

Analysis of the Transfer Curve and the Center of Rotation of Elastic Micro-Positioning Module with Optimized Butterfly Flexures

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Abstract: Micro and Nano- technologies are demanding measurement positioning systems for rotational motions that can cover the requirements for high accuracy, maintenance-free operation and application in different environments with low technical cleanliness or large range of working temperatures. One of the main accuracy parameters is the deviation of the center of rotation during operation. This paper presents the results of the study of the influence on the accuracy caused by different external forces that can be applied to the developed elastic micro-positioning measuring system in the application.

Keywords: technology, positioning, accuracy, rotation, elasticity, flexure, guides, measurements, motion, deformation, rotary stage.

I. INTRODUCTION

Elastic rotary stages and motion devices are widely used for rotational orientation of different components or devices used during scientific analysis, positioning or measurements, especially when high accuracy or maintenance-free system is needed. For such an application where rotational micro positioning is needed the new design of monolithic micro-positioning elastic module with large displacement have been developed. Monolithic design is improving the accuracy of the elastic module and with such a design the errors after assembling are reduced significantly so they are not significant factor influencing the accuracy [14, 17, 19, 20]. The challenge of such a monolithic design is that usually the working range is limited and when the range is increased the accuracy is decreased, but the developed design is showing high accuracy (deviation of the axis of rotation is $1.7\mu\text{m}$) with relatively large working range ($\pm 22,5^\circ$).

The main factors that could have significant influence on the accuracy and performance are the used materials, different kind of external forces that could be applied to the system during operation or the deviation during manufacturing process [4, 7, 8, 9, 10, 11]. Subject of this paper is the analysis of the behavior of the elastic module with the change of the materials used for production or the external forces that are usually undesirable and could be applied axially or radially during operation and what is the influence of the performance [2, 3]. For the purpose of this study the finite element method (FEM) has been used. The micro-positioning elastic module and test scheme is shown on Fig. 1: one of the two outer rings (in this case the lower one pos. 2) is fixed and a torque is applied to the other ring (upper one - pos. 1). The movement or in this case the rotation obtained depend on the size of the applied torque.

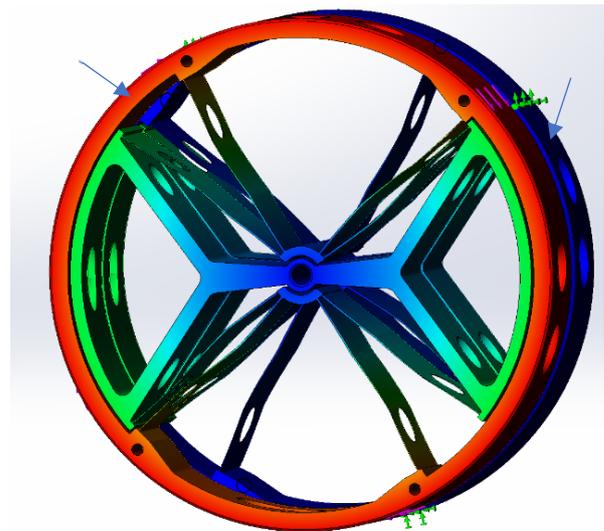


Fig 1. Micro-positioning elastic module with monolithic design – FEM Analysis scheme

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. With the above-described scheme, the following test cases have been analyzed: Analysis of the transfer curve in case different materials are applied; Analysis of the transfer curve in case different axial weight is applied (distributed or nonuniformly distributed). Analysis of the transfer curve in case radial forces are applied.

II. ANALYSIS OF THE TRANSFER CURVE AND THE DEVIATION OF THE CENTER OF ROTATION IN CASE DIFFERENT MATERIALS ARE APPLIED

The material used for production of the elastic module is directly related to the characteristics of the elastic flexures, so an important stage of development is the choice of material. Different types of spring materials suitable for construction were considered and as the most suitable materials for the application were chosen low-carbon stainless steels - AISI 304, 316, 321. These materials are from the group of austenitic stainless steels and have similar characteristics [1, 12, 13, 15]. These are considered as a proper material because they are common stainless steel spring materials and can operate in a variety of working temperatures (low and high temperatures). In this study, all three materials will be

considered in order to be able to choose the one that allows the largest range and the smallest deviation of the centre of rotation, i.e., has the best elastic properties for the specific construction. The material is loaded until an equal safety factor is reached, its value being approximately 1.02, under this factor of safety, the module is going to be destructed. Due to the different strength of materials, the load of each material is different, but the load is increased until the desired safety factor is reached, i.e., the maximum allowable stress is reached.

