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Novel nanopositioning system with improved range, dynamics and accuracy

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Abstract
For a nanopositioning system (NPS), its performance is typically characterised by three categories of specifications: motion range, dynamics, and accuracy. In the development of a NPS, it is generally very difficult to enhance all these specifications at the same time, and often a trade-off between them must be taken. This paper presents a novel design of a NPS with all specifications (i.e. range, dynamics and accuracy) improved. Two important design concepts have been applied to achieve this ambitious goal. The first concept concerns the hybrid application of monocrystalline piezo actuators and polycrystalline piezo actuators. Due to undesired behaviour such as hysteresis, nonlinearity and creep, polycrystalline piezo actuators are often applied with flexure hinge mechanics and operated in closed-loop using accurate position sensors in a NPS. However, the added motion mass of the guideway mechanics and the phase lag of the closed-loop system may deteriorate the dynamics of the NPS. In contrast, monocrystalline piezo actuators do not suffer from hysteresis, nonlinearity and creep. They can be directly applied for generating high accurate and high dynamic motions in open-loop. However, monocrystalline piezo actuator suffers from its very small motion range due to its (much) smaller piezoelectric coefficients than that of polycrystalline piezo actuator. Thus, the hybrid application of two types of actuators is advantageous for realising both a large range and a high dynamic motion. The other concept concerns a mechanism for compensating reaction forces. Accelerated movements generate reaction force, leading to noticeable vibrations in a NPS. It is particularly important in high dynamic motions, as the magnitude of the reaction force relates with the quadratic of frequency. To overcome this problem, compensating actuators which move in an opposite direction are applied. The design concepts have been successfully implemented in the development of a new NPS aimed for a high-speed large-range atomic force microscope.

Keywords: nanopositioning system, dynamic, range, accuracy, piezo actuators, force compensation

1. Introduction

Fast and accurate nano positioning systems (NPS) are an indispensable component for manufacturing and metrology, such as fast tool servo and scanning probe microscopy (SPM). Oftentimes, structural dynamics of NPS have a large influence on the performance of tools. The influence of the moving masses of e.g. scanning platforms can be mitigated passively with careful designs but shows limits when it comes to highly dynamic motions. Measurement results of for instance high-speed are directly affected by mechanical resonances between the probe and sample [1]. Undetected tip-sample displacements and crosstalk lead to uncontrolled movements and measurement artifacts, and consequently to inaccurate measurement results. Under certain circumstances a careful post-processing can be applied but requires additional metrology [2].
Compact design of NPS may bring improved mechanical dynamics but shortens the motion range considerably. It is due to the fact that motion range of actuators is oftentimes proportional to its geometric dimension. A short motion range limits the applicability of NPS. In addition, high measurement bandwidth needed and limited setting time are further challenges in achieving high positioning accuracy.
In this paper, we introduce a novel design of NPS by hybrid application of monocrystalline piezo actuators and polycrystalline piezo actuators. The high dynamic motions are carried out by a in open loop driven monocrystalline piezo stage. To enhance the small motion range of 1x1x1 µm of the 3-axis stage, it is serially combined with a 6-axis polycrystalline piezo stage with 45x45x45 µm motion range, operated in closed loop configuration. To improve motion accuracy, a novel internal compensation mechanism is introduced which actively compensates the appearing retroactive forces from the moving scanning platform.
The following chapter shows the stage combination and properties. A detailed overview of the piezo stages is given in [3]. The next chapters focus on the reduction of dynamic crosstalk during movements in the x-, y- and z-direction from retroactive scanning forces by applying the optimized active x-, y-, and z-force compensation of the 3-axis stage and notch filters on a driven step motion.

2. Design

The 6-axis polycrystalline piezo stage is made of a low expansion material and is operated in closed loop. A full step of 45 µm shows a slope of 7.9 mm/s, 8.8 mm/s and 7.1 mm/s for the orthogonal x-, -y and z-directions, respectively. The settling time (0.2%) is below 13.4 ms and the position noise is smaller than 0.35 nm allowing for fast and accurate movements. The measurement methods are explained in the methodology papers [4,5] and in [3].
This stage's properties are enhanced by the 3-axis stage in terms of dynamics. **Figure 1** shows the hybrid combination of the NPS. All actuators of the 3-axes stage are made from monocrystalline piezo ceramic material, which shows a non-linearity smaller than 1.1 nm over the 1 µm scan range with small hysteresis, allowing open loop operation. The compensation masses 1 and 2 counteract the forces from the scanner (load and mass of the 3-

stage scanning platform) by accelerating in the opposite direction, driven by the compensation piezos 1 and 2.

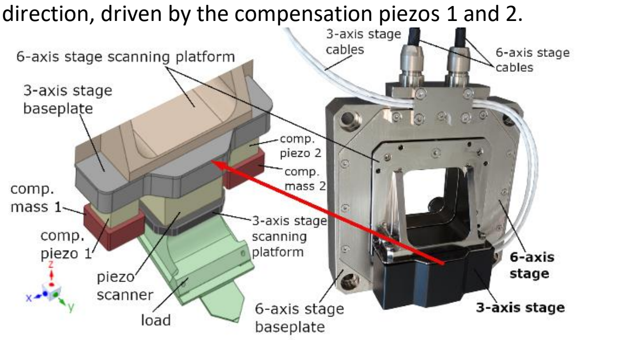

Figure 1. Assembly of the 6-axis and 3-axis piezo stage. The detail shows the inner structure of the 3-axis stage with the piezo scanner (xyz) and xyz-compensation piezo 1 and piezo 2.

