An Elastically Guided Machine Axis with Nanometer Repeatability

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Abstract

This paper focuses on the design and calibration of an elastically guided vertical axis that will be applied in a small high precision 3D Coordinate Measuring Machine aiming a volumetric uncertainty of 25 nm. The design part of this paper discusses the principles of this system, the compensation of the stiffness of the vertical axis in the direction of motion, the weight compensation method and the design and performance of the axis precision drive system, a Lorentz actuator. In the metrology part of this paper the calibration methods to determine the linearity as well as motion straightness and axis rotation errors are discussed. Finally first calibration results of this axis show nanometer repeatability of the probing point over the 4 mm stroke of this axis. The causes of the short-term variations with a bandwidth of about ± 10 nm are under investigation. Error compensation may reduce the residual error of the probing point to the nanometer level.

Keywords:
Coordinate measuring machine (CMM), Design, Calibration

1 INTRODUCTION

The authors of this paper cooperate in a project to build and calibrate a 3D Coordinate Measuring Machine [1] [2] based on measurement by 1 nm resolution scales, a horizontal air bearing system with separate stress frames for pre-load forces, frictionless air supply [3] and an elastically guided fully compensated vertical axis.

2 PRINCIPLE OF THE ELASTICALLY GUIDED AXIS

The vertical stroke of the CMM is provided by an elastic straight-guided mechanism as schematically shown in figure 2. The body on the left is connected to an intermediate body with two leaf springs. Another pair of leaf springs connects the intermediate body to the world. The body and the intermediate body are coupled with a lever. The body will theoretically be guided along a straight line, as all leaf springs have the same length. The probe will be connected to this body and the z-scale is moving with it, relative to a measuring head on the fixed world.

Figure 1: Drawing of the 3D CMM under development

A CMM with nanometer uncertainty which allows measuring of small products with high speed is required for in line measurement purposes. Recent developments like the Zeiss F25 / Vermeulen [4] (100 x 100 x 100 mm) and the IBS ISARA / Ruijl [5] (100 x 100 x 40 mm) don’t allow measuring with high speed because of the considerable moving mass in vertical direction (10 kg for the Zeiss F25 and 30 kg for the IBS ISARA). The CMM described here aims an uncertainty of 25 nm in a 50 x 50 x 4 mm volume and has an elastically guided fully compensated vertical axis.

2.1 Stiffness compensation

Figure 2 shows a compression spring that applies a force on the intermediate body. When this body moves from its mid position the compression spring will extend and compensate the bending stiffness of the leaf springs. The CMM described here aims an uncertainty of 25 nm in a 50 x 50 x 4 mm volume and has an elastically guided vertical axis with a moving mass of 150 g (200 Hz bandwidth), which increases the application for high speed purposes. Because this CMM can’t satisfy the ABBE principle completely (max. 2 mm offset) it asks for repeatability to the nanometer region for the 3D probing point in x, y and z and low driving forces to reduce power consumption and heat development in the drive systems. This paper focuses on the design and calibration of the elastically guided vertical (z) axis of this 3D CMM.

2.2 Weight compensation

The weight of the moving bodies in figure 2 is compensated with a tension spring. This spring is placed on the lever with a ratio of 1 : 10 from the drive system. Thereby the drive system has to overcome 1 % of that spring’s stiffness.
Some construction details of the elastic straight-guided mechanism that provides the vertical stroke of the CMM are shown in figure 3 and 4. The aluminum (high thermal diffusivity) back and forth parallelogram leaf springs (l = 42 mm, b = 40 mm and h = 0.3 mm) have a stiffened mid part (l = 30 mm, b = 40 mm and h = 1.5 mm) which gives them a higher resistance against buckling. Also this provides horizontal compensation for thermal expansion due to room temperature changes, even with the proper time constant.

The stiffness of the mechanism in drive direction is about 2000 N/m. In this case the drive system has to apply a force of about $2000 \times 0.002 = 4$ N to keep the body of this mechanism at the maximum displacement from its mid position, half of the total stroke of 4 mm. The stiffness compensation mechanism also shown in figure 5 gives the possibility to reduce this force significantly. The stiffness compensation mechanism consists of a spring (nr. 1 in figure 3 and 4), a guiding, a differential screw and a plate. The compression of the spring can be adjusted with the differential screw and the plate prevents that the spring torques. This mechanism reduces the stiffness in drive direction with a factor of around 50, i.e. 50 times less force (F) for the same stroke. This reduction also occurs in the motor coil current (I) which will reduce the required power (P) 2500 times as it is proportional to the square of current.

A force alignment mechanism (nr. 2 in figure 3 and 4) is applied to align the pre-load force of the compression spring with respect to the intermediate body of the elastic straight-guided mechanism. Without such alignment mechanism the stiffness compensation mechanism will be bi-stable due to tolerances in the fabrication and assembly process.

