SIMULATING THE DYNAMICS OF NANOPOSITIONING AND NANOMEASURING MACHINES USING METHODS OF MULTI-BODY SYSTEM DYNAMICS

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Abstract

In connection with the Sonderforschungsbereich 622 at TU Ilmenau, the scientific and technical bases to design and construct nano-positioning and nano-measuring (NPM) machines are elaborated. The measuring related characteristics of NPM machines are considerably influenced by the system's behaviour. For simulation, multi-body system (MBS) models were developed in order to determine these influences.
This research is focused on the development of a positioning and measuring machine with a moving range of 200 x 200 x 25 mm³. Therefore a high precision vertical axis has to be designed. High precision guides and drives are needed to satisfy requirements like high resolution, high stiffness and low friction. One main focus is the simulation of vertical drive units (vertical axis) which enable the compensation of the guidance error emerging from movement in three-dimensional space. For this purpose the simulation programs alaska 5 and MATLAB/Simulink were combined. The mechanical subsystem is simulated using alaska 5 and MATLAB/Simulink deals with the drive and control subsystems.
The simulation of a high precision vertical axis as multi-body system (MBS) will be presented in this paper. The results will be used to develop a model based control of the vertical axis. The objective is the optimisation of the complete system in terms of dynamical behaviour and stability. The numerical results of the simulation are evaluated and the models are adjusted by experimental assessments.

Keywords: multi-body system, dynamics, simulation, high precision axis.

Presenting Author's biography

Erik Gerlach was born 1969. He received the degree in electrical engineering in 1996 and the Ph.D. (Dr.-Ing.) in 2003 from the Technische Universität (TU) Ilmenau, Germany. His dissertation was on the optimization of robot trajectory. He was an assistant at the department of quality management, TU Ilmenau, from 1996 to 1997. Since 1997 he is scientific assistant at the department of technical mechanics, TU Ilmenau. His main research field is the simulation of multi-body systems. Since 2003, he has been working with the Sonderforschungsbereich 622 "Nanopositionier- und Nanomess-maschinen" at TU Ilmenau.

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1 Introduction

Nano-positioning and nano-measuring machines are technological means of positioning, measurement, scan, treatment and manipulation of objects with high precision. Current and future high technologies such as microelectronics, micromechanics, optics, molecular biology and material engineering demand increasing ranges of motion, extreme precision and high positioning speeds.

This research is focused on the development of a positioning and measuring machine with a moving range of 200 x 200 x 25 mm^3. Therefore a high precision vertical axis has to be designed [1]. High precision guides and drives are needed to satisfy requirements like high resolution, high stiffness and low friction. 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. Guides also have great influence on the properties of the vertical axis. 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 favourable but their moving range is limited. For these reasons a systematic analysis of different combinations of drives and guides is necessary. A basis for the evaluation and selection of mechatronic movement systems should be the simulation of the dynamic.

This paper deals with some investigations in the design process of NPM machines from the mechanical point of view. Methods of multi-body system dynamics are used for parameter estimation and for the analysis of the dynamical behaviour of the machine and their modules, respectively. The objective is the optimisation of the complete system in terms of dynamical behaviour and stability.

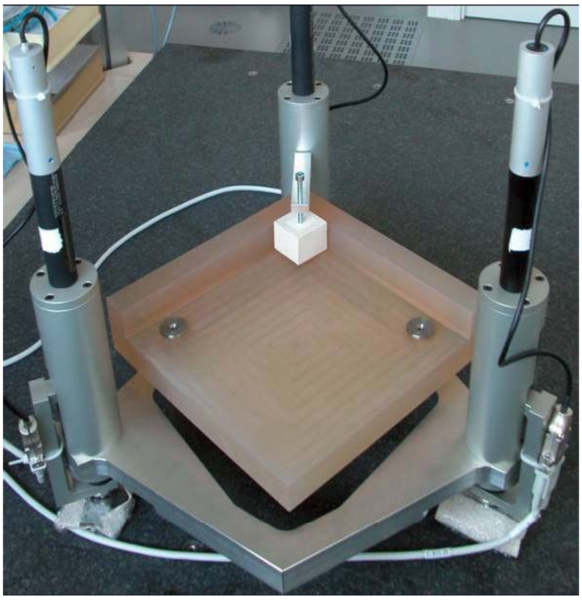

Fig. 1: Design of the vertical axis with mirror

2 Design and Multi-body system models

2.1 Design

Figure 1 shows the assembled vertical axis with a measuring mirror applied. Each drive unit consists of a coarse motion spindle drive, a fine motion piezo element and a ball guide. The three drive units move the plane mirror whose position and angle is measured by laser interferometers.

