euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Development of a precision stage with delta kinematics

Stephan Maag[1], Xinyu Wang[1], Thierry Lachat[2], Markus Vitins[1,3], Jörg Raabe[1] & Mirko Holler[1]

[1]Paul Scherrer Institut, Villigen PSI, Switzerland, [2]EnDes Engineering Partner AG, Kestenholz, Switzerland, [3]Current address: RUAG Space, Zurich, Switzerland,

Stephan.Maag@psi.ch

Abstract

The piezo stage presented here was developed and optimized for scanning x-ray microscopy, but is suited for many other applications. It offers three translational degrees of freedom and provides a travel range of 400 micrometre in each direction. The stage is part of a new instrument that was developed for the Swiss Light Source at the Paul Scherrer Institut to enable non-destructive 3D imaging at the nanoscale using multi-keV ptychographic x-ray computed tomography. In scanning microscopy positioning accuracy is crucial as it is a limiting factor for imaging resolution. Positioning accuracy is achieved via laser interferometry and closed-loop operation. The stage itself was optimised for high stiffness, a resonant frequency above 400 Hz and small angular error motions below twenty µrad to pave the way to scan representative sample volumes with a resolution in the nanometre range and small positioning overhead with positioning times below thirty milliseconds. The stage provides a clear aperture in its centre which is used to connect the sample holder to a continuous flow cryostat. The stage is vacuum compatible down to 10^{-8} mbar.

Keywords: delta kinematics, flexure hinges, cryogenic temperature, high vacuum, high stiffness, nanometre resolution, x-ray microscopy

1. Introduction

Ptychographic x-ray computed tomography (PXCT) enables non-destructive insight into the micro and nanostructure of materials science and biological samples. PXCT is a scanning microscopy technique, where a sample is illuminated at many overlapping positions and coherent far-field diffraction patterns are recorded. 3D information can be accessed via computed tomography by recording many sample projections at different sample orientations. As a scanning microscopy technique, the sample positioning accuracy is a limiting factor for imaging resolution. To achieve high resolution in large sample volumes, the stage and its metrology system must provide high positioning accuracy, small angular error motion and high in-position stability as set out in table 1. On the other hand the sample positioning in 3D needs to be highly dynamic as any positioning overhead is lost measurement time.

Table 1. Requirements for the 3D piezo stage.

Natural frequency	> 400 Hz
Rotational error motion	< 20 µrad
Range in each axis of the coordinate system	± 0.2 mm
Positioning time	< 30 ms
Vacuum conditions	< 10^{-8} mbar
Closed loop resolution	Around 1 nm

Cryogenic sample conditions are desirable as they preserve the sample's structure during the measurement in high vacuum. To reach these goals, a new positioning stage offering three translational degrees of freedom was developed. It uses a virtually backlash-free parallel kinematics flexure design and is optimised for a high natural frequency. For cryogenic sample conditions, the thermal connection to a cryostat and the thermal insulator to the stage had to be considered in the design. Related to this, the thermal expansion, shielding, and isolation became important as well. To minimise abbe errors and residual thermal drift, the sample is directly mounted on the reference mirror, which is used for the multi axis interferometric feedback loop, a concept demonstrated previously in [1]. Figure 1 shows the system with its main components. The system is now in commissioning and first results will be presented at the conference.

2. Development and optimisations

The parallel delta kinematics has been optimised for high natural frequency above 400 Hz to enable high scanning rates. Multiple flexure designs and angular orientations have been compared to reach the optimal trade-off between nominal travel range, high stiffness, repeatability and minimal roll and tilt errors. The three delta kinematic arms also incorporate direct sensor feedback for each axis. The flexure design reaches 400 µm of travel range in the directions of the flexure coordinate system. However, due to the kinematic design, the range in arbitrary directions is limited. The maximum working envelope corresponds to a cubic volume standing on its edge.

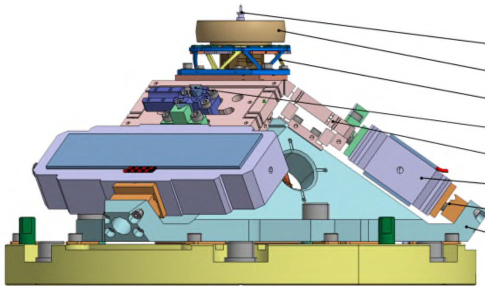

Figure 1. The delta stage with its components.

In the final x-ray microscope the piezo stage is mounted on additional alignment stages to centre the axis in the x-ray beam and bring the sample to the correct height. The coarse alignment stages are firmly fixed with brakes during the scanning process itself to increase the scanning dynamics.

2.1. Natural frequency calculation

Apart from the dimensioning of the monolithic flexure hinges, the natural frequency of the piezo stage itself has been optimised. The system was aimed to have a first eigenfrequency above 400 Hz. This optimization criterion was verified in the FEM calculations. The first eigenfrequency has been determined to be at 530 Hz, neglecting the weight and the flexible structure of the copper strands used for the cryo cooling. Figure 2 shows the first eigenmode of the piezo scanning stage. Considering the simplification of the finite element analysis, a natural frequency above 400 Hz is expected for the piezo stage as can be seen in the stage specifications in table 2.