The tension spring which compensates the weight of the moving bodies (nr. 3 in figure 4 and 5) has a stiffness of 715 N/m and is connected to a lever with a ratio of 1 : 10 from the drive system. This means that the drive system has to apply an extra force of $715 \times 10^2 \times 0.002 = 15$ mN to keep the body of the elastic straight-guided mechanism at the maximum displacement from its mid position. This is negligible compared to the 0.08 N needed to overcome residual stiffness. Finite element modeling showed that the scale tilts about 1 µrad at the maximum displacement form its mid position. From this can be concluded that this tilt has a negligible contribution to the measurement uncertainty. The scale of the measuring system is located in the body of the elastic straight-guided mechanism with three ruby spheres (figure 6). Pre-load rings are used to increase stiffness in the ruby sphere contacts. The other degrees of freedom of the scale are determined with three support points on the supporting surface (not visible in the picture).

Figure 7 shows the drive system of the elastically guided axis (z-drive in figure 3 and 4) based on a Lorentz actuator with a stroke of 4 mm. The coil is connected via two ceramic plates to the lever while the yoke, that creates the magnetic flux ($B = 0.7$ T), is connected to the fixed world.
4 FUNCTIONALITY RESULTS

Figure 8 shows the coil current as function of the position of the mechanism position.

![Graph showing coil current as function of stroke](image)

The required power of the Lorentz actuator as a function of the stroke is given in figure 9. It can be concluded that the power consumed by the actuator is very low when the elastically guided axis makes its vertical stroke of 4 mm.

![Graph showing required power as function of stroke](image)

This means that the applied mechanisms for compensation of stiffness and balancing of weight are suitable to get a significant reduction of heat in the actuator.

After tuning the PID-controller the tracking and positioning error of the servo system was a few nanometer, see figure 10.

![Graph showing tracking and positioning error](image)

Finally the transfer function of the elastically guided axis was measured. This resulted in a bandwidth of 200 Hz (figure 11).

![Graph showing transfer function](image)

5 CALIBRATION

Errors in the guiding of the probe system will directly influence the measurement in x, y and z, so they must be small and repeatable. The calibration of the elastically guided axis was performed by the NMI Van Swinden Laboratorium. In the next two paragraphs the calibration set-ups and some preliminary results are presented.

5.1 Linearity

Figure 12 shows the laser interferometer system used to calibrate the linearity $z T_2$ of the elastically guided vertical axis. A special hardware card (Agilent N1231A with $\approx 0.6$ nm resolution) is implemented in order to reach nanometer uncertainty with a corner cube connected to the moving body of the elastically guided vertical axis at the probe point.
A critical factor in the calibration is the alignment of the laser beam with the moving axis of the elastically guided axis. Therefore a position-sensitive four-quadrant detector is used in the alignment procedure to obtain the necessary accuracy. Hereby it is possible to minimize the effect of the residual misalignment to ≈ 0.1 nm in the calibration of zTz over the full range of 4 mm.

A preliminary calibration of zTz is shown in figure 13. During the calibration the set-up as shown in fig 12 is enclosed in an insulating box to minimize temperature variations during the measurement. The uncertainty of the laser interferometer, including the contributions of misalignment and of refractive index variations due to temperature and pressure variations is < 1 nm. The average sensitivity deviation of the scale is about 20 nm over 2 mm as can be seen from the linear fit through the data in figure 13. The causes of the short-term variations with a bandwidth of about ± 10 nm are under investigation.

5.2 Straightness and rotation

The straightness movement and rotation of the elastically guided vertical axis will be calibrated with four capacitive sensors (the position as indicated with the arrows as shown in figure 14) measuring on the sides of a gauge block that is connected to the moving body. From measurement results zTx, zTy, zRx and zRy will be calculated.

The part connected to the moving body consists of V-grooves under 45 degrees that position 3 ruby spheres that are glued on top of the gauge block. A magnet is used to attach the gauge block to the connection element and to pre-load the spheres in the V-grooves to increase stiffness in the contacts. Calibration results will be presented at a later stage.

6 CONCLUSION

An elastically guided linear high precision axis for CMM applications is presented. It contains an innovative stiffness compensation mechanism as well as weight compensation reducing the driving force to a mN level. This offers very low power consumption of the designed and integrated direct drive Lorentz actuator and therefore low thermomechanical effects. The axis has a moving mass of 0.15 kg and the measured bandwidth is about 200 Hz. First calibration results of this axis show nanometer repeatability of the probing point over the 4 mm stroke of this axis. The causes of the short-term variations with a bandwidth of about ± 10 nm are under investigation. Error compensation may reduce the residual error of the probing point to the nanometer level.

7 REFERENCES

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