POSITIONING WITH NANOMETRE PRECISION REQUIRES A HIGH TECH NANOPOSITIONING AND NANOMEASURING MACHINE AND AN OPTIMAL MACHINE SETUP

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ABSTRACT

The paper deals with an optimal setup of high precision machines, working in nanometre dimensions. On the example of the Nanopositioning and Nanomeasuring Machine (NPM Machine), developed at the Technische Universität Ilmenau, the problems of active and passive vibro-isolation are discussed. In the focus of investigations are the vibrations, induced from the environment to the machine, as they may affect the working accuracy of the machine. Thus, an exemplary hook up for a working NPM Machine is presented.
The results of measurements of the vibration velocity vs. time are introduced and discussed for selected measuring points from ground to the top of the machine. The opportunity of theoretical analysis, using numerical methods, is shown.
Prospects of further estimations are given, including more detailed analysis and analytical analysis.

1. INTRODUCTION

Tendencies of more and more increasing working areas in connection with high precision can be observed in micro-systems technology, precision optical manufacturing or micro-processing technology with additional 3D requirements. The micro- and nanogeometries produced are becoming more complex, and the aspect ratios larger. Precision optics have to be tailored with nanometre precision partially equipped with additional micro- or nanostructures. Here, adequate measurement capabilities are necessary.

The NPM Machine with a measuring range of 25 mm x 25 mm x 5 mm allows large-area measurement of micro- and nanostructures with sub nanometre resolution [Jäg09, Man12]. This is realised by positioning the test object with nanometre accuracy within the working area while the measuring equipment is fixed on a metrological frame.

A NPM Machine can only be as good as the machine setup that was realized to minimize the influence of external disturbance upon the NPM Machine. To ensure the accuracy of NPM Machines as complex mechatronic systems, they need to be protected from environmental influences, such as vibrations, airflow or temperature variations. The first step of avoiding induced vibrations is, to select an installation location, where the machine is exposed only to the lowest possible dynamical load. As a second step appropriate components for the equipment hook-up need to be chosen. For this process both, knowledge of the characteristics of the installation location and knowledge of the dynamical behaviour of the machine, need to be taken into account. This can be done using theoretical and experimental methods together.

2. WORKING PRINCIPLE OF THE NPM MACHINE

The basic concept of the NPM Machine consists of a special arrangement which allows Abbe error free measurements in all measuring axes over the whole measuring range (Fig. 1). This is realised on the basis of fibre coupled laser interferometers, which are fixed on a metrological frame. In expanding the Abbe comparator principle, not only the length offset between the measuring axis and the normal axis will be minimised. An additional angular measurement of the three guiding axis of the 3D-precision stage allows finally an active control of all angular deviations. The laser interferometers achieve a resolution of 20 pm.