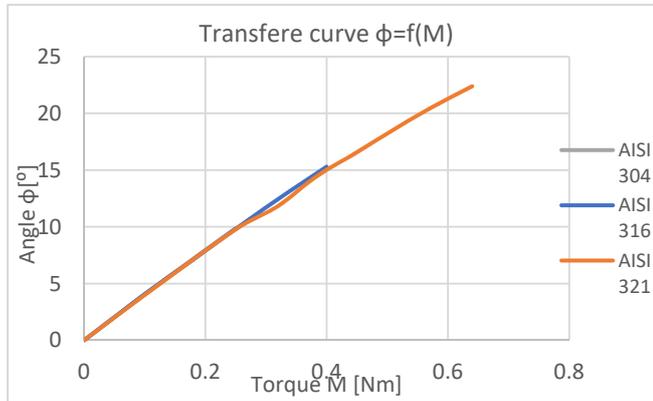


Fig. 2. Transfer curve in case different materials is used

On fig. 2 are the results from the study of the transfer curve of materials AISI 304, AISI 316 and AISI 321, and their maximum loaded are 0,25Nm, 0,4Nm и 0,64Nm accordingly where the maximum allowable stress is reached.

Although with similar composition to AISI 304, AISI 321 has greater strength, which contributes to a significantly larger range, ie. can withstand larger deformations. The difference in composition is that AISI 321 has additional titanium. There is no difference in the linearity of the function for the three materials.

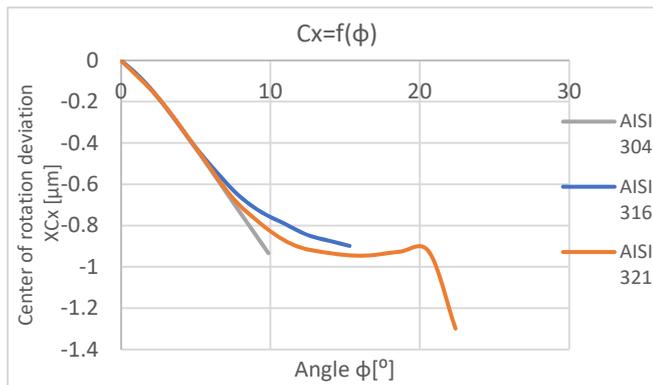


Fig. 3. Deviation of the axis of rotation along X-axis

Deviation of the axis of rotation is measured along X-axis and Y-axis. The results of the study of the deviation of the center of rotation along X-axis are shown in fig. 3, where the results for all materials are similar. Of course, the AISI 321 has a 0.3μm greater deviation of the axis of rotation, but this is also due to significantly greater deformations. This is visible at values for the angle between 21° and 22.4°, where there is a sharp change in the deviation of the axis of rotation. This indicates reaching the limit and the range needs to be limited. The range between 21-22.4° is not recommended to be used and the range should be limited to 21°. With the

limitation of the range, the maximum deviation of the axis of rotation along X-axis remains below 1μm. The three materials show approximately the same deviation of the axis of rotation along X-axis, with the difference that material AISI 321 remains with the highest values for the maximum range and respectively with the best elastic properties. On second position in terms of working range is AISI 316 with ±15° which is significantly less than AISI 321 with ±22,5° working range.

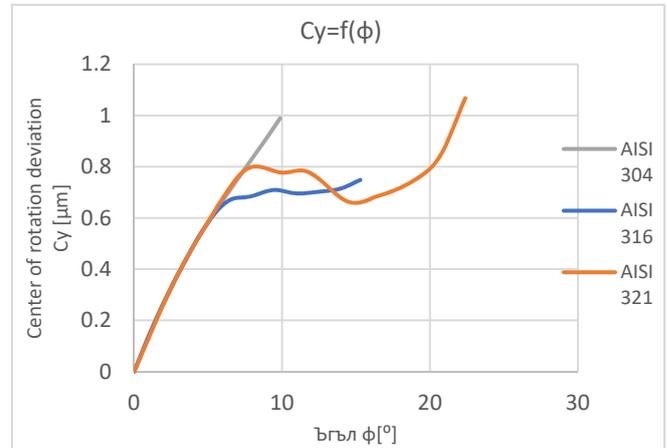


Fig. 4. Deviation of the axis of rotation along Y-axis

Results along Y-axis are comparable to those on the X axis (Fig.4), with maximum deviation at about 1μm. Again AISI 321 has the largest deviation of the axis of rotation, but here the differences are negligibly small, with a maximum difference of 0.3μm between the three materials, even in the maximum values, but the elastic deformations of AISI 321 are significantly greater.

