DESIGN AND TEST OF A VERTICAL AXIS SETUP FOR NANOPOSITIONING APPLICATIONS

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Abstract. *Ultra high precision machines for versatile positioning and measuring applications demand large moving volumes of several hundred millimeters and an absolute accuracy and precision in the nanometer range. Two dimensional x-y-setups are state of the art but an increasing number of applications require three dimensional motion. Therefore the well known technology for two dimensional positioning can be extended by a vertical axis. This can be realized by a semi-parallel setup. The vertical axis setup as well as the horizontal axes are planar guided directly on a base frame. Rotational moments around the vertical axis are inhibited by the horizontal axes*

In order to find the optimal combination of drive and guide a modular design has been incorporated to test and validate several different variants. Preferred drives are hybrid coarse/fine spindle/piezo drives as well as voice coil actuators. Cylindrical ball bearing guides, air bushings and precision roller bearing guides can be used. Each combination has various advantages, therefore a systematic analysis of different combinations of drives and guides is necessary. Thus the vertical axis has been designed modularly under use of favorable design principles. Three drives and guides are arranged symmetrically to the center of gravity of an intermediate frame which holds the stage mirror.

The paper presents systematic design, virtual prototyping and realization of a modular long range travel vertical axis with high precision. This axis is part of the development of a high precision positioning and measuring machine with a moving range of 200 x 200 x 15 (25) mm³. The first tested combination of the vertical axis consists of cylindrical ball bearing guides and a coaxial arrangement of spindle and piezo drives. This design realizes a moving range of 25 mm with a piezo drive resolution of 1 nm or less.

Keywords*: Modular Design, Vertical Axis, Nanopositioning*

1. INTRODUCTION

Ultra high precision positioning and measuring machines have to face the demand for large moving and measuring range while realizing nanometer accuracy. Most setups of three dimensional high precision systems (Fig. 1) use fixed laser interferometers and a moving measuring mirror stage.

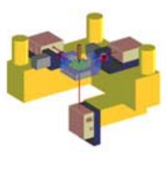
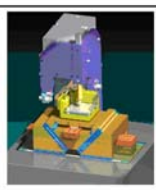
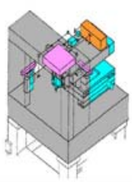
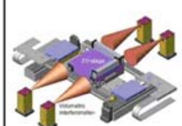
	Ultra high precision positioning and measuring machines					
Name	*NMM 1*	*Molecular Measuring Machine*	*Ultra Precision CMM*	*UA3P-5*	*Ultra Precision CMM*	...
Design						...
Moving range	*25 x 25 x 5 mm³*	*50 x 50 mm²*	*100 x 100 x 40 mm³*	*200 x 200 x 45 mm³*	*300 x 300 x 300 mm³*	...
Designer	*TU Ilmenau Germany*	*NIST USA*	*TU Eindhoven Netherlands*	*Panasonic Japan*	*BUPE Korea*	...

Figure 1. State of the art ultra high precision positioning and measuring machines
(Hausotte, 2002; Kramar et al, 2005; Ruijl, 2002; Tsutsumi et al, 2006; KAIST, 2003)

Because three dimensional applications need both horizontal and vertical motion with a high positioning resolution of the mirror which carries the object. The masses of mirror and object have to be moved and positioned over a long travel range. Thus especially the objective of vertical positioning is challenging. There is an increasing demand for such machines in optical industries to measure aspheric or freeform lenses and mirror shapes with a large moving range in vertical direction, e.g. of 15 mm up to 25 mm would be appreciated (Beckstette et al, 2006).

The described research is based on the work presented at the COBEM 2005 by Höhne et al (2005). Aim of the research is the development of a ultra high precision positioning and measuring machine with improved properties. Based on the state of the art new concepts were developed and need to be implemented. This paper presents the development and test of one assembly of this ultra high precision and measuring machine.

2. PROCESS SPECIFICATION

The design of mechatronic systems like ultra high precision machines starts with the specification of the technological process in which the system is used. At first it is necessary to describe the operations which must be carried out by the machine. In the given case this machine should provide the user with the enabling technology for nanoscale and macroscopic objects (Jäger et al, 2002).

In detail the objective is to serve various technological processes by means of a small number of different technical equipments (Höhne et al, 2005). This leads to the concept of a modular system. In our case the machine should be used for testing and measuring of wafers for micro-electronic circuits and optical parts like lenses and mirrors. To realize these processes the design of the machine has to meet the following main requirements:

- flexible configurability in relation to the required technological process,
- long-term stability of the construction and good dynamic behavior,
- realization of a moving range of 200 mm x 200 mm x 15 (25) mm and more,
- measuring resolution of 0,5 nm or better and measuring uncertainty of 100 nm or better,
- positioning resolution 1 nm or better and positioning repeatability of 1 nm or better.

3. MODULAR CONCEPT

Analyzing the requirements and existing systems a relative multi-coordinate movement between the object to be measured and a tool is necessary. The needed high measuring resolution and accuracy as well as the high positioning resolution require accurate measuring of the object position. Thus principles of small error arrangement are of interest. One fundamental concept to accomplish these objectives is the arrangement of object and tool corresponding to the three dimensional version of Abbe's principle (Hausotte, 2002; Ruijl, 2002). Figure 2 shows one solution of this concept.

