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# FLEXURE BASED LINEAR GUIDE WITH MICROMETRIC PRECISION

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**Rezumat.** *Ghidajele liniare reprezintă un element de bază al mașinilor-unelte. Proprietățile lor influențează direct caracteristicile mașinilor și de aceea li se acordă o atenție deosebită. Sistemele de ghidare liniară cu precizie micrometrică reprezintă un caz special care, în construcție clasică, sunt compuse din elemente care necesită procese de producție costisitoare și proceduri de asamblare complexe. Lucrarea de față propune o soluție alternativă, bazându-se pe avantajele aduse de utilizarea compliantei materialelor. Avantajele se regăsesc într-un proces de producție mai simplu, mai rapid și mai puțin costisitor. De asemenea, sistemul mecanic rezultat prezintă lipsa jocului, durată foarte mare de viață, lipsa mentenanței și capacitate de lucru în medii contaminate cu pulberi și alți agenți abrazivi.*

**Abstract.** *Linear guides represent the backbone of the manufacturing machines. Their properties have a direct impact on the machine characteristics and so they are given a special attention. Among these, linear guides with micrometric precision are a special case, which normally requires expensive manufacturing processes and complex assembly procedures. This work proposes an alternative design, based on the compliance of materials, which implies a significantly simpler production process, lower overall production costs and a much smaller manufacturing time. The resulted mechanical system will exhibit no backlash, does not require maintenance, has a very long life and is suitable to work in particle contaminated environments.*

**Keywords:** Flexure, machine tool, Z axis, linear guide

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## 1. Introduction

CNC machine tools use computer-controlled systems to cut, shape and drill materials with high precision and accuracy. These machines consist of several components, including the X, Y, and Z axes, spindles, tool changers, and control systems.

The Z-axis in CNC machine tools is responsible for the vertical movement of the cutting tool or workpiece. It is typically driven by a motor and guided by linear bearings or ball screws. The precision and accuracy of the Z-axis are critical to the

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performance of CNC machine tools, as it determines the depth and accuracy of cuts and drilling operations.

One approach to Z-axis design in CNC machine tools is to use rigid components such as linear bearings and ball screws. While these designs are effective, they can be heavy, complex, and expensive. Additionally, rigid designs may experience vibrations and other disturbances that can impact the accuracy and precision of the Z-axis.

A flexure-based Z-axis is an alternative design for the Z-axis of a CNC machine tool, which uses flexure mechanisms instead of traditional linear guide rails and ball screws [1]. Flexure mechanisms are made up of thin metal strips that bend and flex under load, providing the necessary support and motion along the Z-axis [2].

Flexure-based designs have several advantages over traditional designs. They are typically more compact, lighter, and require less maintenance, as there are no moving parts that need lubrication or adjustment [3]. They also offer greater precision and stability, as there is no backlash or hysteresis in the system [4].

One of the most common types of flexure-based Z-axis designs is the parallelogram flexure, which uses two or more pairs of parallel metal strips to provide the necessary support and motion along the axis [5]. Other designs include the leaf spring flexure and the compliant mechanism, which use single or multiple metal strips arranged in various configurations to achieve the desired motion and support [6].

Flexure-based designs are becoming increasingly popular in high-precision CNC machining applications, semiconductor manufacturing, optical fabrication, and medical device manufacturing, where accuracy, stability, and reliability are critical [7]. However, their performance may be affected by changes in temperature, humidity, or other environmental factors [8].

Advancements in materials and manufacturing techniques, such as additive manufacturing, are making it possible to develop more effective and affordable compliant mechanisms for CNC machine tools.

The design of the Z-axis and other components in CNC machine tools is a complex and important area of research and development. Both rigid and compliant designs have advantages and disadvantages, and the choice of design depends on factors such as cost, performance, and application requirements. Researchers and engineers are continuously working to develop new and innovative approaches to CNC machine tool design, to improve precision, accuracy, and efficiency in manufacturing processes.

## 2. Requirements

The axis will be used inside a grinding machine and has the following requirements:

- 50µm stroke
- Strict cost constrains
- No maintenance over a period of 5 years
- Lightweight construction
- +/- 0.5µm linearity error over the full stroke
- High stiffness (above 20N/µm)

A high precision grinding machine is a type of machine tool that is used to grind materials to a high degree of accuracy. These machines are typically used in manufacturing and engineering settings where the exact dimensions and surface finishes of a material are critical to the quality and performance of the final product.