From the simulation analysis it can be concluded that AISI 321 is the most suitable material because it has higher strength and can provide a greater range (twice as large as AISI 304) with negligible differences in the deviation of the axis of rotation.

III. ANALYSIS OF THE TRANSFER CURVE AND THE DEVIATION OF THE CENTER OF ROTATION IN CASE DIFFERENT AXIAL FORCES ARE APPLIED

Unlike the ideal case where there are no external forces to influence the transfer curve or the deviation of the center of rotation, during the real application there are multiple forces that could have influence on them. Such a forces are the axial forces that could load the elastic module during the application like gravity, forces created after assembly of the system where the module is used or load on the stage in case it is used as a rotary stage [5, 6]. Scope of the study is going to be the deviation of the transfer curve and the center of rotation in cases different distributed or nonuniformly distributed axial forces are applied [16, 18]. This is going to represent the real application where there is axial load on the elastic module. On fig. 5 is shown the 3D model and settings used for this study. The difference in the setting discussed in the previous point is that there are added vertical (axial) forces on the periphery of the outer ring (distributed and nonuniformly distributed) and gravity acting in the same direction as the force. Three test cases have been developed – load with distributed axial force $F=1N$, load with distributed axial force $F=10N$, load with nonuniformly

distributed axial force $F=1\text{N}$ and additional distributed axial force $F=9\text{N}$.

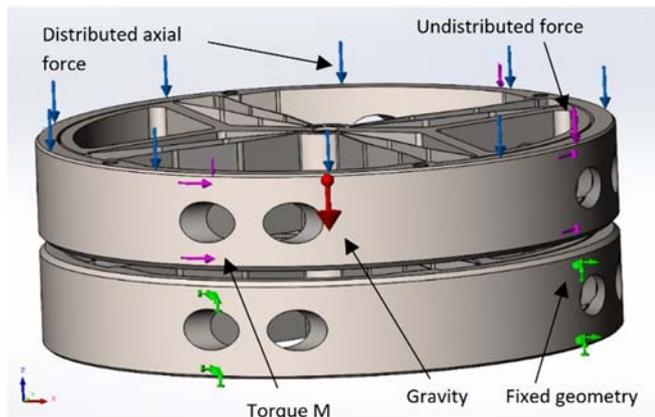


Fig. 5. FEM Analysis in case axial forces are applied – distributed and undistributed

Distribution of the nonuniform distributed force $F=1\text{N}$ is from 0N to 1N along X -axis, additional 9N distributed force is added to the settings in order to simulate slightly nonuniform distribution of the axial forces or specimen placed not exactly in the center of a stage. In addition, it is possible to compare it to $F=10\text{N}$ distributed force.

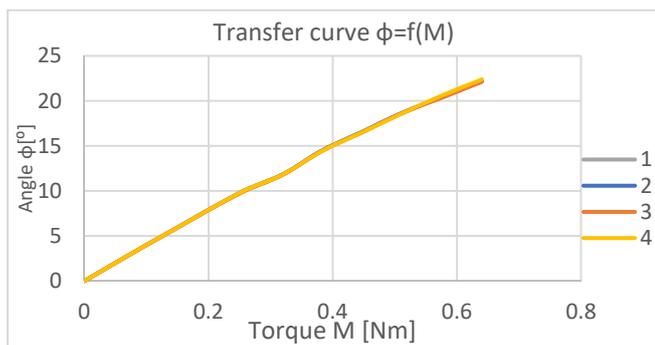


Fig. 6. Transfer curve: 1- Distributed $F=1\text{N}$; 2- Distributed $F=10\text{N}$; 3- Undistributed $F=1\text{N}$ with additional distributed $F=9\text{N}$; 4-ideal case.