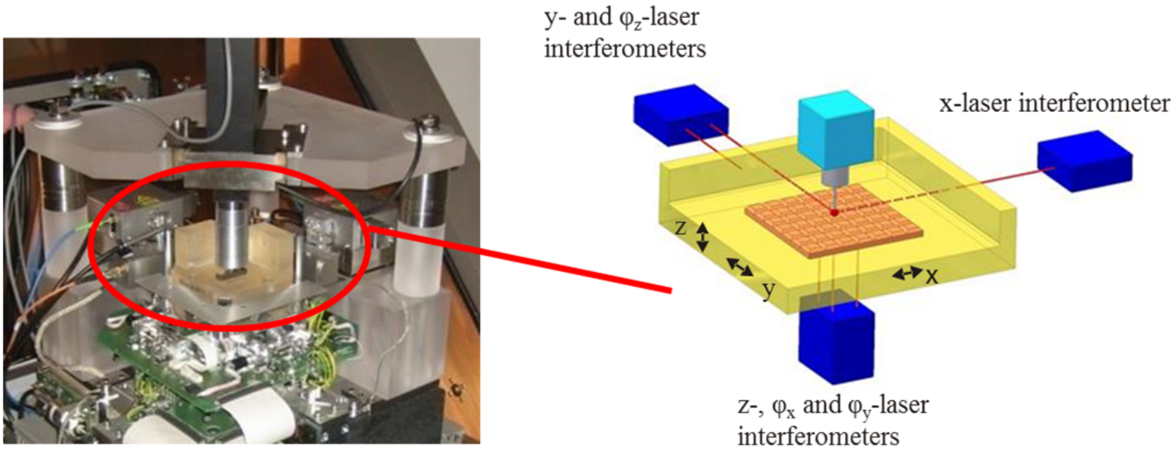

Fig. 1: Working Principle of the NPM Machine

The test object is placed upon a mirror, which is positioned through translational movement in the x-, y- and z- axis. The drive systems of the axis are arranged on top of each other. In the working point, i.e., the intersection point of the laser beams, the test object is touched mechanically or optically.
Seeing the working principle and the resolution of the NPM Machine it becomes obvious, that there must be no relatively movement between the interferometers among each other and compared to the mirror, carrying the test object.

3. DYNAMICAL BEHAVIOR AND HOOK UP OF THE DISCUSSED MACHINE

The NPM Machine is equipped with a stiff frame, containing a monolithic base plate and a metrological frame, made of ZERODUR. Thus, the machine frame maintains a high inertia and a high eigenfrequency.
Moving parts are the x- and y- slides and the mirror, which carries the device under test. Vibration may be induced during the process because of the inertia of the moving parts and because of stick-slip effects in the slide guidings. Friction effects in the guidings and their mechanical description are discussed in [Trö10] and [Zim07]. Appropriate moving concepts may reduce the vibration generation.

To shield the NPM Machine from airflow and temperature variation, it is placed within a climatic chamber, which is combined with a sound protection hood.
By the use of elastomer feet the NPM Machine is mounted upon a table top. The used table contains an integrated isolation system, which includes a pneumatic leveling unit and the opportunity to counter actively occurring vibrations – if they are known. The table is placed upon a pneumatically isolated basement, which provides passive vibration isolation and is leveled to an adjusted position after load changes automatically. Consequently the complete hook up adds three elastic planes (EP 1 to EP3) to the system, as can be seen in figure 2, left side.

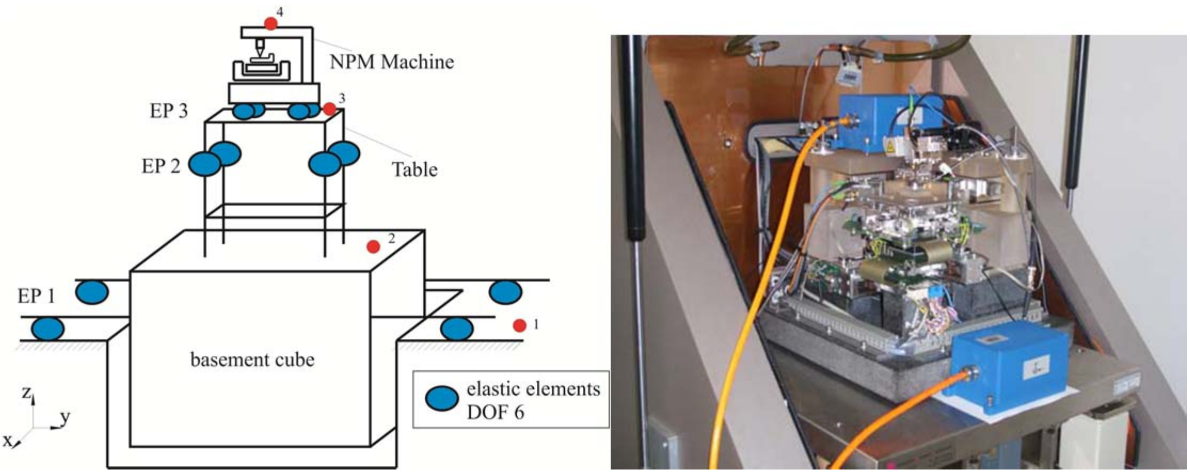

Fig. 2: left: Sketch of the complete hook up, right: Geophones at measuring points 3 and 4

4. MEASURED VIBRATION VELOCITIES

To validate the occurring vibrations, the vibration velocities have been measured at certain points, using geophones as sensors (Fig. 2, right side). The chosen points for measurement are marked red in Fig. 2. While the measuring points 1 and 2 offer information of the dynamic conditions at the location, measuring points 3 and 4 are important for the working conditions of the machine. The measurements were realized for the activated machine while standing still as well as during the positioning process. In order to estimate the influences of the vibrations induced from the environment to the machine, and how they are pursued threw the whole set up, the first analysis were run for measurements, while the machine stands still.

