Optimization of Butterfly Flexures for Angular Positioning

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***Abstract:* Different types of angular orientation and micro-positioning systems with flexures are used in different areas of precision mechanical engineering. Depend on the design, they can be assembly of different components or monolithic. The lack of friction gives them an advantage when they are used in different systems, where there is no possibility for maintenance or the environment is heavily polluted, but requires high accuracy and minimal deviation of the axis of rotation. This report presents the results of a study of different types of flexures based on the "butterfly" design. Based on the results an improved flexure design is introduced to reduce the deviation of the axis of rotation and to increase the working range of the micro-positioning elastic modulus.**

***Keywords:* micro-positioning, accuracy, angular orientation, positioning, elastic guides, flexure, elasticity, measuring device, axis of rotation**

I. INTRODUCTION

Micro-positioning systems with elastic modules are used for orientation and positioning of various optical and laser systems in various types of systems for analysis or measurements, where high accuracy and fixed axis of rotation is required [6, 8, 10, 11].

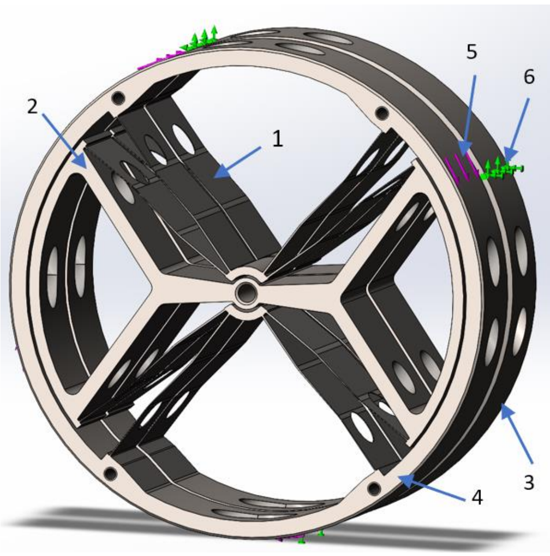

Fig.1. Micro-positioning elastic module with monolithic design - scheme

The main component of the design of a micro-positioning elastic module are the flexures, as their geometry is one of the main factors influencing its accuracy and performance of the elastic module [4, 6, 7, 15]. Generally, one of the main disadvantages of this type of mechanisms is the small range especially when fixed axis of rotation is needed. The range is often in the range of 2-4º. There are also elastic systems that provide a large working range, but the issue is with larger deviation of the axis of rotation, which is also one of the main accuracy parameters [1, 2, 3, 5, 9]. One of the widely used flexures, which provide a relatively large range and fixed axis of rotation are of the "butterfly" type or designs based on it. The developed micro-positioning measuring module with flexures is based on the "butterfly" design but with optimized geometry of the flexures (Fig. 1). Position 1 are the flexures, position 2 is the central movable element which provides the internal connection of flexures and positions 3 and 4 are the outer rings, respectively the lower fixed and the upper movable ring. The design consists of two rotary butterfly modules with one central axis and depending on the operational needs it is possible to choose which one of the two outer rings to be movable or fixed [12, 13, 14].

The nonlinear elastic mathematical model for the finite element analysis was used for the purposes of this study and the material was considered as an isotropic. The simulations were made using the CAD / CAM software SolidWorks. The study scheme shown in fig. 1 is as follows: one of the two outer rings pos. 3 (in this case the lower one) is fixed (fixation is shown on pos. 6). On the ring pos. 4 (upper one) a torque is applied and its direction is indicated by pos. 5. The movement or in this case the rotation obtained depending on the size of the applied torque shows the transfer curve of the elastic module i.e., the angular motion depending on the applied torque. Based on the transfer curve, the angle of the rotation at a certain torque can be determined. In order to be able to compare the different designs of the flexures, the same dimensions of the module are used i.e., all dimensions without the shape of the guides will be the same. The most commonly used modification (classic "butterfly") will be taken as a basis for comparison and the characteristics of all developed variants will be compared with it.