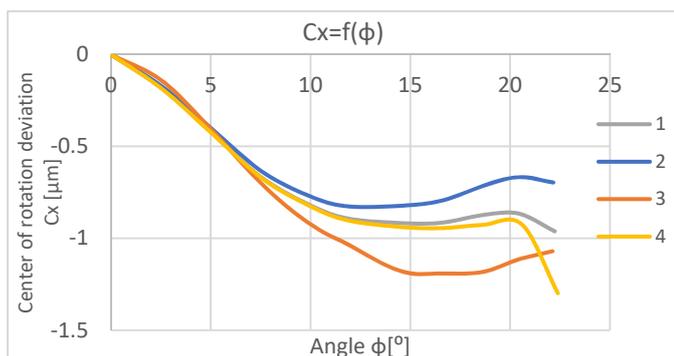


Fig. 7. Deviation of the axis of rotation along X-axis: 1- Distributed $F=1\text{N}$; 2- Distributed $F=10\text{N}$; 3-Undistributed $F=1\text{N}$ with additional distributed $F=9\text{N}$; 4-ideal case

The results of the transfer curve studies of the three test cases are shown on fig.6. There is almost no difference in the transfer curves i.e., the load has a minimal effect on the angular positioning. The main differences are in the deformations along the Z axis and the deviation of the center of the axis of rotation along X-Y axes observed on fig.7-9. The

study of the deviation of the center of rotation along X-axis can be seen on fig. 7. In the case where there is a distributed load, the deviation is lower than the ideal case. With 1N distributed load there is almost no difference but when the load is 10N there is difference of $0,4\mu\text{m}$ in positive direction. This means that distributed load has positive influence of the center of rotation along X-axis, but in case where the load is nonuniformly distributed there is a negative influence. The deviation of the center of rotation is worse than the ideal case. This means that nonuniformly distributed load is not desirable for the application of the elastic module. These observations are made for the full scale of the working range, but if the elastic module is used within $\pm 7^\circ$ working range, the difference in the deviation of the center of rotation is neglectable. Almost the same is seen along Y-axis.

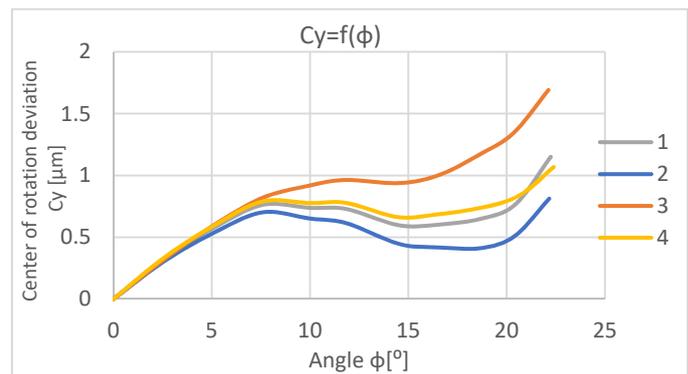


Fig. 8. Deviation of the axis of rotation along X-axis: 1- Distributed $F=1\text{N}$; 2- Distributed $F=10\text{N}$; 3- Undistributed $F=1\text{N}$ with additional distributed $F=9\text{N}$; 4-ideal case

The results of study along Y-axis presented on fig. 8 show behavior similar to the study along X-axis. In case there is distributed load, the deviation is less than the deviation of the ideal case. Almost no difference in case of 1N load and better results when the load is 10N similarly to the result along X-axis. The test case where there is nonuniformly distributed force again shows negative influence on the application of the elastic module. Along Y-axis is significant difference compared to the ideal case and to the results along X-axis, reaching deviation of $1,7\mu\text{m}$.

Nevertheless, that distributed axial forces have positive effect on the deviation of the center of rotation along X/Y axis, these forces have negative influence of the deviation of the center of rotation along Z-axis. Even for distributed load the results from the study along Z-axis presented on fig. 9 show that the deviation is $21\mu\text{m}$. The calculated curve is almost linear and the center of rotation is moved in negative direction. This means that the “drop” of the center of rotation is directly proportional to the axial load applied to the elastic module. This fact needs to be taken into account when there are an external axial loads applied to the module. This movement of the center of rotation could be calculated using the linear nature of the curve before the usage of the module. The graphic on the fig.9 shows that the difference in the deviation of the center of rotation along Z-axis between distributed and slightly ununiformly distributed force is neglectable. The both reached the same level of deformation.

