned in the direction of the *y* axis.

In the presented graph we can see that the natural frequencies of the stage are 337 Hz and 526.93 Hz, in the directions of the *x* and *y* axes, respectively, as shown in Figures 7a and 7b.



a)

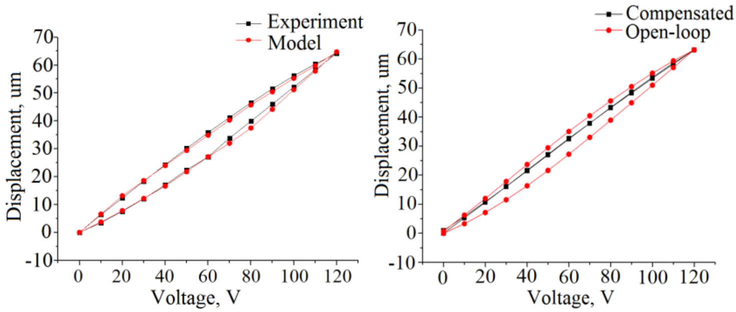


b)

Fig. 8. Resonant frequencies of a micropositioning stage with piezoelectric actuation: a) excitation in the direction of the *x* axis; b) excitation in the direction of the *y* axis

The entire dynamic model of a micropositioning stage with piezoelectric actuation with nonlinear hysteresis has been established using Bouc-Wen equations. The model identification process has been carried out in three steps: firstly, the output displacement of the stage has been measured and recorded with full range input voltage signal applied to the stage; secondly, the dynamic model with Bouc-Wen hysteresis has been implemented with Matlab/Simulink. The dynamic model output has been generated by the simulation; finally, the optimization has been performed while optimizing the parameters of the model in order to match the simulation results with experimental data. Consequently, the comparison of model output and experimental result is illustrated in Figure 9a. There exists, an error between the identified model and experimental result: the maximal deviation with respect to travel range of the stage is 1.05 μm and 0.83 μm in the direction of the *x* and *y* axes, respectively.

The inverse hysteresis model has been established and applied after the optimization of hysteresis model parameters. The experiments have been done using that model (see the results provided in Figure 9b). From the plot, as shown in Figure 9b, we can observe that the hysteresis effect has been compensated significantly, since the width of the hysteresis loop has been reduced to a low level of 0.48 μm and 0.43 μm in the direction of the *x* and *y* axes, with comparison to 7.91 μm and 7.55 μm in the direction of the *x* and *y* axes, obtained by the open-loop test with the same input rate. As a result, the inverse hysteresis model reduces errors by 93.9% and 94.3% in the direction of the *x* and *y* axes, respectively.



a) b)

Fig. 9. Hysteresis loop: a) the measured and modelled hysteresis loop in the directions of the *x* axis; b) open-loop and feedforward control results in the direction of the *x* axis

The obtained results as workspace zone, resolution, and natural frequencies have a good match with analytical and FEM results, therefore the proposed methodology can be applied to the modelling of other types of a flexure based micropositioning stages as well.

General conclusions

1. Analysis of sources of information shows that the available dual axis micropositioning stages are difficult to use for positioning of rotary encoder's raster or code scales on the rotating platform of angle comparator due to their design, architectural parameters, over-weight or limited resolution and it provides the impetus to the development and research of novel micropositioning stages.
2. Not only does proposed micropositioning stages increase or decrease input motion transfer ratio, but also it does decrease motion trajectory linearity errors due to these causes:
   - Decoupled positioning in the *x* and *y* directions;
   - Overacting in a symmetric way, which cause platforms' translation movements in the *x* and *y* directions.

3. According to aggregate characteristics, – ratio of geometrical parameters, weight, stroke, motion trajectory linearity errors and resolution – proposed micropositioning stages have been implemented.
4. The obtained analytical results have a good match with experimental results, the differences of micropositioning stages resonant frequencies obtained obtained analytical and experiment are less than 3.4%, therefore the proposed methodology can be applied to the modelling of other types of a flexure based micropositioning stages as well.
5. The obtained analytical results have a good match with experimental results, the differences of hysteresis form obtained analytical and experiment are less than 1%, therefore the proposed methodology can be applied to the modelling of other types of a flexure based micropositioning stages as well.
6. Application of inverse hysteresis model increases positioning accuracy of micropositioning stage with piezostack actuators by even 93.9% and 94.3% in the directions of the x and y axes, respectively, that is it decrease hysteresis errors from 7.91 µm to 0,48 µm and from 7.55 µm to 0,43 µm in the directions of the x and y axes, respectively.