The flexures of a butterfly type elastic module are generally a leaf springs produced straight with a constant thickness along the entire length without change of the geometry. In order to compare the characteristics of the different developed designs, the maximum deformation will be taken to compare the maximum angle (maximum working range). In addition to the maximum range, the maximum deviation of the center of rotation will be taken into account as these two parameters are important for the functional characteristic of the module. The analyzed elastic module design is based on two paired single modules and is showing the pros and cons of the design in comparison with a single elastic module. The differences between single and double elastic modules are shown in the study below.

II. Butterfly Flexure Type

In the precision engineering the used flexures for rotary and translational micro-positioning elastic modules are made very often by straight flat elastic elements called leaf springs as well as different parallel or series configurations of the leaf springs.

A Butterfly Design with Leaf Springs

The monolithic design of micro-positioning module for angular orientation shown on fig. 2 is based on a butterfly design. The elastic module uses leaf springs for flexures (pos. 1). Often this type of monolithic modules is produced by Electrical discharge machines (EDM). The diameter of the outer ring pos.1 is 108mm. Pos. 2 is the outer ring and pos. 3 is an element used only to measure the deviation of the axis of rotation of the micro-positioning module after deformation.

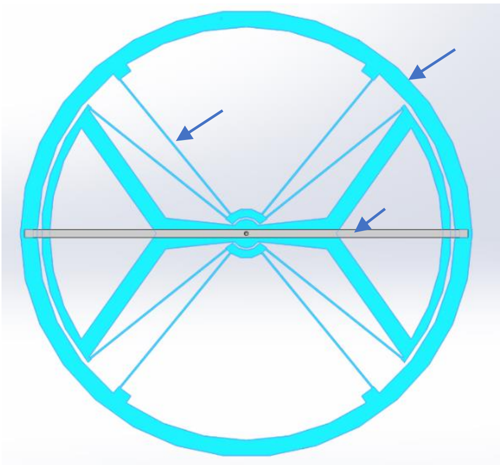

Fig. 2. Butterfly design of micro-positioning module with leaf spring

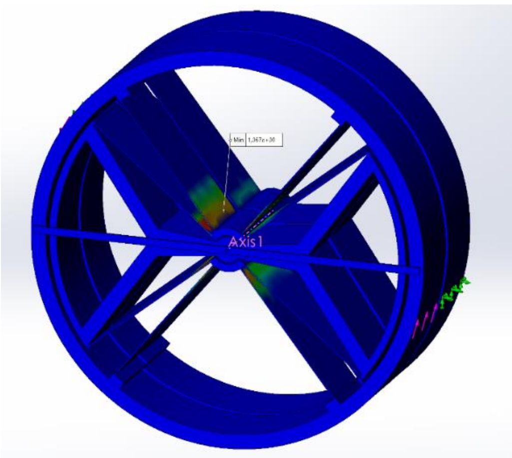

Fig. 3. Safety factor distribution of the elastic micro-positioning module after FEA analysis

The finite element analysis (FEA) of such an elastic module shows an uneven distribution of stresses along the length of the flexures, which shows that the stresses are nonuniform and these stresses leads to nonoptimal deformation and displacements. This kind of deformations leads to larger deviation of the axis of rotation. In fig. 3 can be seen the distribution of the safety factor, where at one end of the flexures it is critical. In this case the deviation of the axis of rotation is 4.5µm at a maximum allowable angle of 9º i.e., the working range is ± 9º. The maximum permissible angle is determined by the safety factor of the design which must be greater than 1 i.e., the structure remains strong after the application of the torque.

B Butterfly Design with Leaf Springs in Parallel/Series Configurations

The leaf spring flexures can be designed in different series or parallel configuration such as those shown in fig. 6 and 7 below. Research of the Laboratory of Precision Engineering at the University of Twente, Enschede Netherlands, led by prof. Dannis Brouwer shows that when the guides are constructed in such a configuration provide much better axial and radial support i.e., stronger in the non-working directions while maintaining the elasticity in the working directions.