As expected, growing amplitudes from the ground to the top of the metrological frame could be observed. Figur 4 shows exemplarily the vibration velocity vs. time of the four measuring points for the x- axis. The identified amplitudes of the vibration velocity at the laboratory floor (measuring point 1) are larger, than the vibration criteria for nanotechnology facilities permit, that were defined in NIST A (Fig. 5) to ensure the claimed accuracy. Thus, it becomes obvious, that the working conditions of the machine should be optimized by the use of valid measures.

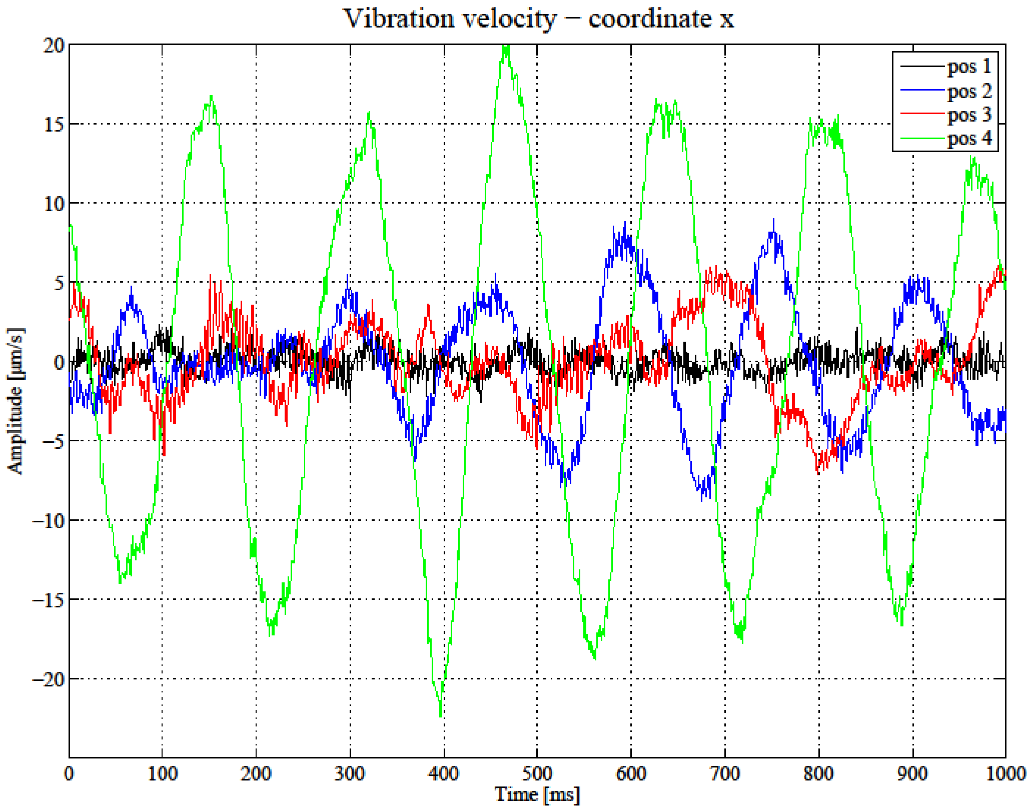

Fig. 4: Vibration velocity vs. time for the x- axis of the four measuring points