High precision grinding machines can be used to grind a wide range of materials, including metals, ceramics, and plastics. They are capable of producing extremely smooth and accurate surfaces, with tolerances as tight as a few microns.

The key components of a high precision grinding machine are the grinding wheel, the workpiece holding device, and the machine itself. The grinding wheel is typically made from a hard abrasive material such as diamond or cubic boron nitride (CBN) and is used to remove material from the workpiece. The workpiece holding device is used to securely hold the workpiece in place during the grinding process, ensuring that it remains in the correct position and orientation. The machine itself is typically a highly automated and computer-controlled system that can perform a wide range of grinding operations with a high degree of accuracy and repeatability.

One of the primary benefits of using a high precision grinding machine is the ability to achieve extremely tight tolerances and surface finishes. This is especially important in industries such as aerospace, medical device manufacturing, and automotive manufacturing, where even small deviations from the desired specifications can have significant impacts on the performance and safety of the final product.

In addition to precision and accuracy, high precision grinding machines also offer several other benefits. For example, they can be used to remove material from a workpiece in a very controlled and precise manner, which can help to minimize waste and reduce overall production costs. They can also be used to create complex shapes and contours on a workpiece, which can be difficult or impossible to achieve using other manufacturing processes.

The Z axis of a grinding machine is a critical component that allows for precise control of the vertical position of the grinding wheel and the workpiece during the grinding process. The construction of this axis is crucial to ensuring that the machine can perform highly accurate and repeatable grinding operations.

The Z axis is typically constructed using a linear motion system, such as a ball screw or linear motor, which allows for precise movement of the grinding wheel and workpiece. The linear motion system is connected to a motor or drive system that provides the necessary power to move the grinding wheel up and down along the Z axis.

The linear motion system is typically mounted to the machine bed or base, which provides a stable platform for the entire grinding machine. The bed or base must be designed to withstand the forces generated during the grinding process, which can be significant due to the high speeds and forces involved.

A flexure-based linear axis is a type of linear motion system that are not yet commonly used in grinding machines to control the movement of the grinding wheel. Unlike traditional linear motion systems, which use bearings or sliding mechanisms to support and guide the moving components, a flexure-based linear axis uses a series of flexible structures or "flexures" to achieve the required motion.

The flexures are typically made from a high-strength material, such as steel or titanium, and are designed to flex in a controlled manner when subjected to a force or load. By carefully designing the shape and geometry of the flexures, it is possible to achieve precise and repeatable motion along an axis, without the need for bearings or sliding mechanisms.

Flexure-based linear axes can provide smoother and more accurate motion, as the flexures are able to dampen vibrations and other disturbances that can affect the performance of the machine. They can also operate at higher speeds and accelerations, as there is less friction and less need for lubrication. Another advantage of flexure-based linear axes is their compact size and low weight, which can be beneficial in grinding machines that require a high degree of mobility or that have limited space for the motion system. They can also be easily integrated with other components, such as motors and feedback systems, to create a complete motion control system for the grinding machine.

When a rod is used as a flexure, it is typically designed to bend or flex in a controlled manner when subjected to a force or load. The amount of bending or deflection that occurs is determined by several factors, including the material properties of the rod, its length and diameter, and the orientation of the force or load.

One common way that rods are used as flexures is in the construction of cantilever beams, which are often used in precision measurement devices, optical systems, and other applications where high accuracy and stability are required. In a cantilever beam, a thin rod is fixed at one end and left free to bend or flex at the other end. By carefully designing the dimensions and material properties of the rod, it is possible to achieve precise and repeatable deflection in response to a given load or force.

In a flexure-based linear axis, multiple rods are typically arranged in a specific geometry to achieve the required motion. The rods are typically preloaded to ensure that they are always under tension, which helps to prevent unwanted lateral motion or vibration. The flexures may be designed to bend or twist in response to the forces applied to them, or they may be designed to have a specific range of motion or stiffness.

In contrast, strip flexures are typically constructed from thin, flat strips of material, which are arranged in a specific pattern. Strip flexures can be designed to bend or twist in response to the forces applied to them, and they may be used in applications where a large range of motion is required, such as in robotic or motion control systems. One advantage of strip flexures is that they can be more compliant than rod flexures, which can be useful in applications where a softer or more flexible motion is required.

While rods are a common choice for flexure-based motion systems, long screws can also be used as flexures in certain applications. When a screw is used as a flexure, it is typically designed to bend or flex in a controlled manner when subjected to a force or load, like a rod-based flexure.

