Micro-positioning Module for Angular Orientation Position of the Axis of Rotation Analysis

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Abstract: Positioning systems with flexures for angular orientation are used in many areas of precision engineering. Used mainly for orientation and high accuracy positioning of components or modules, part of mechanical systems that ensuring a constant axis of rotation and angular deviations. This paper presents the results of the study of elastic micro-position measuring system and the influence over accuracy and characteristics caused by the manufacturing errors.

Keywords: micro-positioning, accuracy, angular orientation, flexure, measuring module, axis of rotation

I. INTRODUCTION

Angular positioning systems with flexures are widely used in spatial orientation of parts, systems, optical elements and lasers, production of semiconductor elements, X-ray structural analyzes, measuring rotationally symmetrical parts, material studies including the cryogenic materials, as well as in a number of other fields of precision engineering [6, 8, 10, 11]. Elastic modules of monolithic type are often used to minimize the errors caused by assembling.

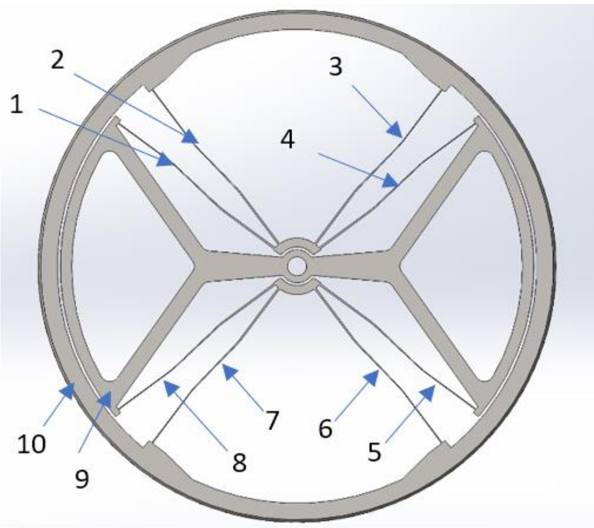

Figure 1. Micro-positioning flexure module with monolithic design - scheme

One of the main factors influencing the accuracy and performance of angular positioning systems is the error caused by manufacturing of the monolithic design. In fact, a manufacturing error could be not only one but a complex combination of several errors simultaneously [1, 2, 3, 5, 9]. In the case when the design is monolithic, errors caused by assembling of the flexures are eliminated, which is one of the advantages of this type of design. Deviations from the nominal value of the geometry of the flexures, although in tolerance, are the main difference between the simulation analyzes and the actual behavior of the system, because under real conditions the behavior is affected by all design deviations allowed during manufacturing, while in simulation analyzes these deviations are not taken into account.

Fig. 1 shown a model of the developed micro-position measuring module with flexures. Positions 1 to 8 represent the flexures, position 9 is the central movable element which provides the internal connection of the flexures and position 10 is the outer rings, one is fixed (*I* at Fig. 2) and the other one – movable (*II* at Fig. 2), depend on the application. The design consists of two rotary butterfly modules with one central axis, and depend on the application, it is possible to choose which of the two outer rings to be movable or stationary.

The monolithic model is theoretical, so initially the deviations are excluded but in reality, these deviations could happen mainly during the manufacturing process. Such kind of deviations are taken into consideration in order to be able more accurately to predict the actual behavior of the system. The accuracy and range of the elastic measuring and positioning systems depend on the geometry of the elastic guides [4, 6]. Geometrical deviations of the flexures lead to a deviation in the accuracy. For example, deviation in the ratio of the size of the cross section and the length of the flexures leads to deviation in the range of the module. This correlation

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

is based on the formula for calculation of the maximum range of a given flexure and the material used. Asymmetry or deviations of the flexure could have big influence on the position of the rotational center and the accuracy of the system. How these deviations are influencing the behavior and the accuracy of the system is subject of this study. There are basically two cases of manufacturing errors - repetitive error, where each guide is made with the same deviation, which could lead to a deviation in the working range but similar results for the position of the center of rotation and an error of the geometry of each guide caused during the manufacturing process. The second case where flexuures with different deviations on every guide separately leads to an increase on the deviation of the position of the center of rotation, i.e., reduced accuracy and change of the working range. Increase or decrease of the working range depend on whether the thickness of the flexures is less or greater than the nominal value. In order to be able to predict the worst case, where the

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module would have the lowest accuracy, different variants with asymmetric thickness of the guides are considered, i.e., one or more flexures are with difference in thickness from the others. This would lead to asymmetry of the design and greater deviation of the position of the center of rotation. Elastic modules of monolithic type are very often produced by wire electrical discharge machine (EDM) [7, 15]. Typical EDM manufacturing error is ± 5 µm, so in the simulation analyzes a maximum permissible deviation of 10 µm is set i.e., the difference in the flexures should not be greater than 10 µm. A 50 µm error is also taken into account in the study for better understanding how the asymmetry and different thickness are affecting the accuracy and the working range of the module.