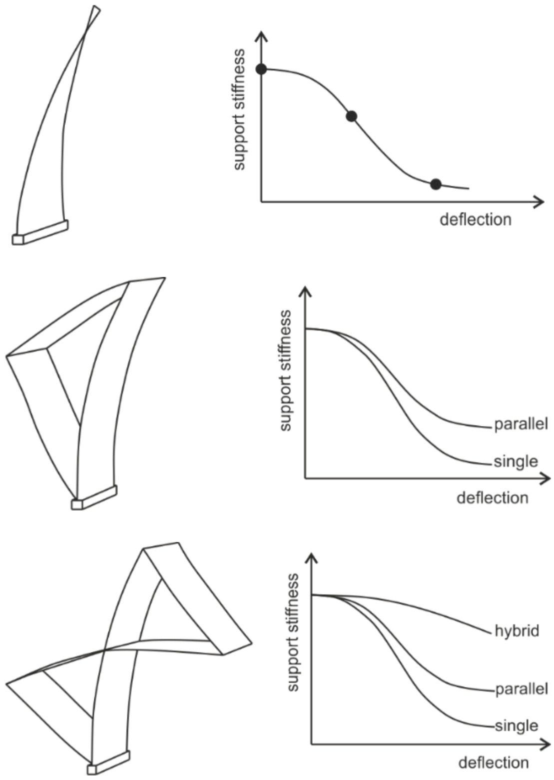

Fig. 4. Butterfly design with leaf springs in parallel/series configurations

Figure 4 shows the various options for strengthening structures and reducing parasitic deformations in the construction of polymer flexures which are the focus of Prof. Brouwer's research. Based on this study is the model shown in fig. 7 and 8. The flexures are coupled in parallel and series design at once called hybrid design which increases the resistance to parasitic deformations in the axial and radial directions.

The analysis of d the hybrid design of the flexures as shown in fig. 5 and fig. 6 shows that the design is stiffer and can withstand larger axial or radial forces, i.e., the module can take a larger load. The elastic module shown in fig. 6 is a double symmetrical reinforcement of the leaf springs with added flexures with the same design as on fig. 5. The negative side of the designs of fig. 5 and 6 is that the torque required to achieve the desired angular positioning is multiplied. In order to be able to reduce the torque and increase the working range it is necessary to thin all the elastic elements which complicates their production. This complex design also leads to a higher probability of manufacturing errors which can lead to a loss of symmetry and a larger deviation of the axis of rotation. The range of the modules using this design is ± 10º with a maximum deviation of the axis of rotation of 3µm at 10º angular positioning. This type of design is more suitable for more elastic materials, such as different types of polymers. Some of them are hyperelastics and cannot provide sufficient structural rigidity.

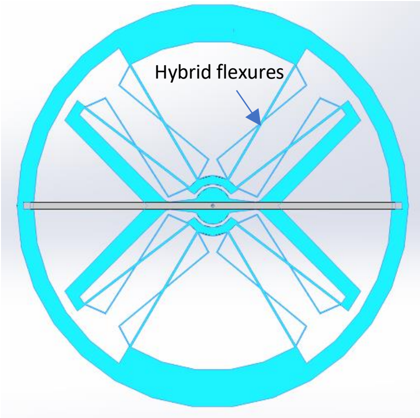

Fig. 5. Elastic module design with one sided hybrid leaf spring configuration

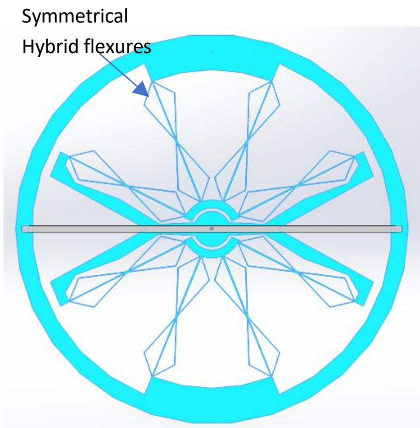

Fig. 6. Elastic module design with double sided symmetrical hybrid leaf spring configuration

III. Optimization of the Butterfly Flexures

A Butterfly Flexures with Optimized Cross-section

To compensate the uneven load of the flexures their geometry is optimized with thinning where the loads are smaller and increasing or keep the size where the loads are larger. In this case in order to increase the working range the thickness 'h' of the flexures is reduced. This dependence of the flexure's thickness and the working range can be taken from the formula for calculating the maximum displacement that a given flexure can withstand depending on the material

$$\frac{\delta_{\max}}{L} \sim \left(\frac{\sigma_{\max}}{E}\right)\left(\frac{L}{h}\right).$$

The dependence shows that the smaller the size for h at the given length L, the larger is the angle at which the flexures can be deformed. In this case the thickness is reduced where the loads are smaller i.e., the size reduction is done at the top of the flexures where the outer ring is. This optimization of the geometry can be seen in fig. 7.