One common technology used to connect flexures to the machine body is clamping. This involves the use of mechanical fasteners, such as screws or bolts, to hold the flexure in place against the machine body. This technology is often used in applications where a large range of motion is required, as it allows for easy adjustment of the flexure position. Clamping can also be used in applications where high load capacity is required, as the fasteners can provide a strong and secure connection.

Another technology used to connect flexures to the machine body is adhesive bonding. This involves the use of a high-strength adhesive to attach the flexure to the machine body. Adhesive bonding can provide a very stable and rigid connection, making it a good choice for applications where high precision and accuracy are required. It can also be used in applications where the load capacity is relatively low, as the adhesive may not be able to withstand high stresses.

Welding is another technology that can be used to connect flexures to the machine body. Welding involves the use of a high-temperature process to fuse the flexure to the machine body. This technology can provide a very strong and permanent connection, making it a good choice for applications where high load capacity and durability are required. However, welding may not be suitable for applications where precision and adjustability are important, as it can be difficult to make changes to the position of the flexure once it has been welded in place.

The current work introduces a new type of flexure, the screw-type flexure (Fig. 1). It has the ability to connect directly via screw nuts to the machine body, without causing distortion, errors and slip, while still being adjustable at any time.

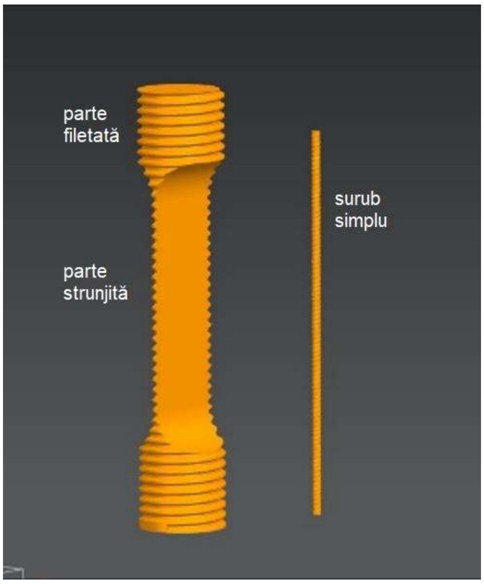


**Fig. 1** Screw-type flexure: grinded M30 screw left and M3 screw right

In the first phase, the behavior of the test specimens under side loading was investigated (Fig. 2). A higher rigidity is preferred. The results indicate excellent behavior for the flexure strip formed by processing the M30 screw. In cases where M3 threaded bars are used, the results in this case are as anticipated. The specimen with three bars has the deviation closest to that of the strip, while the results of the specimens with two and one bar, exhibit increasing deviations.

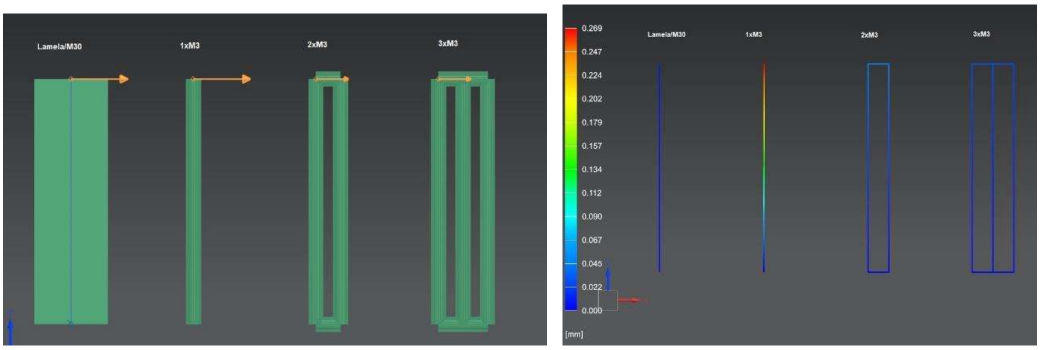


**Fig. 2** Mesh and FEM analysis for the side loading scenario; from left to right: grinded M30 screw, M3 screw, double M3 screw and triple M3 screw

In the second phase, the behavior of the test specimens under frontal loading was investigated (Fig. 3). In this case, a minimal rigidity is preferred. The results indicate that the M3 threaded bar has the best behavior, with its deviation being significantly larger than that of the next specimen in terms of deviation value, namely the flexure strip produced by grinding the M30 screw. In the case of other specimens based on M3 screws, the results are consistent with the number of bars used. It should be noted that the differences between specimens are not significant, which favors systems composed of multiple bars.