List of published works on the topic of the dissertation
In the reviewed scientific periodical publications

Augustinavičius, G.; Čereška, A. 2014. Modelling and design of a flexure-based precision positioning system, *Journal of Vibroengineering*. 16(7): 3372–3382. ISSN 1392-8716 (ISI Web of Science).

Augustinavičius, G.; Čereška, A. 2012. Modeling of a 4DOF precise positioning stage by finite element method, *Mechanika*. 18(4): 442–446. ISSN 1392-1207 (ISI Web of Science).

Bručas, D.; Giniotis, V.; Augustinavičius, G.; Stepanovienė, J. 2010. Calibration of the multiangular prism (polygon), *Mechanika* 4(84): 62–66. ISSN 1392-1207 (ISI Web of Science).

Augustinavičius, G.; Čereška, A. 2015. Modelling of a Precise Positioning System. Solid State Phenomena. Vol 220-221: 374–379. doi: 10.4028/www.scientific.net/SSP.220-221.374.

Augustinavičius, G.; Čereška, A. 2010. Kampų matavimo įrangos apžvalga ir plėtros perspektyvos. *Mokslas – Lietuvos ateitis = Science – future of Lithuania: mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba* 2(4): 46–49. ISSN 2029-2341

Augustinavičius, G.; Čereška, A. 2011. Dviejų ašių precizinio pozicionavimo sistemos skaitinis modeliavimas. *Mokslas – Lietuvos ateitis = Science – future of Lithuania: mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba* 3(6): 79–81. ISSN 2029-2341.

Augustinavičius, G.; Čereška, A. 2012 Aukšto tikslumo pozicionavimo sistemos modeliavimas taikant besideformuojančius mechanizmus. *Mokslas – Lietuvos ateitis = Science – future of Lithuania: mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba* 4(6): 523–527. ISSN 2029-2341.

Augustinavičius, G.; Čereška A. 2013 Didelio tikslumo padėties nustatymo sistemos modeliavimas. *Mokslas – Lietuvos ateitis = Science – future of Lithuania: mechanika, medžiagų inžinerija, pramonės inžinerija ir vadyba* 5(6): 633–637. ISSN 2029-2341.

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MIKROPOZICIONAVIMO SISTEMŲ TAIKANT LANKSČIAS JUNGTIS TYRIMAI

Problemos formulavimas

Sparčiai vystantis šiuolaikinėms technologijoms mikro-, nanoskalės lygmenyje, didėja ir pozicionavimo tikslumo reikalavimai Daugelis sukurtų mikropozicionavimo sistemų veikia tradicinių technologijų pagrindu, – yra veikiamos žingsninių, servo variklių, hidro-, pneumo-, mikrovykdiklių. Tokiose sistemose pagrindinis slenkamojo ar sukamojo judesio perdavimo mechanizmas yra guolių struktūra, kuri turi nemažai trūkumų, tokių kaip trintis, dėvėjimasis, laisvoji eiga, surinkimo paklaidos, reikalingas tepimas, todėl vienas iš būdų pozicionavimo tikslumo padidinimui, – vientisų lanksčių mechanizmų taikymas. Daugelis mikropozicionavimo sistemų, sukurtų taikant vientisus lanksčius mechanizmus, skirtos pozicionuoti vienos ašies kryptimi. Norint pozicionuoti dviejų ašių kryptimis plokštumoje, reiktų kurti naujas sistemas įvairiomis išpildymo formomis. Jungti dvi vienos ašies pozicionavimo sistemas vieną ant kitos, – dėl ko padidėtų Abbe's bei atsirastų surinkimo paklaidos ir tai ženkliai sumažintų pozicionavimo tikslumą. Jungti dvi vienos ašies pozicionavimo sistemas statmenai plokštumoje pozicionavimo ašių kryptimis į vientisą struktūrą, – dėl ko ženkliai padidėtų pozicionavimo sistemos geometriniai parametrai. Trijų sukimosi laisvės laipsnių mikropozicionavimo sistemos, sukurtos taikant lanksčias jungtis yra veikiamos trijų pjezovykdiklių, o tai didina kainą, taip pat pozicionavimas x ir y ašių kryptimis yra sudėtingas, dėl kas 120° išsidėsčiusių vykdiklių. Mikropozicionavimo sistemų, veikiančių svertinių bei „Scott-Russell" lanksčių mechanizmų principu judesio trajektorijos nuokrypiai nuo tiesialinijiškumo yra dideli, o jų kompensavimo algoritmo įtraukimas į valdymo schemą, apsunkina pozicionavimo uždavinį.