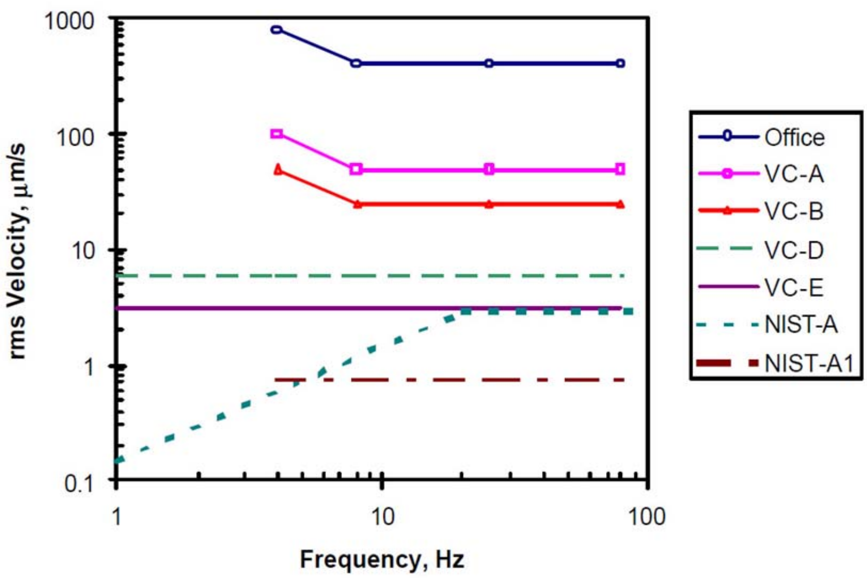

Fig. 5: Vibration criteria introduced in [Ami04]

It attracts attention that the largest change in amplitude appears between measuring points 3 and 4. It was suspected, that one of the reasons for the increasing amplitudes were the elastomer feet. This proved true, during repeated measurements after the elastomer feet had been replaced by rigid steel connections (Fig. 6). If the elastomer feet indeed are abdicable needs further estimations, as they work as dampers to vibrations stimulated by the NPM Machine during the positioning process.

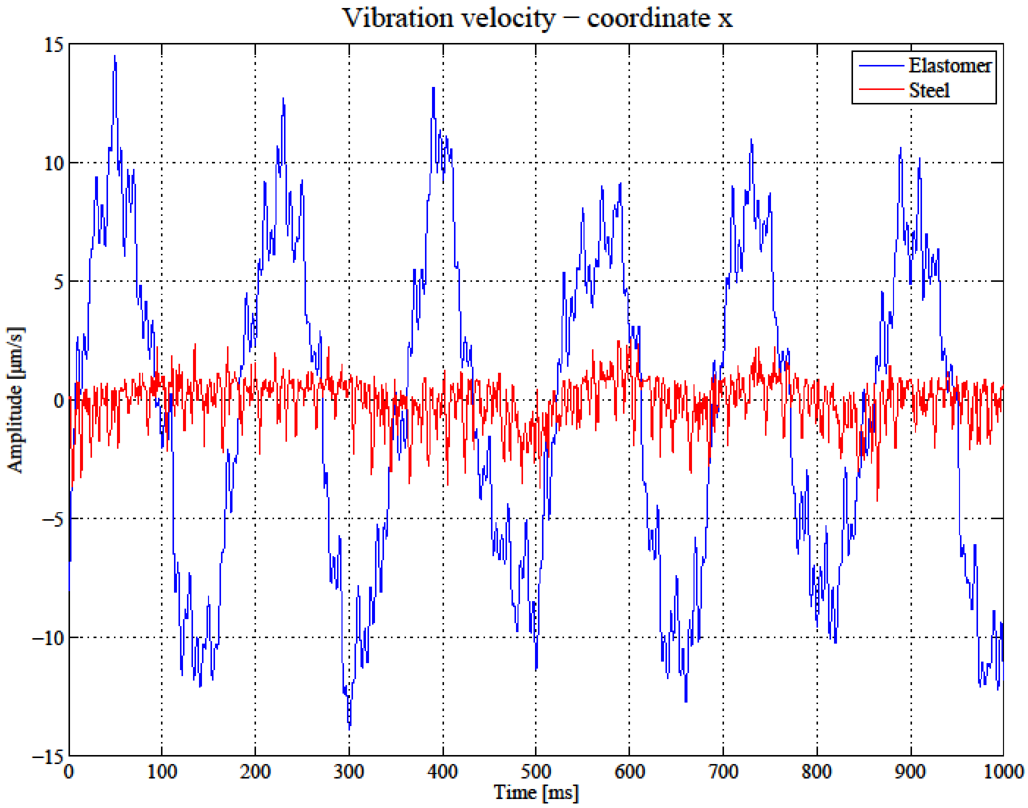

Fig. 6: Velocity Amplitudes for x- axis at measuring point 4 – comparison of different feet