In general, the results of the study show that an axial load has a positive influence of the deviation of the center of rotation in XY plane as the deviation is reduced but in case the load is ununiformly distributed it has negative impact on the

deviation of the center of rotation as the deviation is increased.

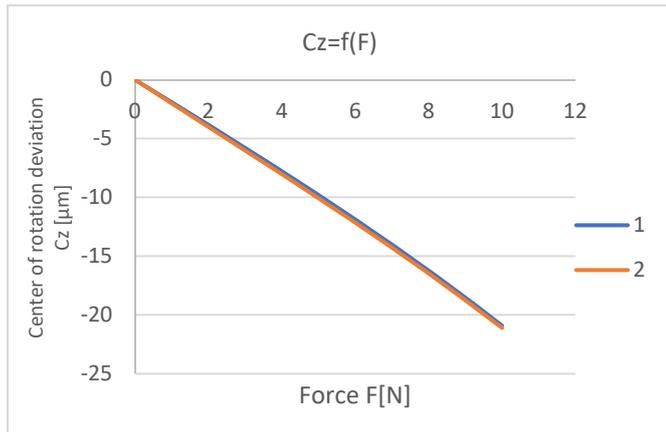


Fig. 9. Deviation of the axis of rotation along Z-axis: 1- Distributed $F=10\text{N}$; 2- Undistributed $F=1\text{N}$ with additional distributed $F=9\text{N}$

Along Z-axis, the axial forces have significant impact on the deformation but this deformation can be calculated as the calculated curve is linear. In terms of the transfer curve the axial load has almost no influence on the angular movement.

IV. ANALYSIS OF THE TRANSFER CURVE AND THE DEVIATION OF THE CENTER OF ROTATION IN CASE DIFFERENT RADIAL FORCES ARE APPLIED

Unlike the axial forces studied in the chapter above, the radial forces are more commonly presented after the assembly of the module in an angular positioning system. The errors created during the assembly could cause unwanted forces in radial direction. These forces directly affect the accuracy of the module due to the fact that they directly affect the deviation of the center of rotation. Therefore, at this chapter, the radial stiffness of the elastic systems is studied in order to determine the maximal radial forces that are permissible for the module.

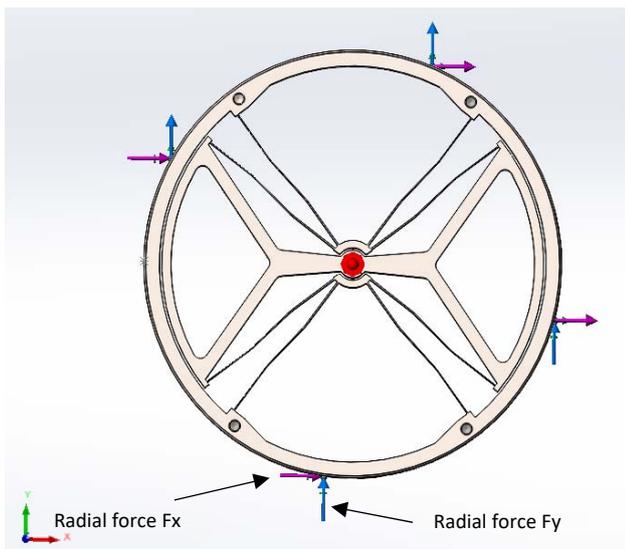


Fig. 10. FEM Analysis in case radial forces along X/Y axis are applied

The scheme of the simulation analysis is shown in fig. 10. In case there is a radial force along X-axis the deviation of the center of rotation along X-axis is greater than if the radial

force is along Y-axis which behavior is expected. At $F_x=5\text{N}$, deviation of C_x is $20\mu\text{m}$ which is significantly greater compared to $5\mu\text{m}$ in case $F_y=5\text{N}$. The both curves are almost linear so the deviation could be calculated.

In order to analyze if there is a difference in the radial stiffness along X and Y-axis the radial forces are applied in both directions. The maximal applied force is 5N and this represents possible displacement between axes of the elastic module's outer and inner ring caused by assembly. Results of the study are shown on fig. 11 where F_x and F_y are the forces acting along X and Y-axis. C_x is the center of the rotation along X-axis at a given moment. On the graphic is seen that the radial forces have significant impact on the accuracy of the elastic module as the deviation of the center of rotation increased.