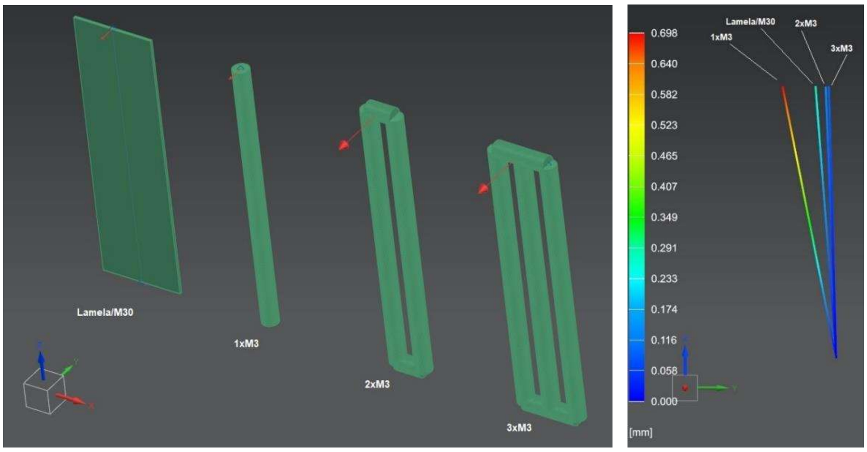


**Fig. 3** Mesh and FEM analysis for the front loading; from left to right: grinded M30 screw, M3 screw, double M3 screw and triple M3 screw

In conclusion, the blade exhibits the most favorable behavior and can be used whenever the system requires high performance. M3 bars can be successfully used in systems that can benefit from ease of use, considering that structures can become relatively complex if the system requires high compliance and rigidity.

## 3. Proposed solution

The solution will make use of the screw-type flexure based on M3 rod, because it is the most economical and it requires no additional machining prior to use.

The schematic of the system is provided in the Fig. 4. It is formed using three mechanical groups: two cantilever multiplication stages and a linear stage. The first two stages reduce the linear motion amplitude at the mechanism entry 100 times, each accomplishing 10x reduction. The linear stage at the exit, allows only the movement along one axis of motion.

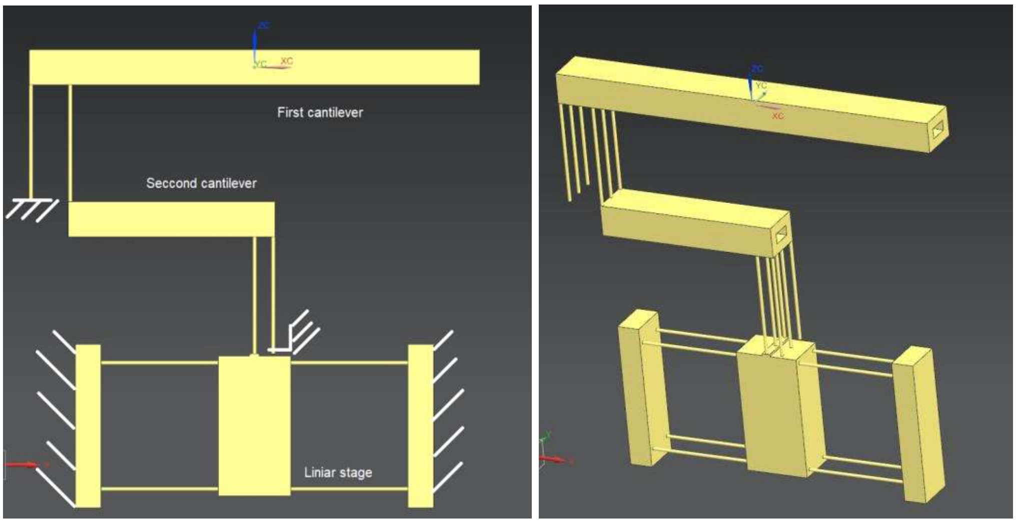


**Fig. 4** Solution draft; 2D left and 3D right

There are several mathematical techniques that can be used to describe the behavior of flexure-based system. Some of the most common ways include:

Hooke's law: This is a basic equation that describes the relationship between stress and strain in an elastic material, such as a flexure. It is typically written as $\sigma = E\varepsilon$, where $\sigma$ is the stress (force per unit area) applied to the material, E is the elastic modulus (a measure of the material's stiffness), and $\varepsilon$ is the resulting strain (the amount of deformation per unit length).