3. Results

A scanning wavelength interferometer with less than 20 pm non-linearities and with 25 kSa/s was used to measure the displacement of the stages. A cube mirror was mounted as a load on the 3-axis stage scanning platform. The displacement measurements were performed in an acoustic isolation chamber in an equilibrate state of the measurement setup. The interferometer itself shows a position noise standard deviation of 0.07 nm with inactive stages. The impact of the active internal force compensation was tested with a voltage step of 25 V (about 50 nm step). **Figure *2*** shows three step-response curves in x-, y- and z- direction and six crosstalk motions. The graphs show that the 3-axis stage with a positioning bandwidth >1 kHz excites the 6-axis stage with a closed-loop bandwidth of about 200 Hz. The high frequency oscillation after the step motion can be mitigated by the notch filters. The notch filter sightly reduces the achievable step slope to about 25% (0.1 mm/s) compared to the step response without notch filter. The low frequency and persistent large oscillations originate from the 6-axis stage scanning platform due to retroactive forces from the moving piezo scanner. These oscillations are reduced by the compensation mechanism without compromising the dynamic behaviour of the 3-axis stage.

To summarise, a serial, hybrid stage combination of a 6-axis polycrystalline piezo stage with 45x45x45 µm motion range and a monocrystalline 3-axis piezo stage with 1x1x1 µm motion range was shown. This serial combination enhances the properties of each stage. The highly dynamic open loop operated 3-axis stage has an internal 3-axis force compensation. The force compensation has a great impact on the step function in the x-y- and z- direction and reduces crosstalk motion by about an order of magnitude. One can conclude that the 3-axis force compensation is mandatory for accurate and highly dynamic motions. The step motion could be improved further by a load with a balanced centre of gravity to reduce momenta acting on the 3-axis stage scanning platform.

In the future this stage combination will be applied in a metrological large-range and high-speed SPM setup for 3D-nanometrology at PTB. Overall, the concept of the internal 3-axis force compensation can be applied to various motion systems with compliant frames to reduce e.g. the settling time and increase dynamics by decoupling the retroactive forces from the motion. Finally, it should be mentioned that although the term "accuracy" is addressed throughout the paper, it can be extended as "repeatability". They are closely related aspects, as the high position accuracy can often be achieved via calibrations if the high positioning repeatability is available.

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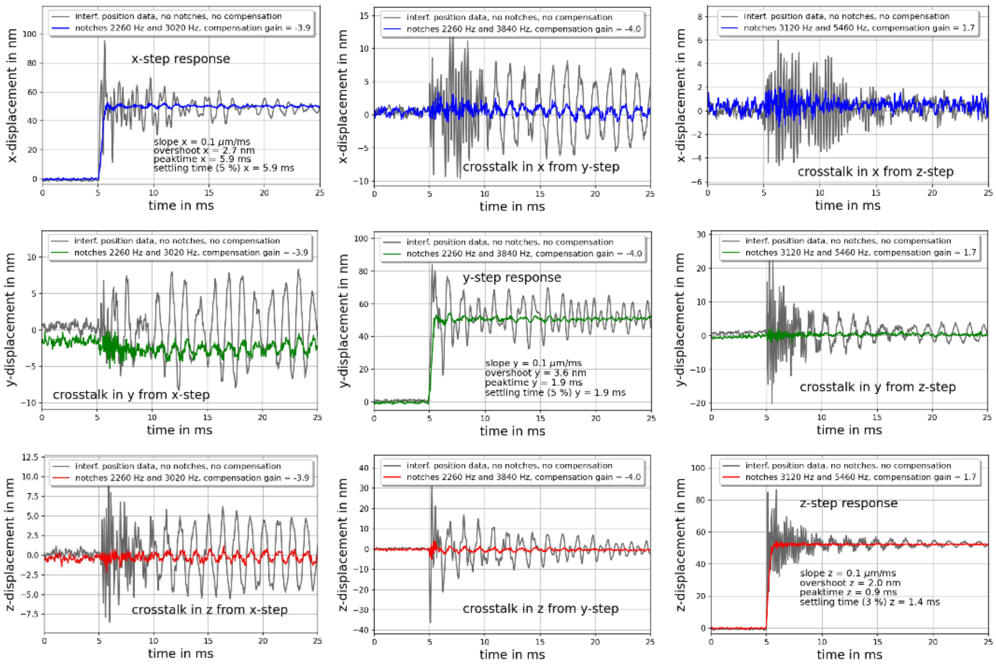

Figure 2. Step functions of the 3-axis stage of 25 V (nominal 50 nm) with and without applied notch filters and force compensation in x-, y-, and z-directions. The force compensation shows an improved and clean step-responses with minimal overshoot and decreased crosstalk and reduced oscillation amplitude of the serially connected 6-axis stage. The notch filters minimize the high-frequency oscillations but reduce the slope.