After analyzing the improved design using the finite element method, the optimization of the stress and the uniformity of the distribution of the safety factor along the entire length of the flexures can be seen. In this case, the flexures are thinner in the area of minimum load and respectively different thickness at both ends. Additionally, holes were made to reduce the material in the less loaded sections and this increases the maximum range to ± 22.5º.

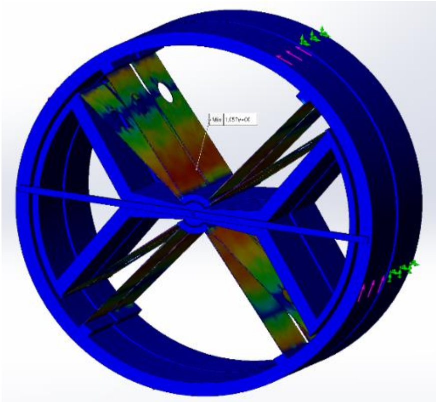

Fig. 7. Safety factor distribution of the micro-positioning elastic module after optimization of the flexures

In this case the maximum deviation of the axis of rotation is 15µm. In order to be able to compare the results with the previous design (fig. 2), where at an angle of 9º the deviation of the axis of rotation is 4.5µm, in this design with optimized flexure profile, the deviation of the axis of rotation is 0.7µm at an angle of 9º, which is multiple times less deviation.

B Butterfly Flexures with Optimized Cross-section and Geometry

The design of flexures for angular positioning has a common issue with the tensile forces that act on the flexures when they are rotated at a certain angle. With increasing the angle these forces are also increased which causes the flexure to be "stretched" because the points at which they are attached to the main structure (inner and outer ring) move away from each other i.e., the length of the guide increases after deformation. These additional tensile forces lead to deformation and asymmetrical (due to the nature of the material and production) radial forces in the outer and inner ring, which leads to an increase of the deviation of the axis of rotation. As the angle of rotation increases, these forces increase as well and higher torque is required to achieve the desired angular positioning in order to overcome the additional radial forces. The larger torque applied to the flexures could lead to local deformation of the outer ring. In order to be able to compensate this effect, the elastic elements need to be with a predefined geometry to allow this stretching without significantly increasing the tensile forces at the points of attachment. A solution is to design the flexures with a shape that allows them to be stretched. One of the most suitable geometries is to be some type of "S" -shaped geometry. This solution reduces unwanted forces and the deviation of the axis of rotation. Combining the advantages of the improved cross-section and using S-shaped flexures is developed the elastic micro-positioning module shown on fig. 1. In addition to the slightly S-shape flexure with an angle of 2.5º (see the next section "optimizing the angle of the S-shaped guides"), this design uses different thickness of the guides along their length. With the developed design the stress distribution therefore the safety factor is improved. Thanks to this improvement the range is increased and the deviation of the axis of rotation is reduced. For the purpose of the analysis, a single elastic module was constructed to compare the two types. In fig. 9 on the left is a single module made with the same geometry of the flexures and on the right (fig.7) is the dual elastic module made from 2 single elastic module. The results of the analysis of the single module show a range of ± 11.5º and a deviation of the center of the axis at a 10º positioning angle within 0.95µm, the range being even larger than the above discussed dual elastic module with flat (not optimized) flexures. By connecting the two single modules, the dual monolithic module, the object of this study, was obtained. The results show a range of ± 22.5º and a deviation of the axis of rotation at the maximum angle - 1.7µm, which is an improvement of the deviation of the axis of rotation given the doubled angle range. At a 10º positioning angle, the deviation of the axis of rotation is approximately 1.25µm, which shows that in the range from 10º to 22º the deviation of the axis of rotation varies within 0.5µm. The main difference in the design of the both elastic modules is that in the single elastic module, the central axis is fixed and the outer ring is movable, while in the dual elastic module, only the lower outer ring is fixed and the central axis is also movable (see Fig. 9). The results of the studies performed on the transfer curve and the deviation of the axis of rotation of the micro-positioning elastic module with improved flexures are presented in the next section, figures 10, 11 and 12.