Disertacijoje pagrindinis dėmesys skiriamas kampų komparatoriaus kampo keitiklių rastrinių bei kodinių skalių mikropozicionavimo metodikos kūrimui ir mikropozicionavimo sistemų, sukurtų taikant pasiūlytą metodiką, tikslumo parametrų bei dinaminių savybių teoriniams ir eksperimentiniams tyrimams.

Darbo aktualumas

Vystantis technologijoms nanometrų ar mikrometrų skalės lygyje siekiama ne tik didesnio pozicionavimo tikslumo, platesnio veikimo diapazono, bet tuo pačiu ir mažesnių pozicionavimo sistemų geometrinių parametrų bei mažesnių judesio trajektorijos nuokrypių nuo tiesialinijiškumo. Atlikta pasaulyje mikro-, nanopozicionavimo įrenginių apžvalga parodė dideles mikropozicionavimo sistemų, veikiančių vientisų lanksčių mechanizmų principu, perspektyvas. Mokslinėje literatūroje siūlomomis dviejų ašių mikropozicionavimo sistemomis, sukurtomis taikant lanksčias jungtis būtų sudėtinga pozicionuoti rastrines bei kodines skales dėl netinkamos konstrukcijos, per didelių geometrinių parametrų, per didelio svorio ar riboto tikslumo, todėl kyla poreikis naujų sistemų kūrimui ir tobulinimui.

Tyrimų objektas

Tyrimų objektas – mikropozicionavimo sistemos, sukurtos taikant lanksčias jungtis su mechaniniais ir pjezoelektriniais vykdikliais.

Darbo tikslas

Šio darbo tikslas – pasiūlyti metodiką kampo keitiklių rastrinių bei kodinių skalių mikropozicionavimui ant sukimosi platformos ir teoriškai bei eksperimentiškai ištirti mikropozicionavimo sistemų, sukurtų taikant pasiūlytą metodiką, tikslumo ir dinamines savybes.

Darbo uždaviniai

Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Atlikti mikropozicionavimo sistemų mokslinės literatūros apžvalgą ir analizę.
2. Pasiūlyti rastrinių bei kodinių skalių mikropozicionavimo metodiką.
3. Teoriškai ištirti mikropozicionavimo sistemų, sukurtų taikant pasiūlytą mikropozicionavimo metodiką, tikslumo ir dinamines savybes.
4. Sukurti natūrinius mikropozicionavimo sistemų modelius – su mechaniniais ir pjezoelektriniais vykdikliais – ir eksperimentiškai ištirti jų tikslumo ir dinamines savybes.
5. Padidinti mikropozicionavimo sistemos su paketiniais pjezovykdikliais tikslumą, taikant atvirkštinį histerezės matematinį modelį.

Tyrimų metodika

Darbe atlikti teoriniai tyrimai pagrįsti teorinės mechanikos, virpesių teorijos bei matavimų teorijos principais, taikant Matlab/Simulink, Ansys, Labview, Origin programinę įrangą.

Eksperimentiniai duomenys buvo gauti Vilniaus Gedimino technikos universiteto Mechanikos inžinerijos katedros laboratorijose, naudojant Lion Precision, Physik Instrumente, National Instruments, Hexagon Metrology aparatinę, bei PI MicroMove, PC-DMIS EMS, Labview programines įrangas.

Darbo mokslinis naujumas

1. Pasiūlyta ir ištirta rastrinių ir kodinių skalių mikropozicionavimo metodika, kurios taikymas mažina judesio trajektorijos nuokrypius nuo tiesialinijiškumo dėl šių savybių:
   - padidinti pozicionavimo tikslumui taikomos lanksčios jungtys su pozicionavimo mechanizmais sudaro vientisą plokščią struktūrą;
   - slenkamojo judesio perdavimo mechanizmai ne tik didina ar mažina perdavimo skaičių, bet kartu atskirai ir nepriklausomai pozicionuoja x ir y ašių kryptimis;
   - x arba y krypties platformų slenkamąjį judesį sukeliančios jėgos veikia simetriškai pozicionavimo ašiai.

2. Sudaryti mikropozicionavimo sistemų dinaminiai modeliai, vertinant lanksčią jungtį kaip tamprųjį elementą, turintį du laisvės laipsnius leidžia nustatyti dinamines savybes.

Darbo rezultatų praktinė reikšmė

Mikropozicionavimo sistemos taikomos kampo keitiklių rastrinių bei kodinių skalių pozicionavimui. Jos gali būti taikomos ir kitose srityse kur yra reikalingas mikrometrų ar nanometrų skyros pozicionavimas dvejomis ašimis plokštumoje.