For the first studied case is simulated occurrence of asymmetric deviation of the thickness of the flexures, where one of the guides is with increased thickness. The increase of the thickness is + 50 µm and the selected flexure is position 3 (Fig. 1). This causes an unacceptable deviation of the accuracy and shows how much this type of error can affect the behavior of the angle micro-positioning module.

II. Analysis of the Movement of the Axis of Rotation Using Flexures with Deviation of the Thickness

1. Deviation of 0.05 mm at one of the flexures

The finite element method (FEM) is used for the study [12, 14]. In this case the CAD/CAM system SolidWorks is used. The test scheme is shown on Fig. 2: one of the two outer rings (in this case the lower one, position *II*, is fixed and a torque is applied to the other ring (upper one - position *I*). The movement or in this case the rotation obtained depend on the size of the applied torque [13]. This correlation between applied torque and the obtained rotational movement is the transfer curve of the micro-positioning elastic module. Based on this function, the value of the angle of rotation at a certain torque can be determined. In the first case studied, as mentioned above, flexure position 3 has a 50 µm larger thickness.

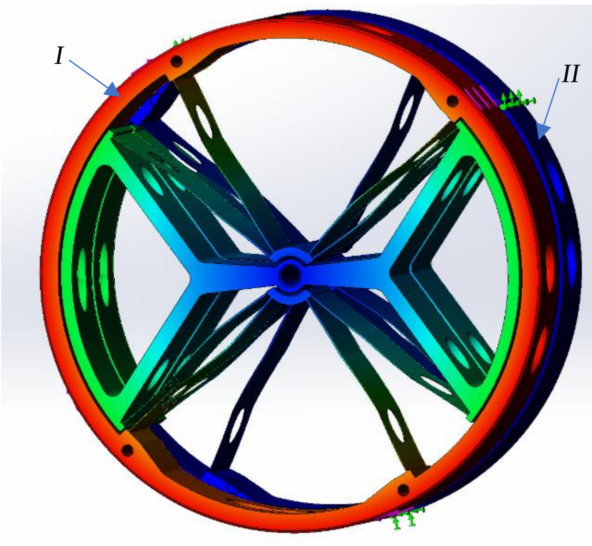

Figure 2. Micro-positioning flexure module with monolithic design – FEM Analysis scheme

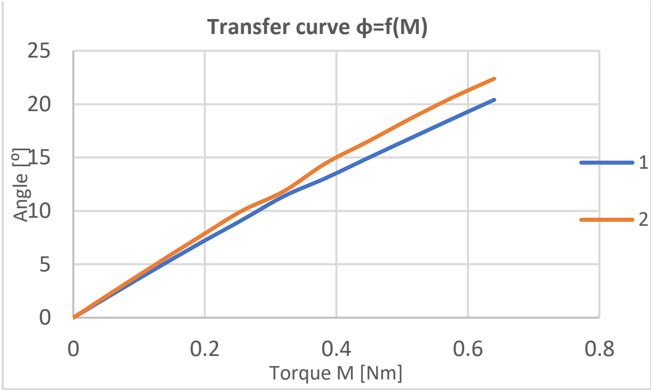

Figure 3. Transfer curve. 1- flexure position 3 (fig.1) with 0.05 mm increased thickness. 2- flexure with nominal thickness

The results of the study of the transfer curve (Fig. 3) show a decrease in the working range, but the curve retains its almost linear character. The range reduction is ± 2º, which is a nearly 10% reduction of the working range. This result is expectable because increasing the thickness of one of the guides leads to negative change of the ratio between guide's thickness and its length and it has a negative influence on the working range.