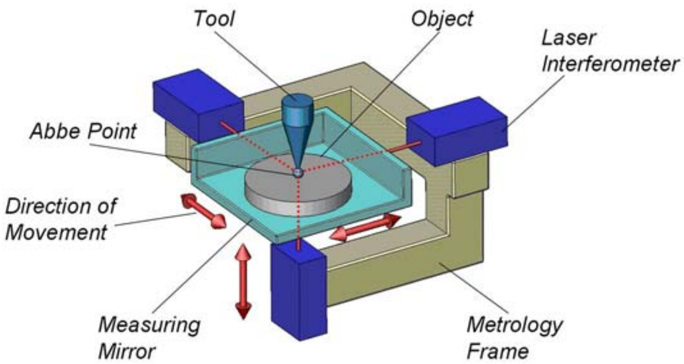


Figure 2. Principle design of the measuring system

Three laser interferometers are used to measure the position in three coordinates (x, y, z) of a three dimensional mirror. The Abbe point is a virtual intersection point of the three interferometer beams and the tool tip. In this case the object carried by the measuring mirror is moving in three directions (x, y and z). The tool itself is fixed to a metrology frame which holds the laser interferometers. However one other combination of the components according to the Abbe principle is possible by kinematic reversal. Here the measuring mirror carrying the object is fixed but the tool and the laser interferometers are moving. Since several tools are available it is useful and often necessary to exchange them. Thus a design with a fixed tool is favorable to offer a flexible configuration.

Following the rules of modularization (Aarnio et al, 2002; Hofer et al, 2001) a generalized function structure forms a platform consisting of the main sub-functions which are shared by all variants of the product family. This maximum function structure can be specified according to the type of object, tool and to the technological needs of the application.

Basic platform components are the positioning subsystems, the measuring units, the frame, and the control and data processing components. Tools and fixtures of objects are so called non platform components designed or selected for each type of machine. With respect to the different applications of such machines a function-oriented configuration is indicated. The platform concept and the function structure are the basis to apply this method. Each sub-function can be realized by a number of different variants. In this way a configuration matrix is established. The matrix contains solution principles and provides the configuration procedure with these virtually stored substructures (Höhne et al, 2005).

4. DESIGN

The research is focused on the development of a ultra high precision positioning and measuring machine with a moving range of 200 x 200 x 15 (25) mm³ (Theska et al, 2004). Its overall concept is based on a semi-parallel kinematic design (Fig. 3). That means the vertical axis is planar guided on a base and the horizontal axes are used only to reduce the rotational degrees of freedom of the vertical axis. Design principles of short and direct force flow and symmetric design are respected. The coupling between the vertical and the horizontal axes is well constraint.

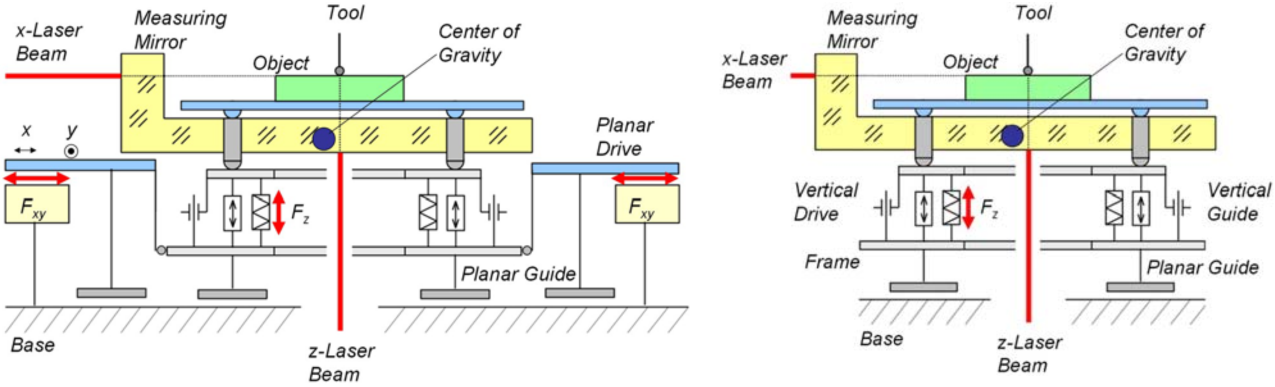


Figure 3. Principle design of the ultra high precision positioning and measuring machine (left) and of the vertical axis (right)

The vertical axis needs high precision guides and drives to fulfill the given requirements of high positioning resolution, high positioning repeatability and good dynamic behavior. Thus the guides should have high stiffness and low or no friction with no stick-slip effects. The drives should cover a long moving range with high resolution and good dynamic. They also should induce to the system less heat because heat influences the measuring accuracy significantly.

Many different types of guides and drives are used in high precision machines. But their properties are not well known for positioning tasks in the nanometer range. Therefore research is necessary. The aim of the research is to find an optimal overall design and combination of elements. Thus the design of the vertical axis should be modular to have the opportunity to build, test and compare different setups. For these reasons a systematic analysis of different combinations of drives and guides is necessary.

4.1. Modular Concept

The design of the vertical axis follows a modular concept. Three drives and guides are arranged symmetrically around the cumulative center of gravity. All guides stay in contact to the base through planar guides e.g. flat air bearings. The arrangement of guides and drives (vertical force) is serial in a short and direct force flow (Fig. 4). Only push and pull forces arise (vertical forces) in the drive units except of lateral forces through horizontal motions induced by the x-y-axes. Vertical forces are realized only be the drives. It is possible to exchange the guides and the drives. The frame holds all functional elements of the driving system and the measuring mirror so the frame remains constant. Also the measuring mirror and the planar guides (air bearings) are used in all setups. Because of this design it is possible to vary elements of the vertical axis under constant boundary conditions. Thus it seems possible to make statements about the behaviour and properties of the varied elements. This approach is important because measuring results and dynamic as well static behaviour are system depended properties.