C Optimization of the S-shaped Flexures

The main parameters of the profile of the flexures are their length, thickness and geometry (straight / with variable geometry, with the same or different thickness along the length). The introduced S-shaped flexures for improvement of the deviation of the axis of rotation, which deviation is mainly due to larger tensile forces caused by stretching of the flexures during the rotation of the outer ring and leading to an uneven distribution of the forces. The S-shaped profile further increases the length of the guides and this increases also the working range.

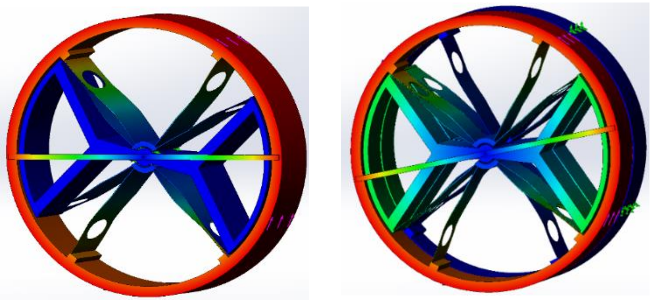

Fig. 8. Single (left) and dual (right) micro-positioning elastic module

The profile shown on fig. 10 is divided into three sectors where the thickness along the length of the flexure is different but the angle between them is the same. In this case the angle is 2.5º and this is the angle of the S-shaped flexures subject to this study. The use of such a profile reduces the deviation of axis of rotation, but has negative impact of the radial stiffness.

The following study examines the influence of the angle of the S-shaped flexures and what is the optimal angle for this design. The scheme of the research is the same shown on fig. 1. The applied torque is not changed at the different angles of the S-shaped flexures. The geometry of the elastic module also remains unchanged, except for the angle of the S-shaped flexures, which changes with values of 1º, 2º, 2.5º and 3º.

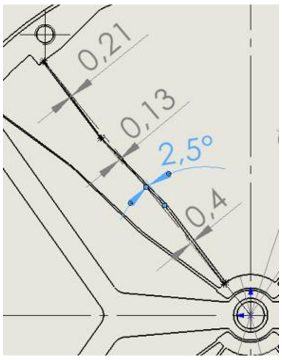

Fig. 9. S-shaped flexures scheme

The results of the study and how the angle of the S-shaped flexure influence the transfer curve is shown on the graph of fig. 10.

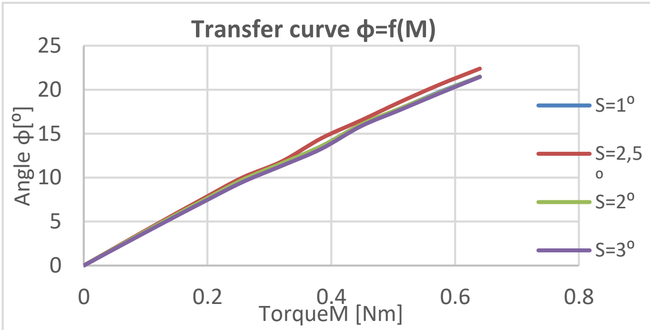

Fig. 10. Transfer curve for different angle of the S-shape of the flexures

The results show that the angle does not have a significant effect on the transfer curve. The range remains in the comparable range of ~ 22.5º and is comparable to the range observed during the study of the design using improved cross-section but without using the S-shaped flexures. The main difference and improvement with the use of S-shaped flexures is on the deviation of the axis of rotation. The influence of the angle on the deviation of the axis of rotation is shown in the following graphs. The deviation along the X axis can be seen on fig. 11. The study shows that at an angle of 1º and 2º the deviation of the axis of rotation along the X axis is negative but at 3º it turns into a positive value which shows that the optimal values for the angle of the S-shaped flexures are between 2º and 3º.