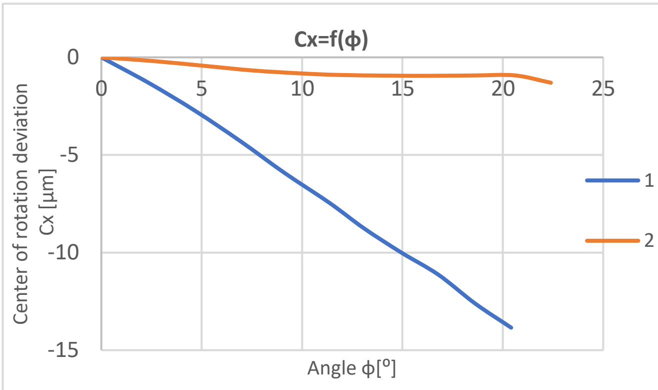

Figure 4. Movement of the center of rotation on X-axis. 1- Flexure position 3 (fig.1) with 0.05 mm increased thickness. 2 – flexure with nominal thickness

Unlike the relatively small change of the working range, the deviation of the position of the center of rotation is significantly degraded. The deviation of the position of the center of rotation along the X axis (Fig. 4) is significantly increased as the deviation is approximately 14 µm, which is more than 10 times increase of the deviation compared to the nominal values that can be seen on the graph. This shows that such an error, combined with the asymmetry of the design, leads to unacceptable values for the deviation of the position of the center of rotation along the X axis. The analysis of the deviation of the center of rotation along the Y axis (Fig. 5) shows an improvement compared to the nominal values if the geometry. This decrease of the deviation along Y axis could be due to the increase of the forces along the X axis and a decrease of those along Y axis.

In this case the deviation along Y axis changes its direction, accepting also negative values. This behavior is due to the asymmetry of the design and increase of the forces on X axis and decrease of the forces on Y axis.

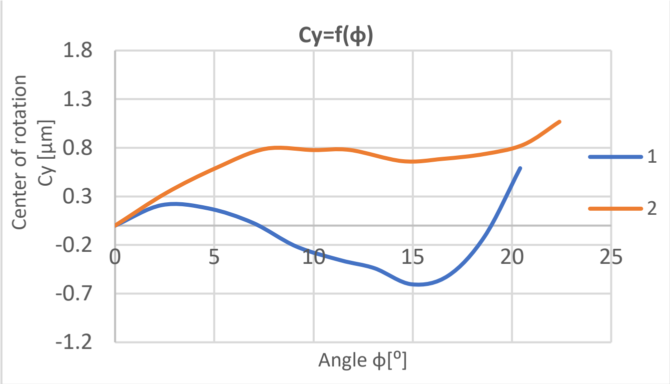

Figure 5. Movement of the center of rotation on Y - axis. 1- flexure position 3 (fig.1) with 0.05mm increased thickness. 2 - flexure with nominal thickness

The maximum deviation in Y is comparable to the nominal values. As a conclusion from the results, an error of 0.05 mm combined with asymmetry of the flexures leads to unacceptably large values for the deviation of the position of the center of rotation and reduction of the working range by approximately 10%.

2. Deviation of 0.01mm at one of the flexures

Taking into account the typical error of ± 5 µm, with which the flexures can be produces by wire electrical discharge machine, the maximum allowable dimensional tolerance could be within 10 µm. Therefore, the following analysis was performed in a similar way to the first case, but this time flexure position 3 (Fig. 1) have been made with the maximum allowable tolerance of 10 µm, i.e., the thickness of one of the flexures is increased with 0.01 mm. This approach is going to predict the behavior of the module in case it is produced with the maximum allowable deviation. On fig. 6 are the results of the study of the transfer curve compared to the results with nominal values of the flexures.

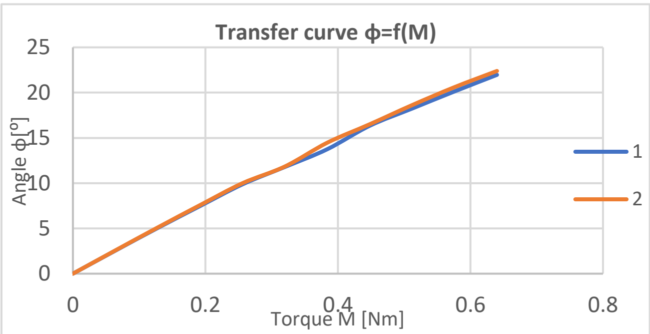

Figure 6. Transfer curve. 1- flexure position 3 (fig.1) with 0.01 mm increased thickness. 2 - flexure with nominal thickness