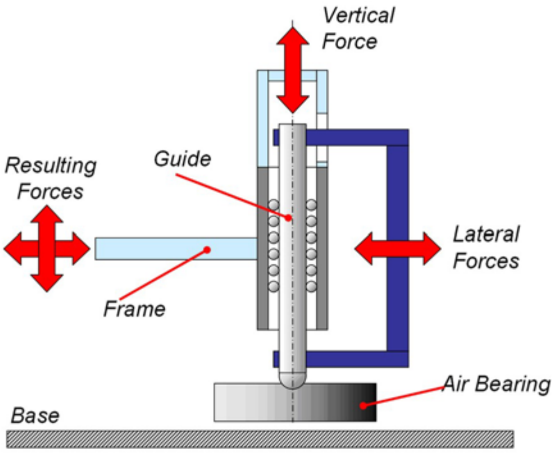


Figure 4. Principle design of the vertical axis with forces

4.2. Modules

The guides and drives of the vertical axis have to fulfill the given requierments. Furthermore the guides should be rotational symmetric to offer equal stiffness in x- and y-direction and the drives should not induce heat into the system. Unfortunately drives like voice coils are not self locking. Thus they need to actively hold the masses and induce unwanted heat into the system because of power loss. Self locking spindle drives do not have the needed resolution and piezo elements have a limited moving range. Known ball guides are stiff but they are a source of stick-slip effects. Aerostatic guides are free of stick-slip but can cause vibrations and induce unwanted air flow. Flexure guides seem to be favorable but their moving range is limited. To verify the mentioned advantages and disadvantages three different commercially available guides and drives were selected and can be used and combined (Tab. 1).

Table 1. Function elements which can be combined to different setups (s – moving range, Δs – theoretical resolution).

Guides		Drives	
Ball Bearing	s > 25 mm	Spindle Drive	s > 25 mm, Δs = 1 µm
Roller Bearing	s > 25 mm	Piezo	s = 15 µm, Δs < 1 nm
Air Bushing	s > 25 mm	Voice Coil	s = 16 mm, Δs < 1 nm

All guides can realize the needed moving range of 25 mm. The drives need to be combined to realize the moving range as well as the resolution in the nanometer range. One combination consists of spindle and piezo drives. Another combination can consist of spindle drives and voice coil actuators to realize a moving range of 25 mm. But the voice coil actuator moving range is 16 mm so the second combination is neglected yet. For the use of them additional weight compensation elements are favorable to reduce unwanted heat. Several different designs were developed (not shown here) which can be integerated in the vertical axis.

The research is focused on the development of an optimal overall design, test and comparison of different combination of elements. Thus several parameters need to be constant to compare for example the guides. Therefore two different major setups were developed. In the first setup the combination of spindle drive and piezo is realized (Fig. 5, left). Both elements are aligned serial and lift or sink the guided frame. The spindle drive uses a ball screw and is self-locking. It is used to realize the long range movements with less resolution. The piezo has very high resolution and compensates the lower dynamic and resolution of the spindle drive. Through this arrangement large moving ranges and high resolution can be combined with only little heat sources. Both elements can be driven separately and work in a hybrid system.

The second setup uses voice coil actuators (Fig. 5, right). They are aligned collinear to the gudies and lift or sink the frame in the same way like the other setup. Voice coil actuators combine high dynamic and resolution but they are not self-locking. That means they induce unwanted heat into the system actually at no movement. Thus gravity force compensation elements are needed to reduce the needed static forces. Therefore several approaches are possible. In this setup different rolled springs are used. They offer an almost constant force over large moving ranges. By combining different springs the forces can be adapted to the mass which needs to be compensated.

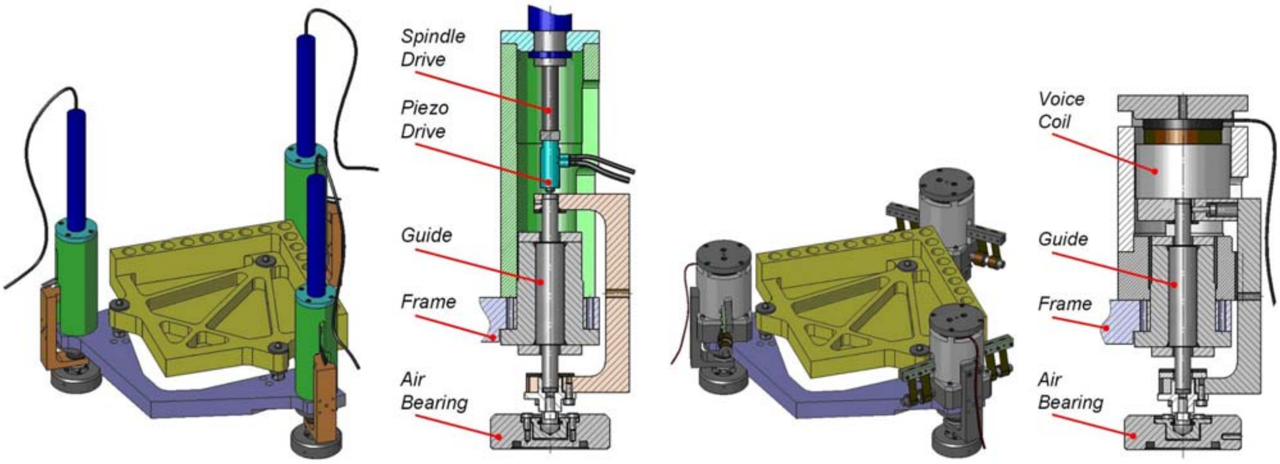


Figure 5. CAD model of the vertical axis, with spindle and piezo drives and section view of one drive unit (left), with voice coils and gravity force compensation through springs and section view of one drive unit (right)

In both setups the guides can be exchanged too. Because of the modular design the three available guides (Fig. 6) have the same basic conditions. This means they are arranged collinear to the drive, are rotation-symmetric, have the same coupling to the x-y-axes and are directly connected to the planar air bearing by their guiding rod. Thus it is possible to compare between their behaviour. Especially friction forces, stick-slip and vibrations are of great interest. They influence the reachable positioning resolution and position stability. But also the cross stiffness against lateral forces needs to be examined. This property has influence to the dynamic of the whole system especially during lateral movements caused by the x-y-axes. Here ball bearings and air bushings seem to be stiffer against lateral forces compared to guides with roller bearings. But this approach needs to be proved.