The vertical axis itself is designed modularly. Three drives and guides are arranged symmetrically around the cumulative centre of gravity. All guides stay in contact to the base through planar guides e.g. flat air bearings. The arrangement of guides and drives is serial in a short and direct force flow. Only push and pull forces arise except of lateral forces through horizontal motions.

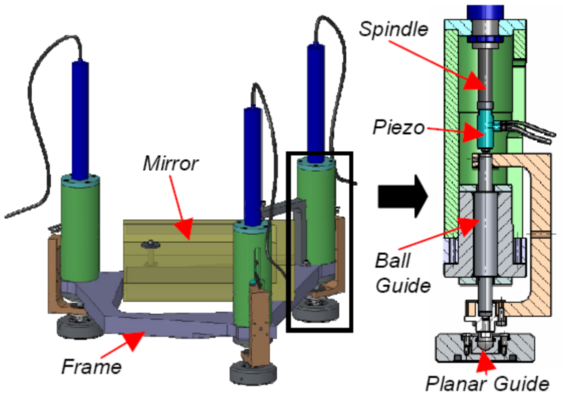

Fig. 2: Model of the vertical axis with spindle and piezo drives [1]

In Figure 2 the overall design of the vertical axis in this combination is shown. The section view shows one drive unit consisting of drive and guide. Spindle and piezo drive are collinear aligned. By this arrangement both elements can be driven separately and work in a hybrid system. Thus a moving range of 25 mm with a theoretical positioning resolution of 1 nm can be covered.

2.2 Reduced MBS-model

This device is the basis for the following steps. At first the model was reduced to two drive units, to analyse the dynamic performance elementary. The presented MBS-model is aiming to the modelling of the z-axis to allow some comparison between measurements of the real machine and simulations. The model includes the following parameters (Fig. 3):

- mass and mass-moments of inertia of the led parts of the z-axis,

- elasticity of the guidance of the z-axis and the frame support,
- elasticity of the linear ball bearings of the z-axis,
- frictional forces acting along the guidance of the z-axis.

For a realistic simulation of the dynamical behaviour of the machine it was necessary to define the friction coefficient in the guidance of the z-axis experimentally [2].

The frame is modelled as a joint-beam. This is a special element of the simulation-tool alaska. The joint-beam is able to simulate the behaviour of an elastic beam with the MBS.

2.3 MBS-Model of the vertical axis

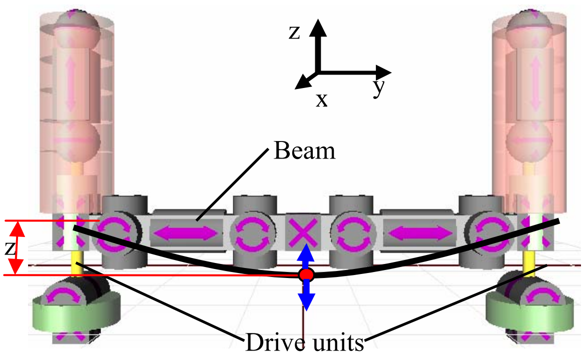

Fig. 3: MBS-model of the reduced vertical axis

In the next step a realistic MBS of the vertical axis was created. This model consists of the following components:

- three drive Units with ball guides,

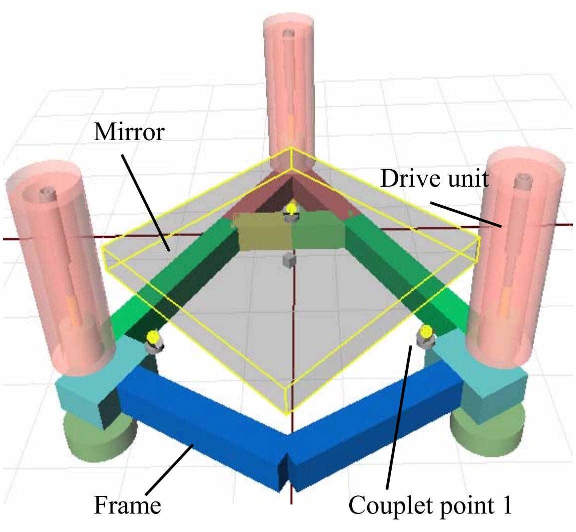

Fig. 4 MBS-model of the vertical axis

- the frame modelled as an elastic body,
- the ball-V-groove coupling between mirror and frame,
- the mirror as rigid body.