The graph shows that the reduction of the range is minimal, as the function retains its linear character, i.e., a difference of 0.01 mm has minimal effect on the range. Although there is not much difference in the range, and again have a more significant influence on the deviation of the position of the center of rotation. The study of the deviation along the X axis is shown on fig. 7, where it can be seen that it is a over 2 times larger, reaching a value of 3.3 µm. Analysis of the deviation of the position of the center of rotation along the Y axis compared to the previous study with 0.05 mm increased thickness of the flexure where the difference in the deviation along the Y axis is minimal, here there is larger deviation along the Y axis (Fig. 8) and reaches approximately 5 µm.

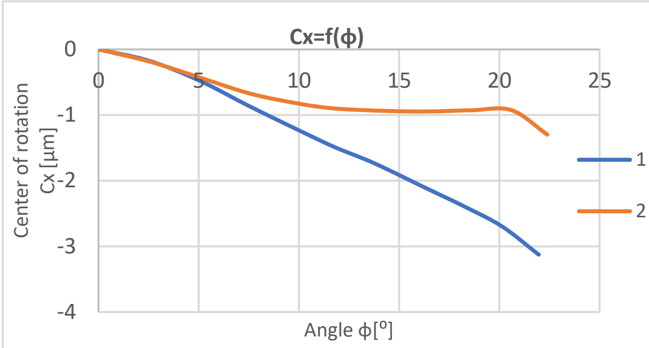

Figure 7. Movement of the center of rotation on X-axis. 1 - flexure position 3 (fig.1) with 0.01mm increased thickness; 2 - flexure with nominal thickness

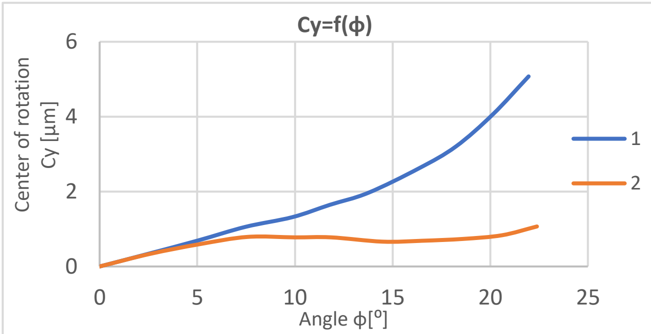

Figure 8. Movement of the center of rotation on Y - axis. 1- flexure position 3 (fig.1) with 0.01 mm increased thickness. 2 – flexures with nominal thickness

This shows that when increase the thickness with 0.01 mm, the forces acting on the X-axis and Y-axis remain relatively distributed. This distribution leads to decrease of the overall deviation of the position of the center of rotation compared to the previous study with increase of the guide's thickness with 0,05mm but compared to the nominal values the deviation is larger.

3. Deviation of 0.01 mm at two of the flexures

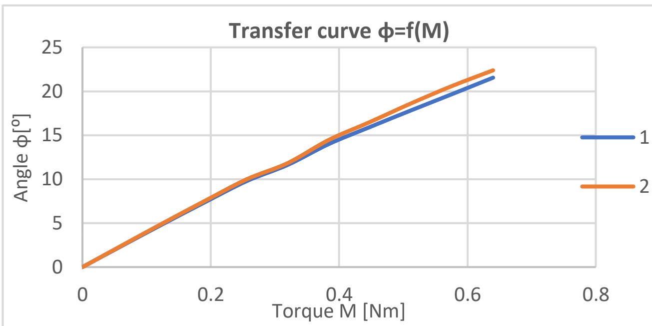

Figure 9. Transfer curve. 1- C 3 and 6 (Fig.1) with 0.01 mm increased thickness; 2 - flexures with nominal thickness

In this case, two of the flexures have a different thickness than the others and are located in the right half of the module relative to the Y-axis (flexures position 3 and 6 shown on Fig 1). The results from these deviations of the design could predict the behavior of the system provided by asymmetry of the thickness of the flexures located on only one half of the module. The flexures positions 3 and 6 are with 0.01 mm increased thickness than the others. The results of the transfer curve shown in Fig. 9 s.how that the working range decreases by approximately ± 1^o, which is expected result given that the total thickness increases by 0.02 mm (two of the flexures with increased thickness of 0.01 mm). This difference of working range is acceptable because this represents less than a 5% difference in the range and the transfer function remains approximately linear.