Euler-Bernoulli beam theory: This equation is commonly used to describe the behavior of thin, flexible structures such as beams or flexures. It relates the bending moment and curvature of the structure to the material properties and geometry of the beam. The equation is often written as M = EI(d^2y/dx^2), where M is the bending moment, E is the elastic modulus, I is the area moment of inertia (a measure of the beam's stiffness), y is the deflection of the beam, and x is the position along the beam.

Timoshenko beam theory: This equation is similar to Euler-Bernoulli beam theory, but takes into account the effects of shear deformation in the beam. It is often used to describe the behavior of more complex or non-uniform beams or flexures. The equation is typically written as M = EI(d^2y/dx^2) + GAK(d^4y/dx^4), where G is the shear modulus, A is the cross-sectional area of the beam, and K is a geometric factor that depends on the shape of the beam cross-section.

In general, Timoshenko beam theory should be used instead of Euler-Bernoulli beam theory when studying compliant mechanisms that have relatively short, wide or thick flexure elements, or when the aspect ratio (length-to-thickness ratio) of the flexure is small. This is because Timoshenko theory takes into account the effects of shear deformation and rotational inertia of the flexure, which become increasingly important as the aspect ratio decreases.

On the other hand, Euler-Bernoulli beam theory can be used to analyze compliant mechanisms that have long, thin flexure elements, where the effects of shear deformation and rotational inertia are negligible compared to bending deformation. This is because Euler-Bernoulli theory assumes that the flexure undergoes pure bending deformation and neglects the effects of shear deformation and rotational inertia.

Higher-order beam theories are more advanced mathematical models used to analyze the behavior of flexible beams or flexures. They are an extension of Euler-Bernoulli or Timoshenko beam theory and take into account additional effects that may be important in certain applications, such as transverse shear deformation or warping of the cross-section.

In Euler-Bernoulli and Timoshenko beam theories, the deformation of the beam is described in terms of a single function (the deflection or rotation) that varies along the length of the beam. However, higher-order beam theories introduce additional functions to account for other modes of deformation, such as transverse shear or warping. These additional functions can improve the accuracy of the analysis and allow for a more detailed understanding of the behavior of the beam or flexure.

Finite element analysis (FEA): FEA is a computational technique that can be used to model the behavior of complex structures, including flexures. FEA involves dividing the structure into small elements and solving a set of equations to determine the stresses, strains, and deformations in each element. FEA can be used to predict the behavior of flexures under various loading conditions and can help optimize the design of a flexure for a specific application.

This work uses Finite element analysis (FEA) as its analytical technique to determine the characteristic behavior of the system as it has several advantages over other methods when it comes to flexure analysis:

Flexibility: FEA is a very flexible method that can be applied to a wide range of geometries and loading conditions. This makes it ideal for analyzing complex flexure designs that cannot be easily solved using analytical methods.

Accuracy: FEA can provide accurate predictions of the behavior of flexures, especially for more complex geometries and loading conditions. This is because FEA models can capture more detailed information about the stress and strain distribution within the flexure.

Parametric analysis: FEA allows for parametric analysis, where different design variables can be changed and their effects on the performance of the flexure can be evaluated. This makes it easy to optimize the design of the flexure for a specific application.

Visualization: FEA provides graphical visualization of the stress and strain distribution within the flexure, making it easier to understand the behavior of the flexure and identify potential failure modes.

Time and cost efficiency: FEA can save time and cost by reducing the need for physical prototyping and testing. This can lead to faster and more efficient design iterations, and ultimately a better performing flexure.

Nonlinear analysis: FEA can be used to perform nonlinear analysis of flexures, taking into account large deformations, material nonlinearity, and contact between parts. This allows for a more accurate prediction of the behavior of the flexure under real-world conditions.

Dynamic analysis: FEA can be used to perform dynamic analysis of flexures, taking into account the effects of vibration and other dynamic loading conditions. This is important for applications where the flexure will be subjected to high-frequency loading.

Optimization: FEA can be used to optimize the design of flexures, taking into account multiple design variables and constraints. This can lead to a more efficient and effective design, and ultimately a better-performing flexure.

Design iteration: FEA allows for design iterations to be performed quickly and easily, making it possible to explore multiple design options and refine the design as needed.

Safety: FEA can be used to predict failure modes and ensure that the flexure will be safe to use under all anticipated loading conditions.

Material selection: FEA can be used to compare the performance of different materials for a given flexure design. This can help to identify the most appropriate material for a specific application based on factors such as strength, stiffness, and cost.