The subsequent technical measurements depend significantly on the boundary condition of the structure. The properties of every model element have to be considered to build the sub models as accurate as possible. For highly precise systems new model components must be used, in order to copy substantial effects in the system.

For example the coupling between the Mirror corner and the frame is modelled with contact elements. Three supporting elements with spherical contact surfaces are mounted to the Mirror corner. As counter pieces the imbedded V-flutes are used. The V-flutes include an angle of 120°. This results in a non-constrained 3-point support with zero degree of freedom. In order to decrease the surface pressure in the contact areas the flanks of the V-flutes are dished. These bodies are linked by elastic properties between the counteracting ball/V-flute. The properties are calculated by the theory of Hertz: contact of curved areas under load [4].

Fig. 4 shows the MBS-model of the vertical axis in alaska.

2.4 Sub model in MATLAB/Simulink

In Figure 2 the design of the vertical axis is shown. The section view shows a drive unit consisting of Spindle and piezo drive. They are collinear aligned. Through this arrangement both elements can be driven separately.

The spindle drive is able to realize long range movements with lower dynamics. The piezo element realizes the short range movements below the position resolution of the spindle drive with high dynamics and accuracy. As output the sum of both movements will take effect. The positioning task is split up to the actuators by adding the piezo stroke to the control deviation of the spindle drive. The models of the drive unit are realised in MATLAB/Simulink. For example Fig. 5 shows a simple model of the piezo.

2.5 alaska and MATLAB/Simulink

Methods of virtual prototyping are used to simulate the behaviour of the system to optimize its design. The simulation of the multi-body system (MBS) is necessary to analyse the movement in three-dimensional space. One main focus is the simulation of vertical drive units (vertical axis) which enable the compensation of the guidance error.

Therefore an MBS of the vertical axis, see chapter 2.2 and 2.3, was developed. Also a sub model was realised for the drive units, see chapter 2.4. In the nex step the simulation programs alaska 5 and MATLAB/Simulink were combined. The mechanical subsystem is simulated using alaska 5 and MATLAB/Simulink deals with the drive and control subsystems.

The coupling between Alaska and Matlab/Simulink is based on the *S-function* concept. An *S-function* is a computer language description of a Simulink block. Figure 3 shows the assembled model of the vertical axis in the described setup. This test device is the base for the following steps.

During the simulation the forces and torques of the drive units are calculate in Simulink. These values are the input of the *S-function* block. The outputs are the movement and the reaction forces and torques of the mechanical system. The control of the simulation task is made in Simulink. Before the simulation starts the assembly state must be calculated with alaska.

3 Results

The first results of the computer simulation were received with the reduced model of the vertical axis. The realised simulations calculate the bending deformation from the frame on the couple point, for definition see figure 3. In figure 7 the static displacement is shown. The MBS-model is conforming to the reality.