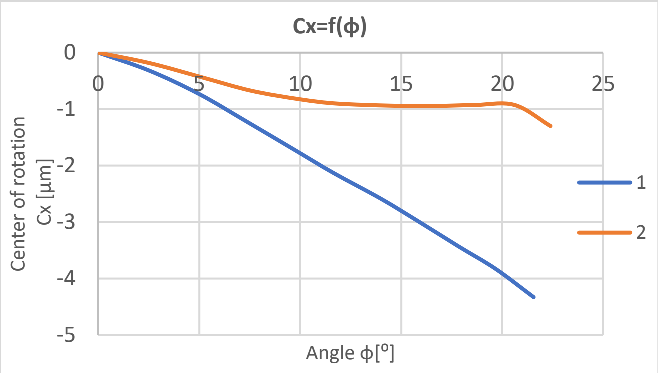

Figure 10. Movement of the center of rotation on X-axis. 1- flexures positions 3 and 6 (Fig.1) with 0.01mm increased thickness; 2 - flexures with nominal thickness

The analysis based on the results for the deviation of the position of the center of rotation along the X axis (Fig. 10) shows an increase of the deviation from the nominal values. Increased deviation is also observed compared to the previous study where only one of the flexures is with 0.01 mm increased thickness, which is expected given that the asymmetry of the structure increases. The deviation's value reaches 4.3 µm, which is approximately with 3 µm more than the flexures with nominal value of the thickness.

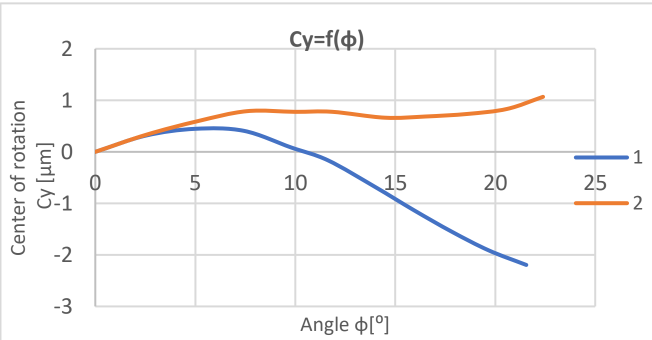

Figure 11. Movement of the center of rotation on X-axis. 1- flexures positions 3 and 6 (Fig.1) with 0.01 mm increased thickness; 2- flexures with nominal thickness

The results after the study of the deviation of the position of the axis of rotation along the Y axis (Fig. 11) show a decreased deviation compared to that with only one elastic guide with 0.01 mm increased thickness. The difference here is that the direction changes its direction with increasing the applied torque and the maximum value of the deviation is 2.2 µm.

The analysis of the accuracy characteristics in the case of two flexures with an increased thickness of 0.01 mm shows a similar behavior, as in the case of only one flexure with an increased thickness of 0.01 mm, but the size of the overall deviation of the position of the axis of rotation is larger than the deviation in the case where only one of the guides is with 0.01 mm increased thickness. This is due to the fact that there is a total difference of thickness with 0.02 mm.

4. Deviation of 0.01 mm at three of the flexures

One of the worst cases that we could have during the manufacturing process of the flexures is to have a deviation of the thickness of three of them. Such a case is taken into account and considered in this study. Three of the flexures have a 0.01 mm deviation from the nominal thickness. The worst-case scenario could be when two of the flexures have 0.01 mm increased thickness and the third has 0.01 mm decreased thickness. The two of them that are larger are located on the right half relative to the center and the Y axis, while the third, which is thinner, is on the left.