Thermal analysis: FEA can be used to perform thermal analysis of flexures, taking into account the effects of temperature on the material properties and the resulting deformation and stress.

Prototyping: FEA can be used to guide the design of physical prototypes and to evaluate their performance. This can help to ensure that the prototype will be optimized for the desired application and can reduce the time and cost required for physical prototyping and testing.

In the context of FEA, the choice between using a 1D mesh or a 3D mesh depends on the nature of the problem being analyzed and the level of detail required in the analysis. A 1D mesh is typically used when the structure being analyzed can be approximated as a series of connected one-dimensional elements, such as a beam or a rod. This is often the case for flexures, which can be modeled using 1D beam elements. A 3D mesh, on the other hand, is typically used when the structure being analyzed is more complex and requires a more detailed representation, such as for analyzing the stresses in a solid part or a complex assembly. 3D meshes are generally more computationally expensive and require more resources to run than 1D meshes, but can provide more accurate and detailed results. The work at hand took usage of both 3D and 1D meshing elements to provide the needed accuracy and a low level of computational resources (Fig. 5).

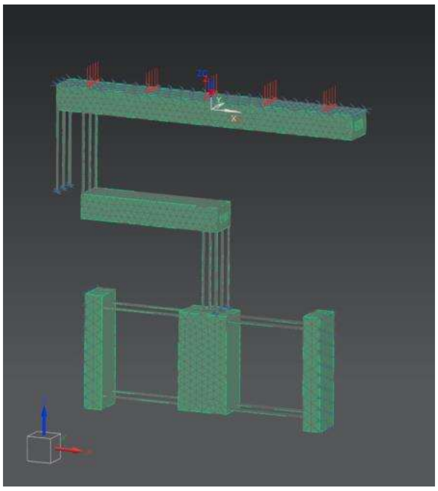


**Fig. 5** System mesh and boundary conditions during forward motion

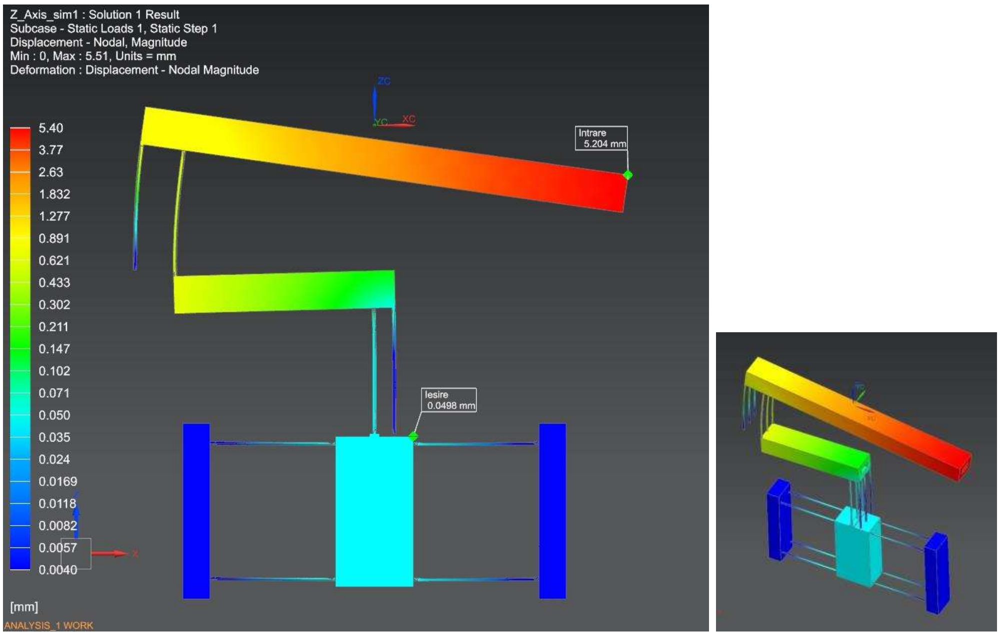


**Fig. 6** FEM results in the case of forward motion 2D and 3D

The working principles are easily identified by analyzing Fig. 6. The input motion reads 5.204 mm while the produced linear motion is evaluated at 0.0488 mm. This is a reduction of ruffly 100 times. Fig. 7 identifies the stresses that occur during normal traverse motion of the axis. As anticipated, the stress is concentrated in the flexures.