The amplitudes of the stimulated vibrations on top of the metrological frame are larger for the x- and y- axes, than for the z- axes (Fig. 7). Two reasons may lead to this effect. First, the geometric reason - the vertical distances of the measuring point and the center of mass to the ground-location where the machine is planted, are much smaller for the x- and y- axis, than for the z- axis. As the vertical distances work as an amplifier, the effect of the larger z-distance on the x- and y- axis must be larger, than vice versa. Also the design of most devices to plant a machine (machine feet, vibration isolators, dampers) focuses on the z- direction and neglects the effects on vibrations in the x-y-plane.

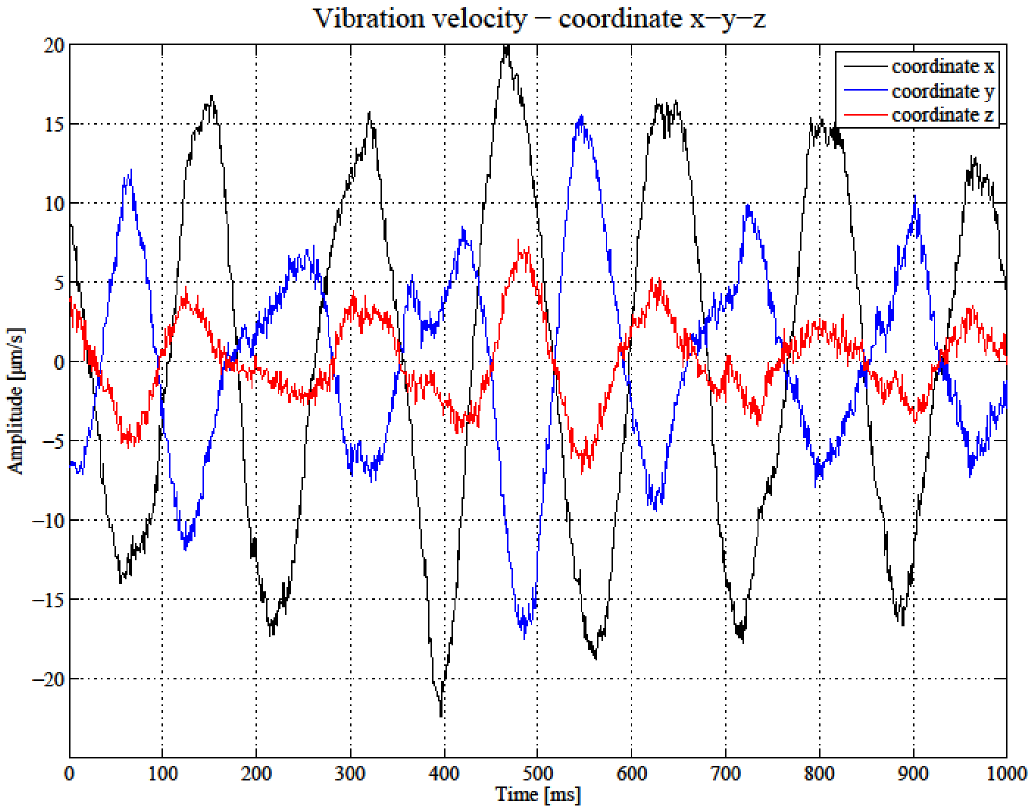

Fig. 7: Amplitudes of Vibration Velocity on top of the metrological frame

5. THEORETICAL METHODS

Theoretical considerations may be done, using analytical and numerical methods.
To obtain an understanding of the dynamic behavior of the whole mechanical system, multibody system (MBS) models in varying degrees of detail are helpful. For numerical analysis the simulation program alaska® of the Institute of Mechatronics (Chemnitz) is used [Ger07, Zim04]. Beginning with simple, highly abstracted models, containing only a few rigid bodies, connected geometrically and physically, more and more relevant details need to be considered. If it is to assume, that the elastic or dynamic properties of one part are relevant for the dynamic behavior of the whole system, it should be tried, to portray it´s properties in a MBS model instead of abstracting it to a rigid body. With the joint beam (Fig. 8, left side) a valid model for beams exists, which renders the first eigenfrequency and natural mode rightly. Likewise solutions may be found for plates (Fig.8, right side), but require knowledge of the material-properties, especially the damping parameters. The plate of interest is pieced together from a number of sub-plates, which are linked three-dimensionally, taking cognizance of stiffness and damping properties [Her12]. An experimental validation is advisable.