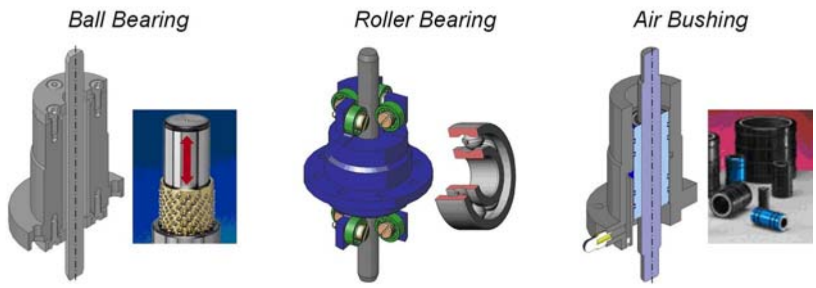


Figure 6. Different guides of the vertical axis, ball bearing (left), roller bearing (middle) and air bushing (right)

The first setup which is realized consists of spindle drives with piezos and ball bearing guides (Fig. 7). All components of the frame are made of aluminium. A model of a light weight measuring mirror made of aluminium used as base for a planar mirror (100 mm x 100 mm, $\lambda/4$) made of Pyrex represents the measuring mirror. This so called mirror dummy is well constrained and connected to the frame by three V-groove-ball couplings. Three laser interferometers detect its vertical position (z) and rotation (φ_x, φ_y). They offer a measuring resolution of about 0.1 nm.

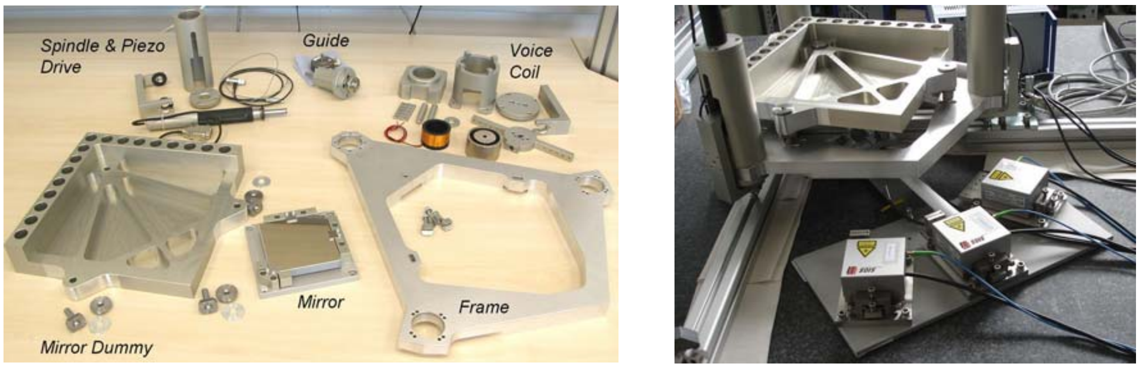
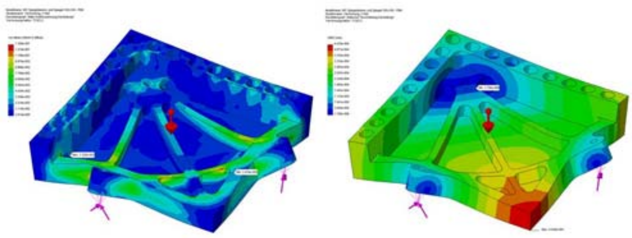


Figure 7. Parts (left) and physcial setup of the vertical axis in its first setup (right)

The whole vertical axis stands well constrained on a granite table which is placed on a vibration damped base. No further measures are taken for temperature control yet. Thus the environmental conditions of the labortary have direct influence to the measuring results. Its temperature constant is about ± 0.3 K but with disturbing air flow.
To identify the dynamic behaviour and mechanical properties of the vertical axis and its components high measuring resolution and repeatabilty is sufficient. Therefore there is no need to increase measuring accuracy yet. If the setup is integrated in a three dimensional device to measure objects than measuring accuracy needs to be increased.

5. MODELLING AND SIMULATION

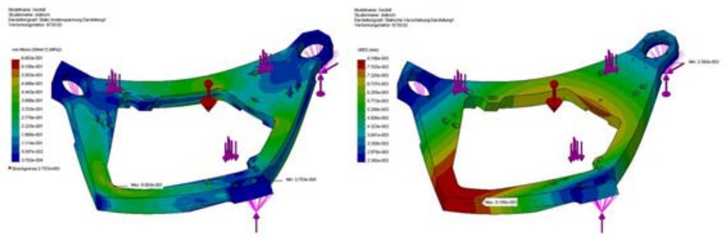
Methods of virtual prototyping are used to simulate the behavior of the vertical axis to identify weak points and to optimize its design. The measuring mirror has been identified as one weak point. Its behaviour influences directly the measuring results and so the control and the dynamic of the vertical axis. Therefore the mirror dummy has been modelled and simulated using finite element analysis (FEA) (Fig. 8). The constraints given by the V-groove-ball couplings have been modelled with the same degrees of freedom in the designed directions. Also the applied square mirror used for the reflections of the laser beams is included in the modell. As result the 1. Eigenfrequency was found at 513 Hz.