Ginamieji teiginiai

1. Sukurtos mikropozicionavimo sistemos mažina judesio trajektorijos nuokrypius nuo tiesialinijiškumo 44 % su mechaniniais ir 17 % su pjezoelektriniais vykdikliais, lyginant su tradicinėmis mikropozicionavimo sistemomis.
2. Atvirkštinio histerezės matematinio modelio įdiegimas į mikropozicionavimo sistemos su paketiniais pjezovykdikliais valdymą padidina pozicionavimo tikslumą net 94%.

Darbo apimtis

Diertaciją sudaro įvadas, trys skyriai, bendrosios išvados ir dešimt priedų. Darbo apimtis yra 114 puslapių, neskaitant priedų, tekste panaudota 119 numeruotų formulių, 58 paveikslai ir 14 lentelių. Rašant disertaciją buvo panaudoti 75 literatūros šaltiniai. Pirmasis skyrius skirtas literatūros apžvalgai. Jame apžvelgiamos mikropozicionavimo sistemos, sukurtos taikant lanksčias jungtis. Skyriaus pabaigoje formuluojamos išvados ir tikslinami disertacijos uždaviniai. Antrame skyriuje aprašomi teoriniai mikropozicionavimo sistemų tyrimai. Trečiajame skyriuje pateikti mikropozicionavimo sistemų, sukurtų taikant lanksčias jungtis eksperimentiniai tikslumo ir dinaminių savybių tyrimai bei jų rezultatai.

Bendrosios išvados

1. Atlikus mikropozicionavimo sistemų mokslinės literatūros apžvalgą nustatyta, kad sukurtas dviejų ašių pozicionavimo sistemas būtų sudėtinga montuoti ant kampų komparatoriaus dėl netinkamos konstrukcijos, didelių geometrinių gabaritų, didelio svorio ar riboto tikslumo, todėl yra poreikis kurti tobulesnes dviejų ašių pozicionavimo sistemas.

2. Pasiūlytų mikropozicionavimo sistemų poslinkio perdavimo mechanizmas ne tik keičia įvesties poslinkio perdavimo skaičių, bet ir mažina judesio trajektorijos nuokrypius nuo tiesialinijiškumo pozicionavimo ašių kryptimis dėl šių veiksnių:
   – nepriklausomo pozicionavimo *x* ir *y* ašių kryptimis;
   – slenkamuosius judesius sukeliančių jėgų, veikiančios simetriškai.
3. Pagal judesio trajektorijos nuokrypius nuo tiesialinijiškumo sukurtos mikropozicionavimo sistemos pranašesnės, lyginant su tradicinėmis mikropozicionavimo sistemomis. Mikropozicionavimo sistemos su mechaniniais vykdikliais judesio trajektorijos nuokrypiai nuo tiesialinijiškumo mažesni 44 %, o mikropozicionavimo sistemos su pjezoelektriniais vykdikliais mažesni 17 %, imant tą patį pozicionavimo diapazoną.
4. Skaitinių ir eksperimentinių tyrimų metu nustatyti mikropozicionavimo sistemų savieji dažniai pozicionavimo ašių kryptimis skiriasi mažiau nei 3,4 %. Tai rodo, kad sudaryti mikropozicionavimo sistemų dinaminiai modeliai gali būti taikomi tiriant mikropozicionavimo sistemas su lanksčiomis jungtimis.
5. Skaitinių ir eksperimentinių tyrimų metu nustatytos histerezės kilpos rezultatai skiriasi apie 1 %, o tai rodo, kad parametrai, apibrėžiantys histerezės kilpos formą yra nustatyti labai tiksliai ir kad modelio sudarymo metodika gali būti taikoma tiriant kitas mikropozicionavimo sistemas, kuriose pasireiškia histerezės efektas.
6. Atvirkštinio histerezės kompensavimo modelio taikymas padidina mikropozicionavimo sistemos su paketiniais pjezovykdikliais pozicionavimo tikslumą net 93,9 % – *x* ir 94,3 % – *y* ašių kryptimis, t. y. sumažina histerezės paklaidas nuo 7,91 µm iki 0,48 µm – *x* ir nuo 7,55 µm iki 0,43 µm – *y* ašių kryptimis.

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RESEARCH OF A FLEXURE BASED MICROPOSITIONING STAGES

Summary of Doctoral Dissertation
Technological Sciences, Mechanical Engineering (09T)

Giedrius AUGUSTINAVIČIUS

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Daktaro disertacijos santrauka
Technologijos mokslai, mechanikos inžinerija (09T)

2014 12 18. 1,5 sp. l. Tiražas 70 egz.
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