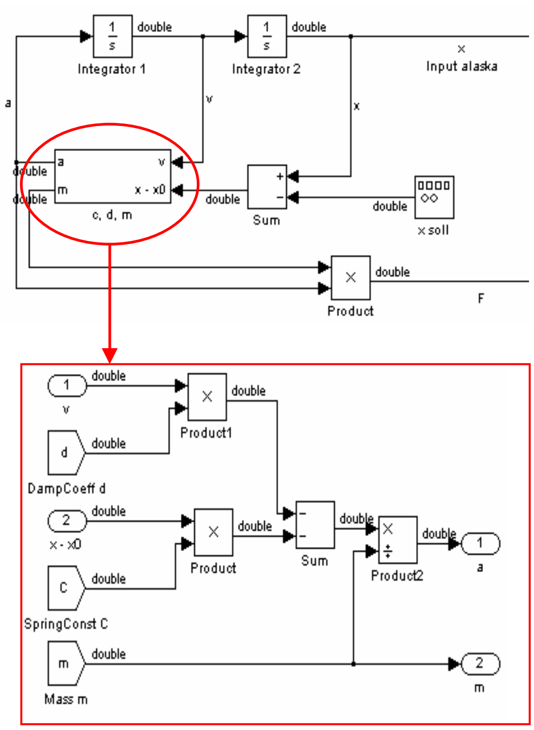

Fig. 5: Simulink model of the piezo drive

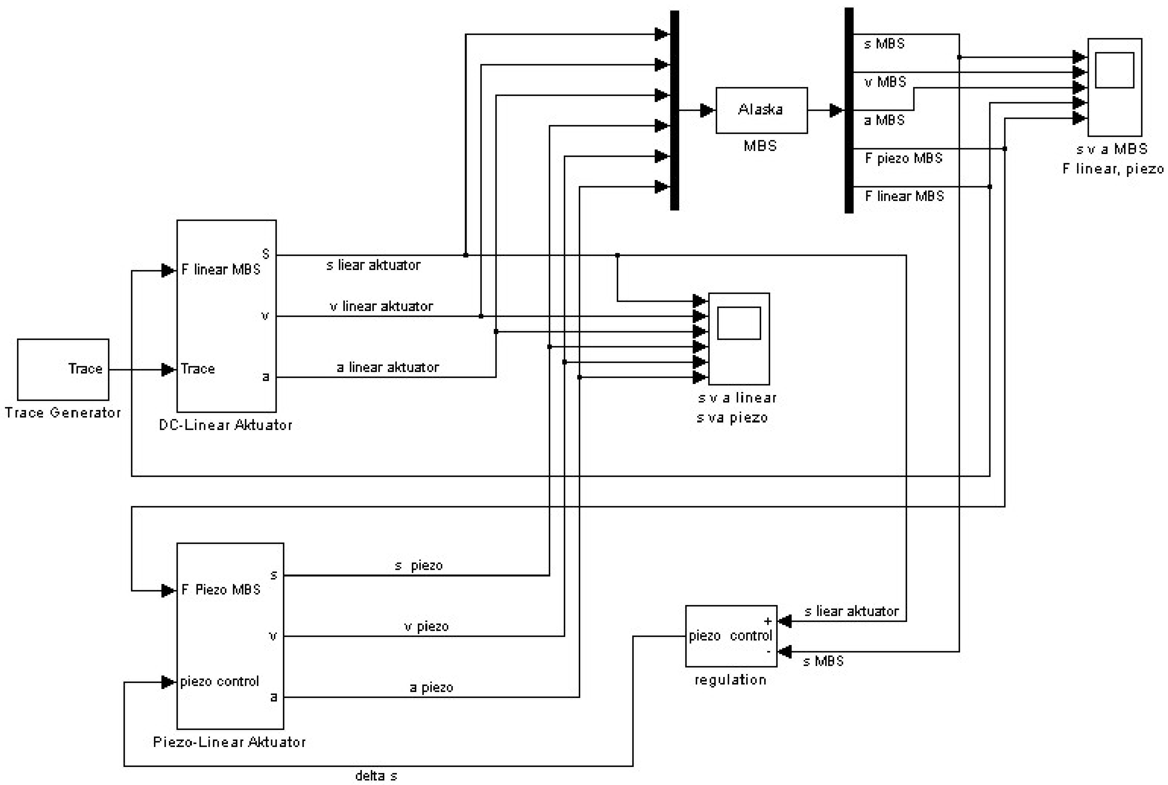

Fig. 6: Simulink block diagram of the vertical axis

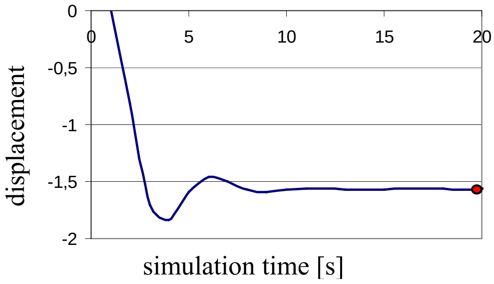

Fig. 7: Static displacement of the frame

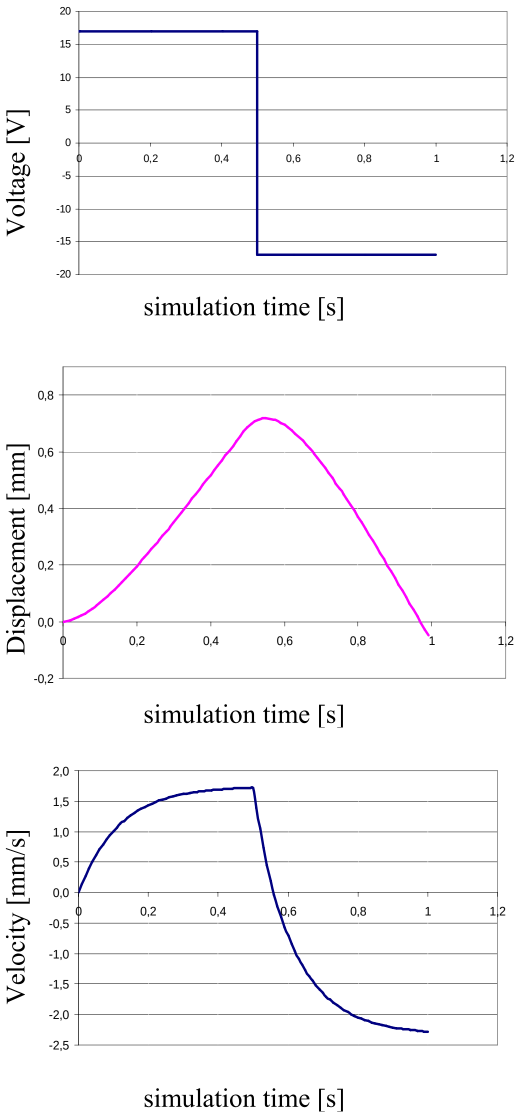

Fig. 8: Activation und motion of one drive

In the following simulation the sub models in alaska and MATLAB/Simulink are coupled. The spindle drive is able to realize long range movements with lower dynamics. The piezo element realizes the short range movements. In the case of open-loop control the reference motion is give only for the spindle drives as electrical actuation. See Figure 8 for the details.

Through these different tests the MBS-model of the vertical axis was checked. In the next step of the model the arrangement of three drive units will be used to simulate the dynamic behaviour. The results will be used to calculate the platform position and angle deviation.

Figure 9 shows the movement of drive unit 1 of the vertical axis. Die activation is the same as before. The final result is the displacement of the measuring point at the mirror of the z-axis laser interferometer, see figure 10. Clearly, a control device (closed loop control) must be used to generate a movement with nanometer precision.