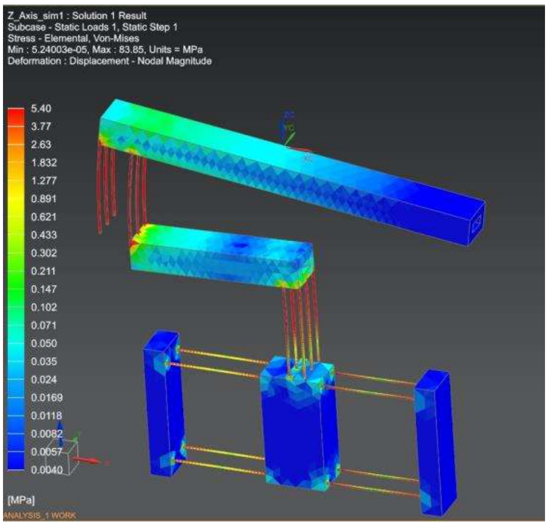
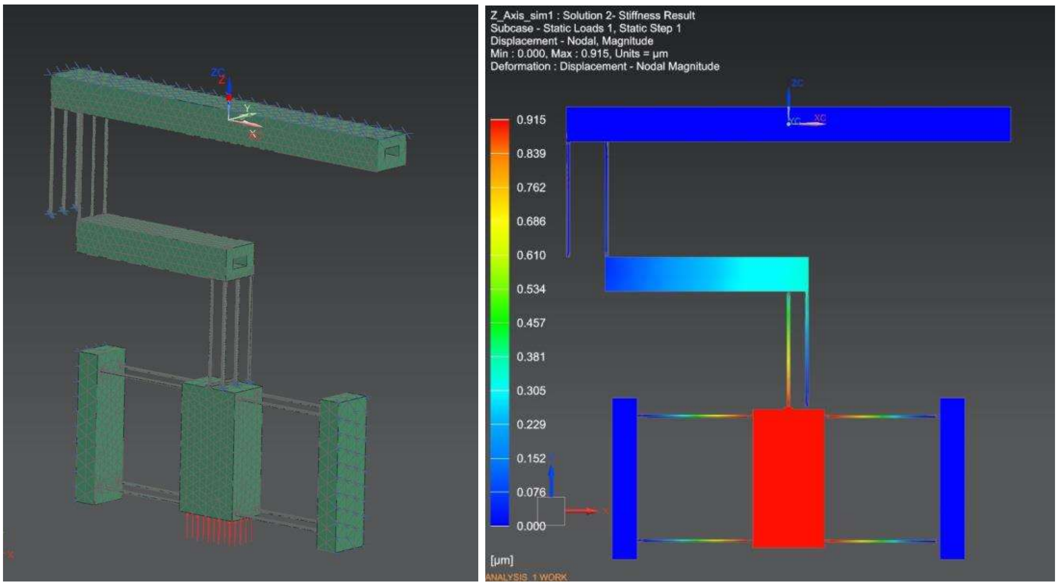


**Fig. 7** Von-Mises stress during forward motion loading

Using FEM methods, the stiffness that is to be expected from the mechanical system may be obtained. In this case the boundary conditions change slightly. The first cantilever beam will be fixed in all directions, as its motion is locked by the leadscrew assembly that drives it. This is assumed not to be back drivable. Next, to determine the stiffness in Z direction, a 10N force is applied to the bottom of the linear stage along the Z axis direction. The produced displacement is observed in Fig. 8.



Z_Axis_sim1 : Solution 2- Stiffness Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.000, Max : 0.915, Units = µm
Deformation : Displacement - Nodal Magnitude

**Fig. 8** Stiffness analysis in Z direction; mesh and boundary conditions left and results right

The values gained by using FEM analysis indicate that the stiffness lies around 10N/µm, which is proximately half of what is needed. The design may be easily improved in this regard and the minimum requirements be fulfilled.

The dynamic behavior of the mechanical structure will be analyzed using modal analysis. This is a powerful mathematical technique that provides vital information about the natural frequencies, damping and mode shapes of the drafted solution. In this stage of development, the mode shapes are of primary importance since it has the greatest impact on the geometrical shape of the device.

The modal analysis brings a lot of useful information. One point of improvement becomes apparent. The linear stage construction allows unwanted deformations to occur in X and Y directions, which greatly diminishes the stiffness in these directions. The design can be easily improved by increasing the number of flexures that connect the carriage in XY plane up to the point where the stiffness and the deformations of the relevant mode shapes fall within acceptable levels.