Base area	*280 mm x 280 mm*
Height	*60 mm*
Material	*Aluminium*
Mass	*4.5 kg*
Max. Stress (v. Mises)	*0.133 N/mm²*
Max. Deformation	*0.444 µm*
1. Eigenfrequency	*513 Hz*

Figure 8. FEA of the mirror dummy, stress v. mises (left), resulting deformation (middle) and values (right)

Another weak point which has been identified is the frame. Therefore the frame has also been modelled and simulated using FEA (Fig. 9). Its couplings to the base have been realised with equal degrees of freedom. As result the 1. Eigenfrequency was found at 137 Hz. Compared to the Eigenfrequency of the mirror it is significantly lower. The mirror is carried by the frame which leads to a two-mass-oscillator. This additional mass reduces the resulting Eigenfrequency of the vertical axis which will be lower than the calculated value of the frame. This shows that the frame influences and limits the dynamic of the vertical axis. Thus it needs to be redesigned in the next steps to increase its stiffness.



Length	*520 mm*
Width	*485 mm*
Material	*Aluminium*
Mass	*3.8 kg*
Max. Stress (v. Mises)	*0.666 N/mm²*
Max. Deformation	*8.186 µm*
1. Eigenfrequency	*137 Hz*

Figure 9. FEA of the frame, stress v. mises (left), resulting deformation (middle) and values (right)

Further weak points are the couplings between the elements of the vertical axis. They consist mostly of balls which are in contact to planes or V-grooves. Thus only point contacts exist. All couplings have been calculated using Hertzian equations. Compared to the frame they are much stiffer and have less influence to the dynamic behaviour.

Based on this work a multi-body system modell has been developed to simulate effects in vertical direction. It is necessary to find limitations of the dynamics (Jakobi, 2007). The model consists of all major parts of the vertical axis and their couplings (expect of the mirror). But the modell is limited by the given parameters of its elements like stiffness, friction or damping. The stiffness of couplings can be calculated using Hertzian equations. But for complex elements for example the frame it is not possible to define its stiffness or damping easily. Thus these parameters need to estimated. Another error source in the MBS are friction models which describe only a small part of the friction behaviour. Thus the realized MBS model can be used only to simulate major effects in vertical direction yet. For example deflection of different couplings and components can be simulated dependig on stroke, velocity and acceleration. Figure 10 shows the given function of movement and resulting deformations of the frame, a V-groove and the ball in contact. Also vibrations can be seen which only last less than 0.02 seconds. Experimental results of the vertical axis are needed to validate the MBS model and to identify parameters.

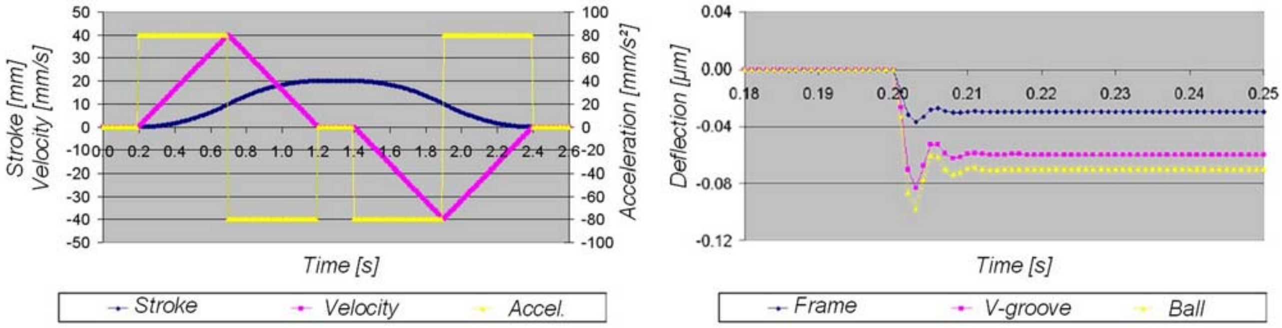


Figure 10. MBS simulation of the vertical axis,
stroke vs. time function (left) and resulting deflection at turning points (right)

6. CONTROL AND EXPERIMENTAL RESULTS

For performance testing of the vertical axis a complete experimental setup with included power supply and control system was built. Figure 11 shows the principle design of the vertical axis. Each of the three pillars consists of a coarse motion spindle drive, a fine motion piezo element and a ball guide. These three drive units move the plane mirror whose z-position and tilting angles are measured by three laser interferometers.

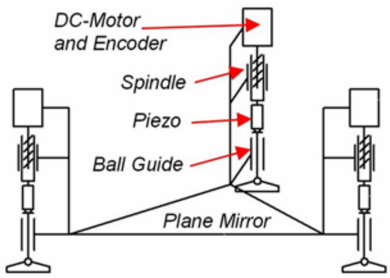


Figure 11. Principle design of the vertical axis

Figure 12 shows in principle the control concept of one drive unit. The spindle drive realizes long range movements with lower dynamics. The piezo element supports short range movements below the position resolution of the spindle drive with high dynamics and accuracy. By coupling the two branches the piezo stroke is added to the control deviation of the spindle drive. Thus the coarse drive does not stop when the fine drive actuator is at an extremal position and the piezo can act both ways for fine positioning. As output the sum of both movements will take effect. The big differences in dynamics of the actuators avoid vibrations. (The integral element in the controller deals with non predictable stick-slip effects in the spindle drive.). Figure 13 shows how the three drive units and three measuring tools are arranged. The idea is to reach the specified target value on this interferometer that is aligned with Abbe's point. The other measuring values are used in addition to detect and adjust the platforms angle deviation.