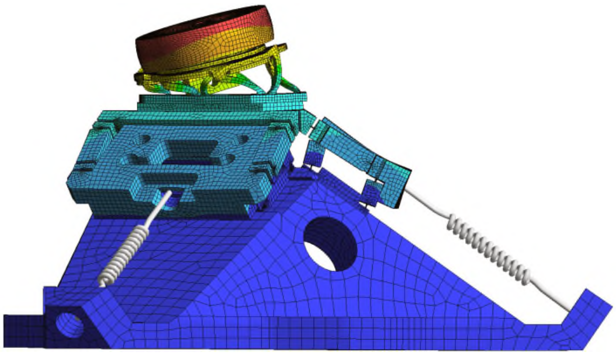

Figure 2. The first eigenmode of the piezo stage at an eigenfrequency of 530 Hz.

2.2. Thermal insulation

To reach the specified sample temperature of ten kelvin, the heat conduction and shielding has been carefully designed. The cooling path itself starts from the cryostat and goes all the way through the centre of the stage and up to the sample holder. The corresponding heat loads transferred by thermal radiation and by thermal conduction have been considered in the design calculation. An elaborate shielding system allows for the low heat loads. Since the piezo stage itself is mounted on coarse alignment stages including a rotation stage, the cooling system needs to be able to cope with the corresponding degrees of freedom.

2.3. Mirror holder

The design of the mirror holder is driven by a balance between the stability requirement for a robust structure, and the competing thermal insulation requirement. Extensive thermal and thermomechanical finite element analysis has been performed to achieve the desired high structural stiffness and in addition a low thermal conductance. The further challenge was to attain the structural integrity of Vespel mirror holder, and its joints both to the aluminium mirror and to the titanium stage structure under the extreme temperature change. The final design is proven to be capable to accommodate thermal expansions and stresses resulted from temperatures between the high bake-out temperature at 393 K and the required cryogenic operating temperature of 10 K at the mirror surface.

3. Measurements

In the currently running commissioning, the angular errors of the piezo stage have been measured with an autocollimator. For this purpose the 3D stage has been mounted and put into operation on an optical table. The reference mirror and thermal insulation have been replaced with a reference mirror for the autocollimator measurement. The curve in figure 3 shows the angular errors at various equidistant positions. The angular errors stay within an error band of four arcsec also for the vertical movement.

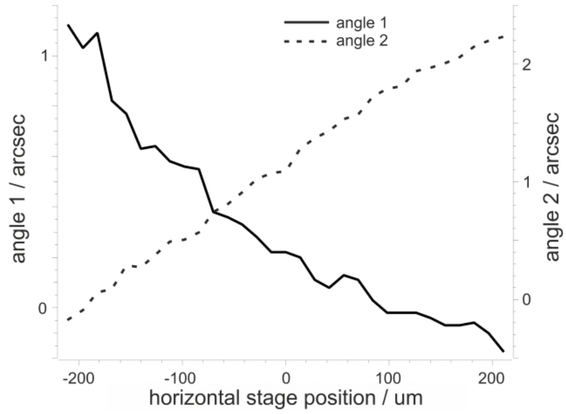

Figure 3. Autocollimator measurement data of the angular errors while moving along a horizontal axis. The Autocollimator is mounted above the stage, measuring pitch and yaw angular errors.

4. Conclusion

The results from first tests and commissioning measurements seem to confirm, that the desired characteristics could be met. The angular error motions are within specifications. For the final application it is of great importance that the stage will perform as expected. Since the stage is still in commissioning at the moment, the results of the positioning and eigenfrequency of the final stage will be presented at the conference.

Table 2. Specification of the 3D piezo stage.

Natural frequency	> 400 Hz
Rotational error motion	< 20 µrad
Range in each axis of the coordinate system	± 0.2 mm
Positioning time	15 ms
Max. temperature of actuators	50 °C
Vacuum conditions	< 10^{-8} mbar
Closed loop resolution	1 nm
In-position stability	1.7 nm SD
Piezo stage weight	2.8 kg
Outer diameter	182 mm
Height with reference mirror	97 mm

5. Acknowledgments

We want to thank the team at Dynamic Structures and Materials, LLC (DSM) for their cooperation in custom actuator design and for dissemination and commercialisation of the final stage. We also want to thank Simon Henein, Wayne Glettig and the team at CSEM for their collaboration during the concept phase of the project.

This work was supported by the Swiss National Science Foundation SNF (Funding scheme R'EQUIP, Project number 145056, “OMNY”), the Competence Centre for Materials Science and Technology (CCMX) of the ETH-Board, Switzerland.

References

[1] Holler M, Diaz A , Guizar-Sicairos M, Karvinen P, Färm E, Härkönen E, Ritala M, Menzel A, Raabe J and Bunk O 2014, X-ray ptychographic computed tomography at 16 nm isotropic 3D resolution *Sci. Rep.* **4** 3857