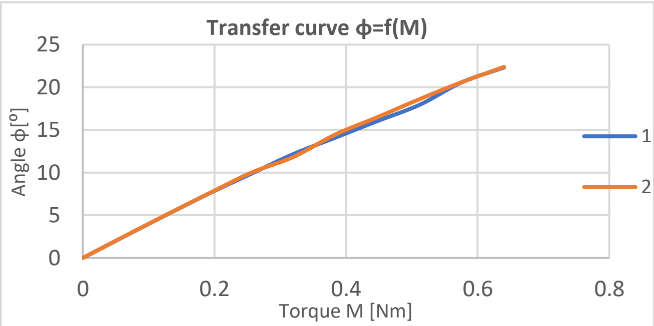

Figure 12. Transfer curve. 1- Elastic guides pos. 3,6 (fig.1) with 0,01mm increased thickness, pos. 8 with 0,01 mm decreased thickness. 2- Nominal thickness

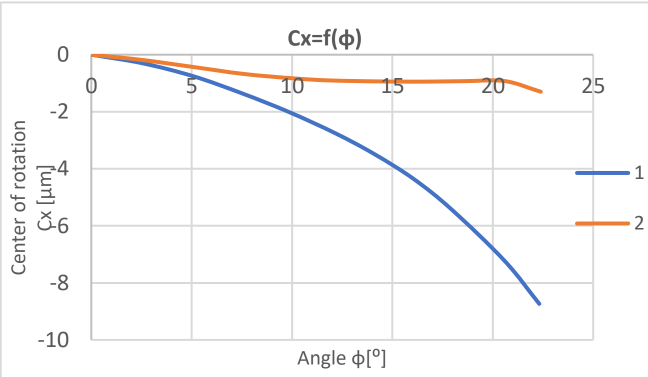

Figure 13. Movement of the center of rotation on X-axis. 1- flexures positions 3 and 6 (Fig.1) with 0.01 mm increased thickness, position 8 with 0.01 mm decreased thickness; 2- flexures with

In such a case there is an asymmetry with respect to both axes X and Y and the two thicker flexures are acting against the thinner one. Similar to the previous cases, the given results are for the transfer curve and deviation of the position of the center of rotation along X-axis and Y-axis. The graph in Fig. 12 represents the transfer curve of the system and in this case, there is almost no difference between guides with a nominal value and the guides with the given deviation of the thickness so the influence of the chosen deviations on the working range of the module is negligible. Similar to the previous studies such deviations have bigger influence on the position of the center of rotation. The graph on Fig. 13 shows that the asymmetry of the guides lead to a greater deviation of the position of the center rotation along the X-axis. The deviation along the X axis reaches approximately 9 µm, which is almost 7 times more than the deviation in case where the flexures are with nominal dimensions. Similarly, the deviation along the Y axis is shown in the graph of Fig. 14. The value reaches 12.3 µm, which is 12 times more than the deviation with flexures with nominal dimensions.

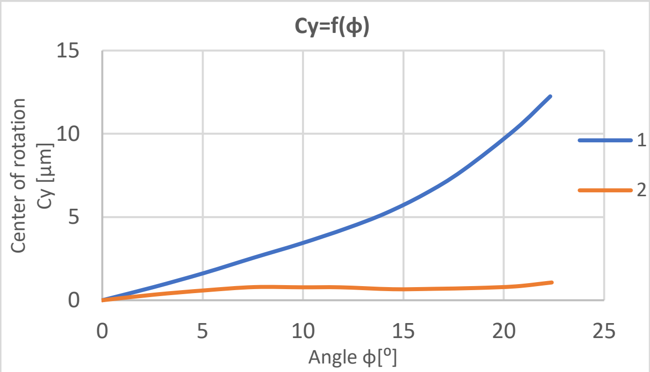

Figure 14. Movement of the center of rotation on Y-axis. 1- flexures positions 3 and 6 (Fig.1) with 0.01 mm increased thickness, position 8 with 0.01 mm decreased thickness. 2 - flexures with nominal thickness

The analysis shows that in case there are three elastic guides with asymmetrical arrangements and different deviation of the thickness within +/- 0.01 mm leads to unacceptable deviation of the position of the axis of rotation of the module.

CONCLUSION

The influence of the thickness deviation of the flexures of the developed micro-positioning measurement module has been studied.

The results of the conducted analyzes show that the asymmetry of the flexures has a significant influence on the deviation of the position of the center of rotation, i.e., this is one of the main factors that has big influence and is directly related to the accuracy characteristics of the elastic micro-positioning measurement module. Equal deviations in several symmetrically placed guides have a smaller effect than deviations on asymmetrically arranged flexures. One of the options for minimizing this effect is to allow the flexures to be made with a tolerance of up to ± 0.01 mm, and the difference in the sizes between them not more than 0.01 mm.

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