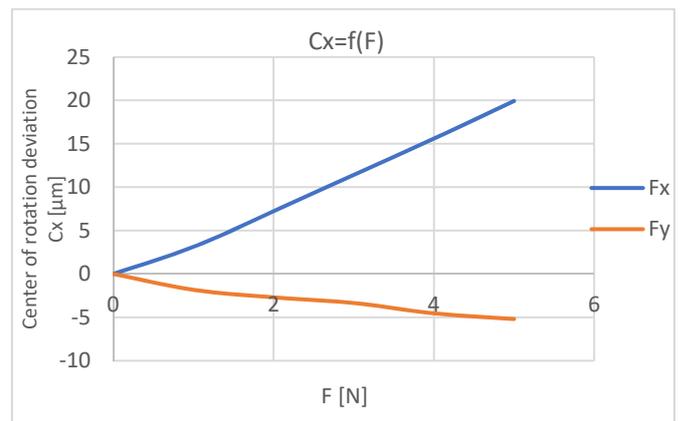


Fig. 11. Deviation of the axis of rotation along X-axis in case radial force is applied

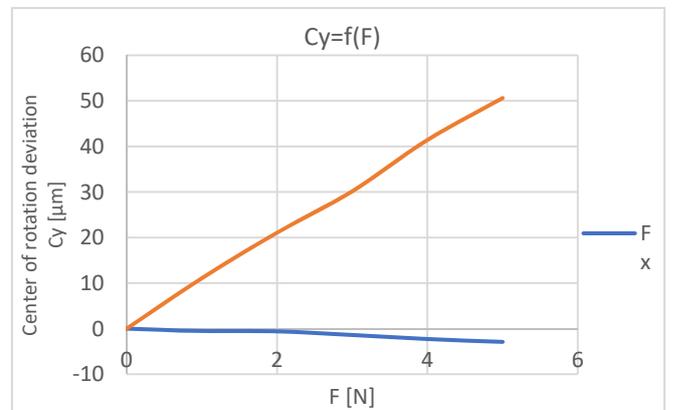


Fig. 12. Deviation of the axis of rotation along Y-axis in case radial force is applied

On the next fig. 12 are shown the results of similar study but this time the deviation of the center of rotation along Y-axis is calculated. Expectedly, similar to the previous case the deviation along Y-axis is significantly greater when a force along Y-axis is applied (F_y). This deviation reaches $50\mu\text{m}$ and compared to the deviation of $20\mu\text{m}$ along X-axis in case a force along X-axis (F_x) is applied showed that the deformations in direction of Y-axis are larger i.e., the radial stiffness along Y-axis is more than 2 times less than the radial stiffness along X-axis. The deviation along X-axis in this study is $5\mu\text{m}$ which is in the same range with the deviation along Y-axis if a force along X-axis is applied.

The results of the both studies show that the worst case is when radial force along Y -axis is applied due to the elastic module has less stiffness along Y -axis. The deviation is in such a range that additional deviation added during rotational motion of the elastic module is negligibly small.

V. CONCLUSION

The results of this study confirms that the material used for the production of the elastic modules has significant affect on the working range respectively to the elastic properties at a given design. The accuracy is not so affected in case we are testing similar materials, in this case austenitic stainless steels.

Distributed axial forces are not affecting the accuracy of the design of the elastic module since they are not reaching the maximum allowable load for the construction. This kind of forces even increase the accuracy as they reduce the deviation of the center of rotation along X/Y -axis. The deviation of the Z -axis is significant in negative direction but this “drop” of the working plane could be calculated and taken into account for the positioning system. Nonuniformly distributed axial forces need to be avoided as such forces have negative impact on the accuracy as the deviation of the center of rotation is increased. Distributed or not the axial forces have almost no influence on the transfer curve of the micro-positioning elastic module.

Radial forces need to be avoided as they are causing significant impact on the accuracy especially along Y -axis as the results show less design stiffness compared to the stiffness along X -axis. Additional flexible coupling needs to be used in order to reduce in the allowable tolerances the radial forces created due to deviations during assembly of the system where the elastic module is used.

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