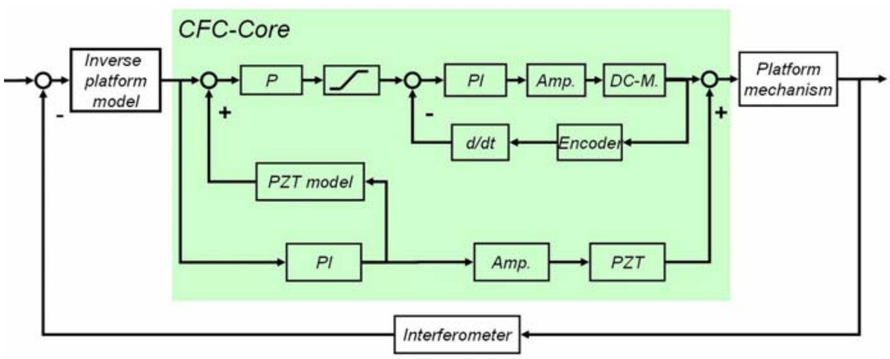


Figure 12. Control scheme of one drive unit

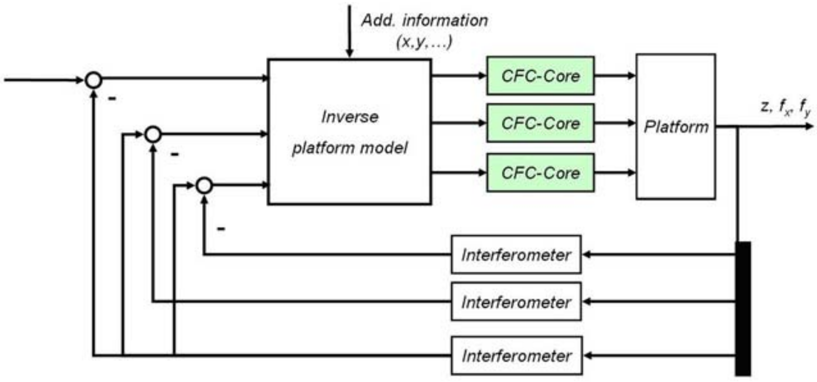


Figure 13. Control scheme of overall vertical axis

The vertical axis has been tested with different functions. At first the axis had to follow several steps. Below are given two examples of the response of the vertical axis tracing target positions in different step sizes. The shown measuring values are all unfiltered raw data. Figure 14 (above) shows a plot of very small steps combining nm and µm range. The target positions are 0 µm, 0.02 µm, 0.05 µm, 0.1 µm, 0.5 µm, 1 µm, 5 µm, 1 µm and 0 µm again. Fig. 14 (below) gives a detailed view of reaching the 0.1 µm position.

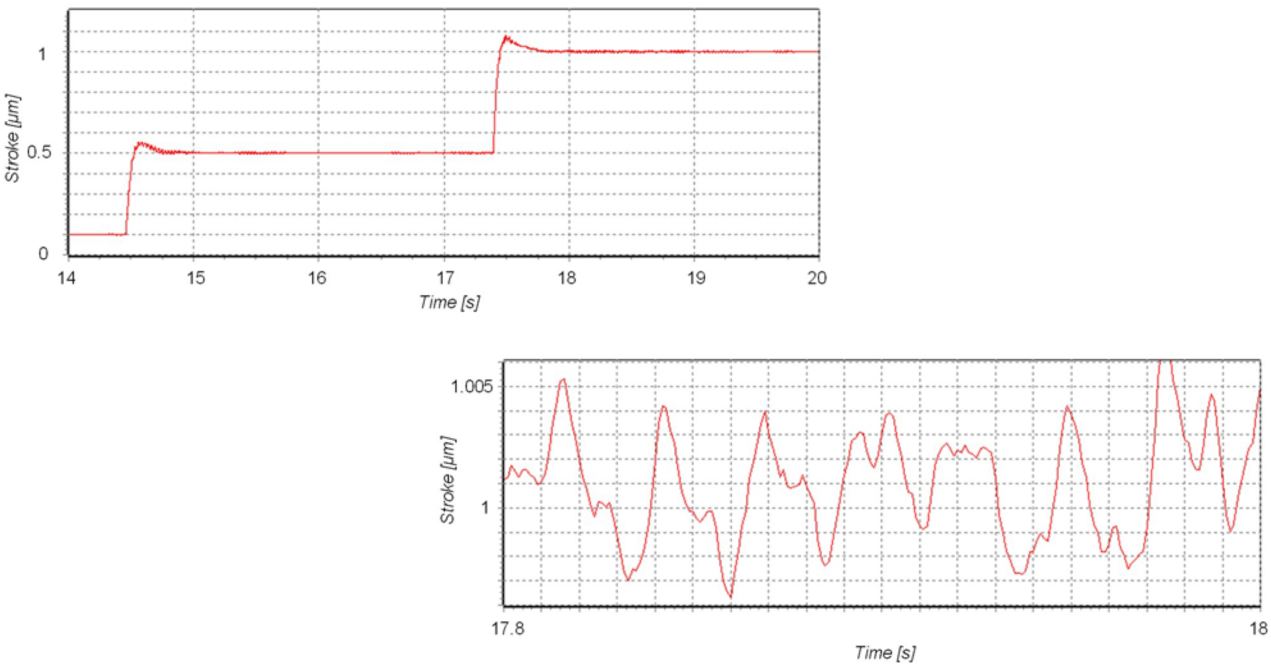


Figure 14. Positioning of the mirror in vertical direction in small steps over time (top),
stability of position at 100 nm over time after step (below)

Figure 15 (above) shows how the vertical axis drives through the travelling range of 20 mm with stopping at every 5 mm. Figure 15 (below) gives again an examplary detailed view of the 10 mm position. Both plots show how the macroscopic target position is reached with a very high position resolution of better then ±5 nm. The experimental setup had to deal with several environenatal influences, specially temperature deviations, air flow and subsonic noise coming from the building. But the vertical axis can follow the given target position. Stick-slip effects of the guides cannot be obtained. Thus the mechanical device does not limit the positioning resolution. There is a great potential left for upgrading the dynamic behavior like rising time and overshoot by fine tuning the control. Further improvements of the motion and position stability will be reached by optimizing the climate control of the room or at least the environment of the vertical axis.