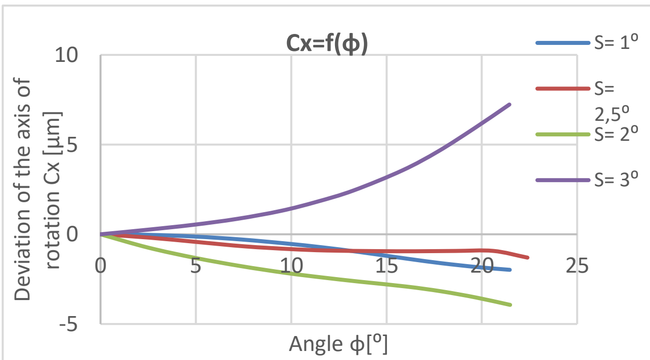

Fig. 21. Deviation of the axis of rotation along X-axis for different angle of the S-shape of the flexures

The values at 2º for the deviation of the axis of rotation along the X axis reach approximately 4µm, at 3º - the value is over 7µm, and at 2.5 the value is 1.3 µm which is the lowest value during this study.

The following graph fig. 12 shows the deviation of the axis of rotation along the Y axis. Here again the transition from negative values to positive values is observed which shows that the optimal values are again between 2º and 3º. Based on the results the optimal angle that is selected is 2.5º. The value for the deviation of the axis of rotation is minimal so it is the most suitable for the design.

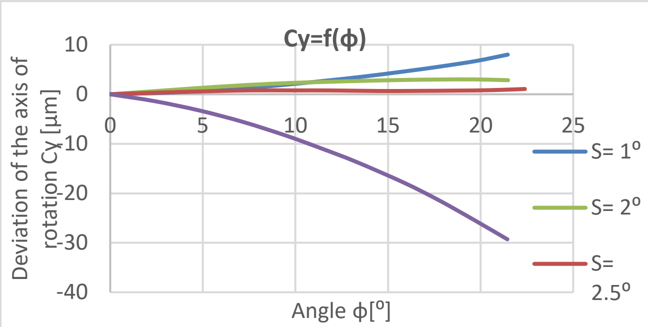

Fig. 32. Deviation of the axis of rotation along Y-axis for different angle of the S-shape of the flexures

The results show that the elastic module with optimized geometry of the flexures has the same range (± 22.5º) as the elastic module with flexures with only optimized cross-section (Fig. 4), but the deviation of the rotation axis is reduced to 1.7µm compared to the results of 15µm with only optimized cross section.

Conclusion

The results of the simulation analysis of the elastic micro-positioning module using flexures with optimized geometry show an improvement of the accuracy and the functional characteristics. The difference in the range (± 22.5º) compared to non-optimized flat flexures is more than a double which confirms the need of an even distribution of internal stresses, i.e., the distribution of the safety factor along the length of the flexures that is achieved by reducing the dimensions in places where this does not affect the strength of the structure. Improvement of the deviation of the axis of rotation is observed not only after optimization of the cross-section which improves the deviation approximately 7 times but also after the introduction of S-shaped flexures as the deviation of the axis of rotation is improved approximately 9 times at its maximum range of ± 22.5º compared to those with only optimized cross-section. This confirms the need of predefined geometry to reduce the uneven distribution of the forces caused by the deformation of the flexures used in elastic angular positioning systems.