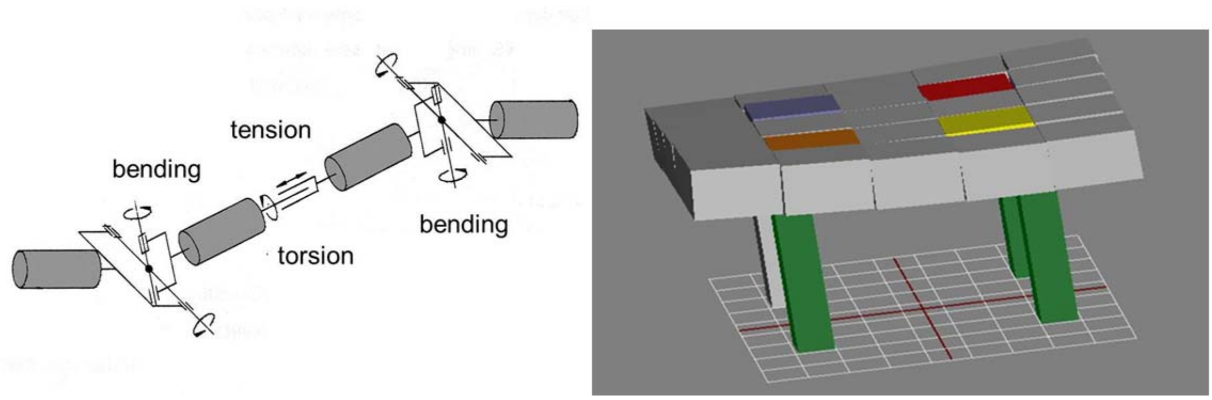

Fig. 8: left: MBS model of a joint beam [Ala08] right: MBS model of a plate [Her12]

For better understanding of the influence of a particular part on the dynamical behavior of the whole system, for example the base plate of the machine, FEM may be used (Fig. 9). The knowledge of the eigenfrequencies and natural modes of a part may allow estimating the relevance of its dynamical properties for the dynamical behavior of the whole system. Also it may help to define the parameters of a MBS- plate, introduced above.

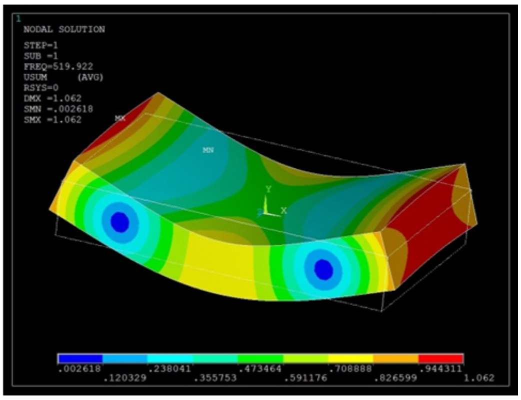

Fig 9: First natural mode of a plate

6. CONCLUSION AND OUTLOOK

The NPM Machine offers the opportunity of positioning and measuring with nanometer accuracy within a working area of 25 mm x 25 mm x 5 mm. To assure the accuracy of the NPM Machine, it is necessary to reduce the susceptibility to vibration of the machine. In the article it is shown, that beside design measures, that are taken to reach that aim, the conditions at the location, where the machine is set to work, need to be regarded. Also suitable elements for the hook up of the machine need to be chosen.

The identification of occurring vibration stimulation from the environment was reached, measuring the vibration velocity vs. time by the use of geophones. The results for the activated, not running machine were introduced. Numerical analyses were done, using MBS- and FEM- Models. Furthermore, the estimations need to be carried out for the working machine also. Experimentally and numerically received results need to be combined too.

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