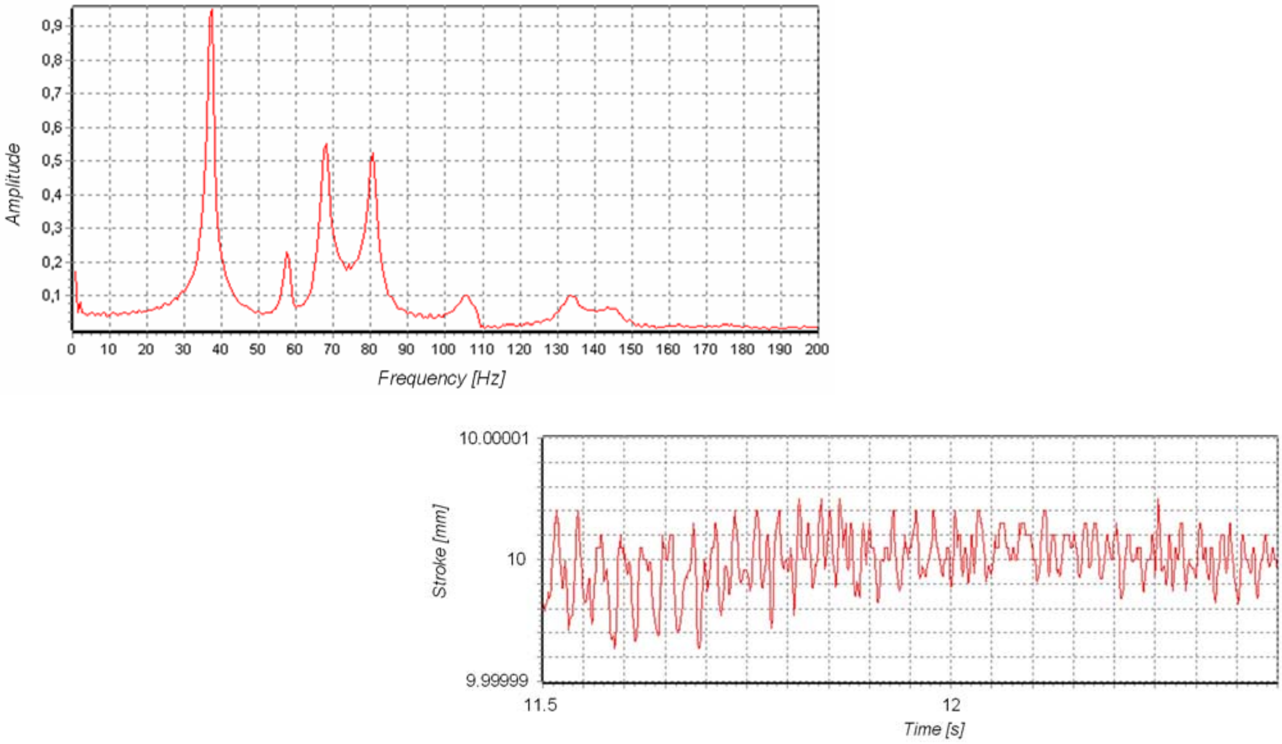


Figure 15. Positioning of the mirror in vertical direction with max. travelling range in 5 mm steps over time (top), stability of position at 10 mm over time after step (below)

Another test was carried out to detect the impulse response of the verical axis. This test is necessary to get informations about the Eigenfrequencies and so of the dynamic behaviour. For this purpose the piezo elements had to follow a jump of 3 µm. This jump leads to an oscillating of the vertical axis as an multi-body system which can be measured on the mirror (Fig. 16 top). All components of the axis have effect to this oscillating. After a Fast Fourier Transformation (FFT) the frequency spectrum of the oscillation can be seen (Fig. 16 below).