Acknowledgments

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References

1. Dichev, D., Koev, H., Bakalova, T., Louda, P. A Model of the Dynamic Error as a Measurement Result of Instruments Defining the Parameters of Moving Objects. Measurement Science Review, Volume 14, Issue 4, 2014, 183-189, ISSN 1335-8871, https://doi.org/10.2478/msr-2014-0025
2. Dyakov D., I. Kalimanova, Opredelyane polozhenie na osta na rotatsiya na goniometrichni pozitsioneri, Sbornik dokladi ot 1-va konferentsiya s mezhd. uchastie "Mashinoznanie i mashinni elementi", Sofiya, 4-6 Noemvri 2004
3. Dyakov D, E. Apostolov, I. Kalimanova, Otsenka na tochnostta na pozitsionirashti sistemi, Sbornik dokladi ot 13-ti Natsionalen Nauchen Simpozium s mezhd. uchastie "Metrologiya i metrologichno osiguryavane 2003", Sozopol, 16-20 septemvri 2003, s. 305-309, ISBN 954-9725-76-6
4. Hui Tang, Yangmin Li and Jiming Huang, Design and analysis of a dual-mode driven parallel XY micromanipulator for micro/nanomanipulations, Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science 1989-1996 (vols 203-210) 226(12):3043-3057, DOI:10.1177/0954406212442272
5. ISO 230-7:2015 Test Code For Machine Tools. Geometric Accuracy Of Axes Of Rotation
6. Kim, Yong-Sik & Shi, Hongliang & Dagalakis, Nicholas & Gupta, Satyandra. (2016). Design of a MEMS-based motion stage based on a lever mechanism for generating large displacements and forces. Journal of Micromechanics and Microengineering. 26. 095008. 10.1088/0960-1317/26/9/095008
7. Michael F. Ashby - Materials Selection In Mechanical Design 4Ed, Butterworth-Heinemann 2010, ISBN-13 978-9380931722
8. Qian LU, Optimization Design of Flexible Micro-Displacement Amplification Mechanism Based on Parameters, School of Mechanical Engineering, Yancheng Institute of Technology, Yancheng City, Jiangsu Province 224051, P.R. China, https://doi.org/10.6180/jase.2015.18.4.05
9. Stranczl M., E. Sarajlic, H. Fujita, M. A. M. Gijs and C. Yamahata, "High-Angular-Range Electrostatic Rotary Stepper Micromotors Fabricated With SOI Technology," in Journal of Microelectromechanical Systems, vol. 21, no. 3, pp. 605-620, June 2012, doi: 10.1109/JMEMS.2012.2189367
10. Todorov, T.S., Mitrev, R.P., Tudjarov, B.N., Nikolov, R.F.; Qualitative analysis of oscillating magnetomechanical system (2019) IOP Conference Series: Materials Science and Engineering, 618 (1), art. no. 012054, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85076113277 &doi=10.1088%2f1757-899X%2f618%2f1%2f012054 &partner ID=40&md5= 7829b3eb372c2b4bcc37279851692721, DOI: 10.1088/1757-899X/618/1/ 012054
11. Todorov, T., Nikolov, N., Nikolov, R., Sofronov, Y., Kochev, L., Optimization of micro-electro-mechanical piezoelectric energy harvesters with interdigitated electrodes, (2019) Journal of the Balkan Tribological Association, 25 (3), pp. 535-545, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85081207578 &partnerID=40&md5=e4419478ba2ec9d0683bf15 fed897984
12. Vasilev V., Nikolova H., Programno osiguryavane na sistemi za izmervane na otkloneniyata na formata i razpolozhenieto na povŭrkhninite i osite na detaĭlite, Sofiya, Softtreĭd, 2020, ISBN 978-954-334-231-0
13. Xu Pei1, Jingjun Yu, Guanghua Zong, Shusheng Bi, A Family of Butterfly Flexural Joints: Q-LITF Pivots, School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, R.P. China, DOI:10.1115/DETC2011-48394
14. Zentner L, Linß S. Compliant Systems – Mechanics of Elastically Deformable Mechanisms, Actuators and Sensors. München: De Gruyter Oldenbourg; 2019, 166 p., ASIN: B06Y6FNSXB
15. Malakov, I., Topalova, I., System development of representative criteria for choosing an optimal variant of technical product (2009) Annals of DAAAM and Proceedings of the International DAAAM Symposium, pp. 1335-1336. https://www.scopus.com/inward/ record.uri?eid=2-s2.0-84904336234&partnerID=40&md5=067a9 d35912eeca806e7344421aceb8d, ISSN17269679, ISBN 978-390150970-4