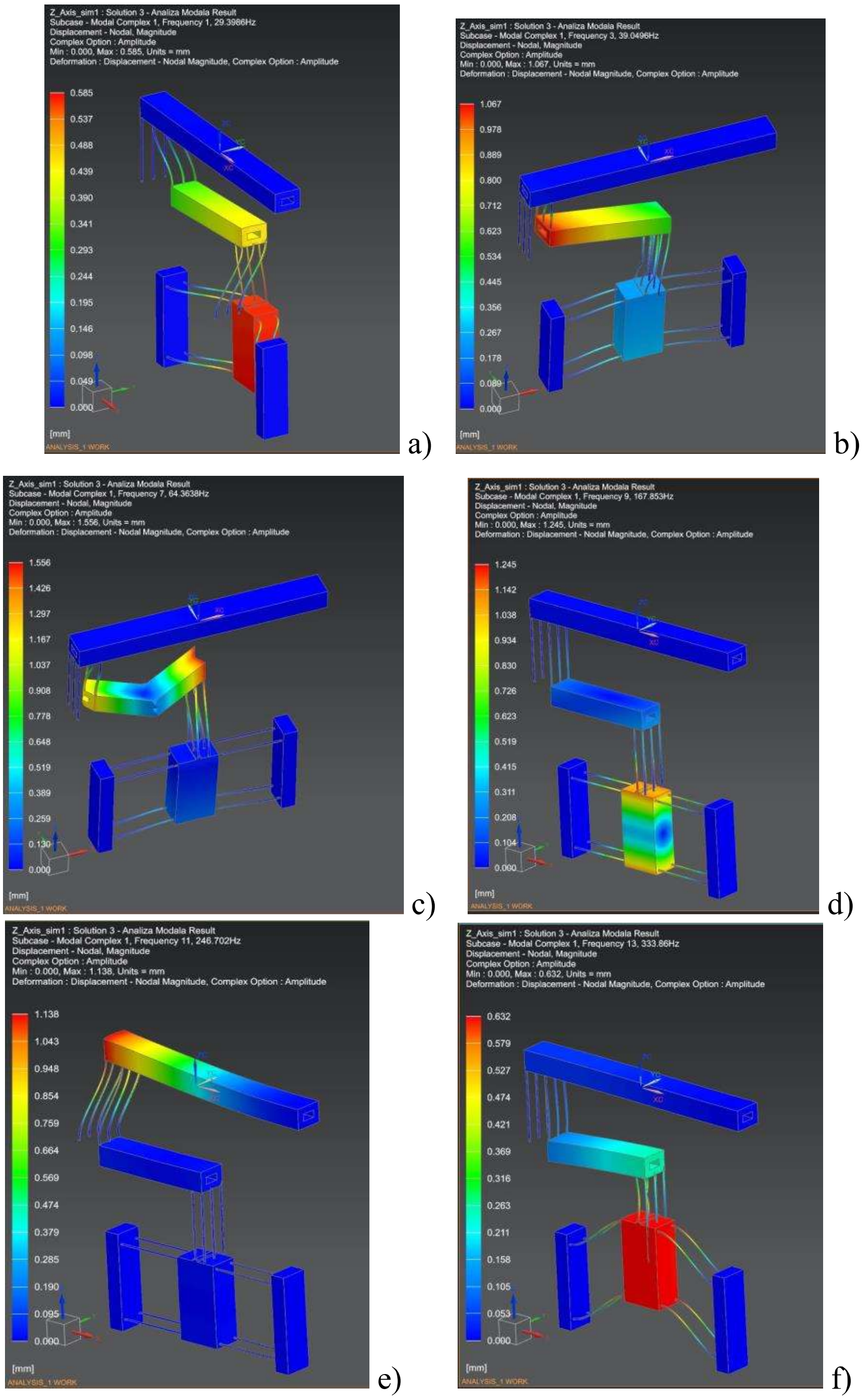


**Fig. 9** Modal Analysis: a) Mode 1-29.3Hz, b) Mode 2-39Hz, c) Mode 3-64Hz, d) Mode 4 - 167Hz, e) Mode 5 - 246Hz, f) Mode 6-333Hz

## Conclusions

This work introduces a new approach towards designing a high precision linear axis that may be used as Z axis of precision grinding machines. The approach uses compliant rods as its main construction block, making it cost effective and easy to build. Only the basic principles are covered in this work, yet the results indicate that the design seems to be very promising, allowing for various adaptations to be build and possibly serving in many similar purposes.

## Acknowledgment

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