Also the natural frequencies of the linearised system are calculated, depending on the working point. This gives conclusions concerning the metrological properties of the system.

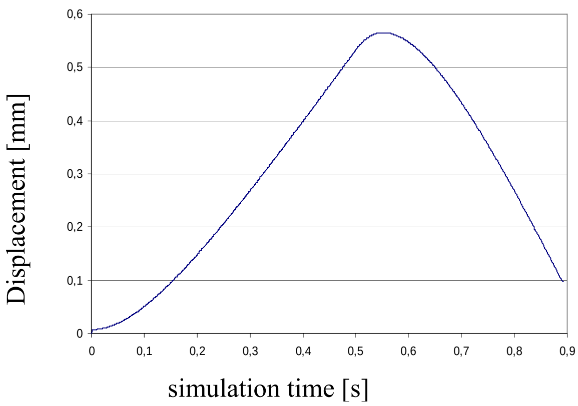

Fig. 9: Motion of drive unit 1

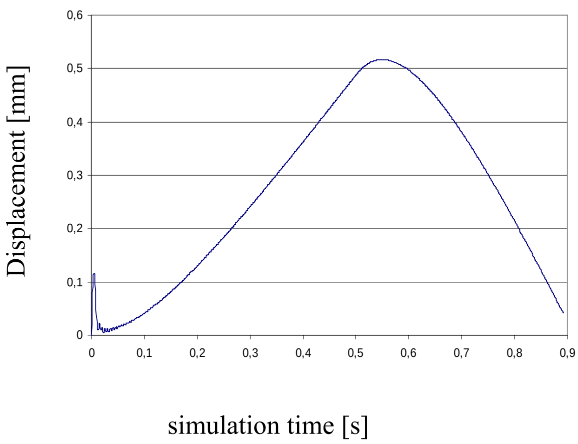

Fig. 10: Dynamic displacement of the laser interferometer measuring point at the mirror

4 Conclusions and further works

For redesigning the nano-positioning- and nano-measuring machine virtual prototyping is used as a supporting design method. The examinations performed have the purpose to study dynamical influences toward the system behaviour of the machine. Especially, the dynamical displacement and tipping of the Mirror corner regarding the respective model configuration were analysed.

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. Measurements of the real machine should be comparing to the results of the simulation. After this in the next steps will be realised the simulation of other combinations (consisting of voice coils, aerostatic guides, weight compensation mechanisms and spring guides).

5 Acknowlegements

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