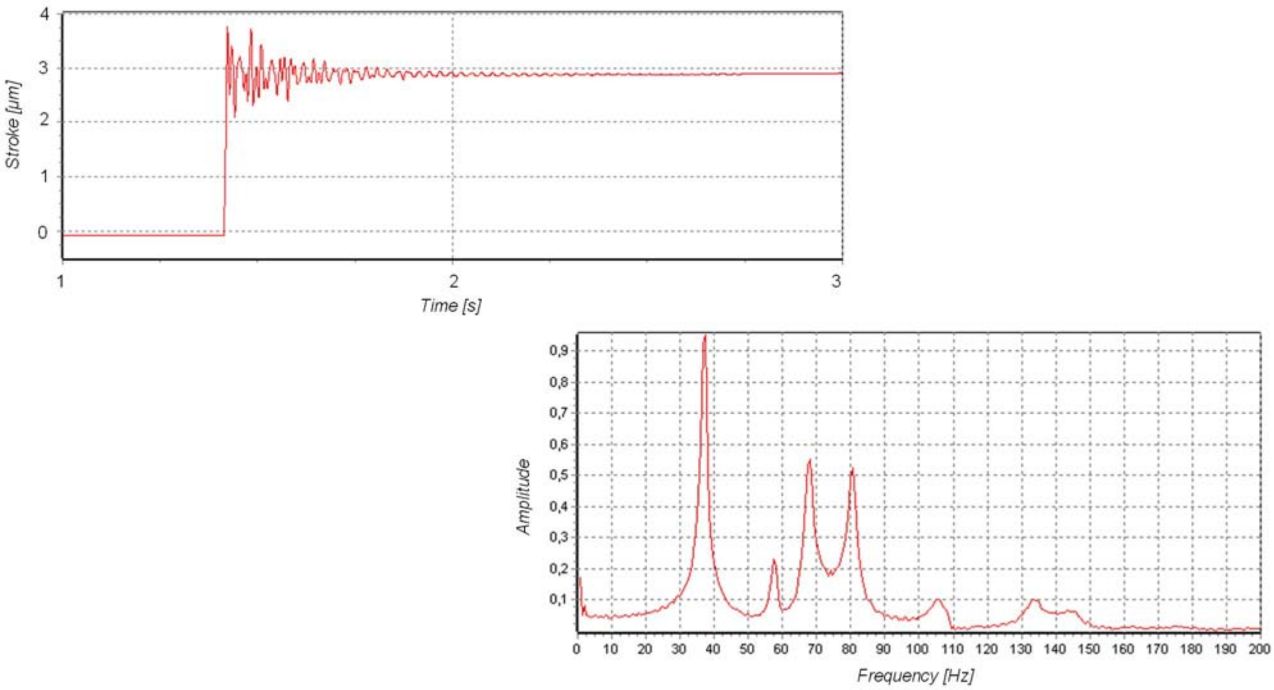


Figure 16. Impulse response of the vertical axis over time (top) and frequency spectrum (FFT) (below)

The 1. Eigenfrequency has been found at 37 Hz. This frequency limits the dynamic of the axis. That means disturbances with a frequency near or higher than 37 Hz cannot be compensated by the control. After approximately 1 second the oscillating has been fade away. These results are of interest because they can be compared to the results of the virtual prototyping. Compared to the FEM simulations the 1. Eigenfrequency of the axis is much lower than the one of the frame which can be explained with the behaviour of the vertical axis as a multi-body system. Here a mass (mirror) is coupled with springs (frame and couplings) and gudies (ball bearing gudies) to a base. Therefore the Eigenfrequency can be increased by stiffer springs and a smaller mass. Thus the dynamic behaviour of the axis can be improved. The developed MBS-model shows different results of the oscillating time than the measurement. Here further parameters of the axis need to be identified and integrated in the model.

8. CONCLUSIONS AND FURTHER WORK

The work described here showed that the designed modular long range vertical axis can be used for high precision positioning. It also showed that a MBS-model of such device is complex but useful to examine the dynamic behaviour. The measurement results of the first setup showed a good behavior of the guides as well as the drives. It was possible to reach a positioning resolution in the nanometer range with a special arrangement of different commercial components. The positioning resolution and accuracy of the test device is not limited by the mechanical components.

Nevertheless there are a lot of different points which have to be solved in the future. The existing MBS-model, the control and the environmental conditions need to be further improved. Also the mechanical components especially the frame need to be redesigned. After this the next steps will be the realization of other combinations. Then the different designs can be compared to make states about the dynamic behavior and which combination is preferable for devices working in the nanometer range.

9. ACKNOWLEGEMENTS

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10. REFERENCES

Aarnio, J. P, Riitahuhta, A.O., 2002, “Modularisation by integration (MBI) a means to modularise a mechatronics product”, Proceedings of NordDesign 2002, Trondheim, Finland, pp.1-8.

Beckstette, K. F. et al., 2006, “Aspheres & Freeform Manufacturing”, Proceedings of the Optonet Workshop, Jena, Germany.

Hausotte, T., 2002, “Nanopositionier- und Nanomessmaschine”., ISLE, Ilmenau.

Hofer, A.P., Gruenfelder, M., 2001, “Product family management based on platform concepts“, Proceedings of ICED ´01, Vol3, Glasgow, pp. C 586/631.

Höhne, G. et al, 2005, “Design Of High Precision Positioning And Measuring Machines Using Virtual Prototyping”, Proceedings of the 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil.

Jäger, G. et al., 2002, “Operation and Analysis of a Nanopositioning and Nanomeasuring Machine”, Proceedings of 17th ASPE Annual Meeting, St. Loius, USA.

Jakobi, M., 2007, “Modellierung und Simulation einer präzisen Vertikalpositioniereinheit”, Diplomarbeit, TU Ilmenau.

KAIST - BUPE Annual Report 2003, http://pem.kaist.ac.kr/bupe (2003-11-05).

Kramar, J. et al., 2005, “Nanometre resolution metrology with the Molecular Measuring Machine”, Institute of Physics Publishing, Measurement Science and Technology Volume 16, Number 11.

Ruijl, T., 2002, “Ultra Precision CMM: Design, Calibration and Error Compensation”, Ponsen & Looijen.

Theska, R. et al., 2004, “Design Principles for Highest Precision Applications”, Proceedings of 19th ASPE Annual Meeting, Orlando, USA.

Tsutsumi, H. et al, 2006, “Presentation of Ultrahigh Accurate 3-D Profilometer and Case Examples of Measurement”, Panasonic – Matsushita Electronic Industrial Co LTD, http://industrial.panasonic.com/ww/products_e/product_cat2/ADAH000_e/ADAH000_e/img/kouhou_e.pdf (2006-08-24).

11. RESPONSIBILITY NOTICE