Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 62 (2017) 335 – 339
www.elsevier.com/locate/procedia

10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Analysis of an ultra-precision positioning system and parametrization of its structural model for error compensation

B. Denkena, D. Dahlmann and N. Sassi*

Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, An der Universität 2, D-30823 Garbsen, Germany

* Corresponding author. Tel.: +49-511-762-5262; fax: +49-511-762-5115. *E-mail address*: sassi@ifw.uni-hannover.de

Abstract

Conventional compensation of position errors of machine tools relies only on measured values. Due to this principle it is not always possible to compensate the errors in time, especially dynamic ones. Moreover, the relevant control variables cannot always be measured directly. Thus, this approach proves to be insufficient for high precision applications. In this context, a model-based error prediction allows for minimal position errors. However, ultra-precision applications set high demands for the models' accuracy. This paper presents the design of an accurate and real time-capable structural model of an ultra-precision positioning system. The modeling method for the developed ultra-precision demonstrator is shown and the initial parameter identification is presented.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Structural modelling; parametrization; model-based compensation; ultra-precision

1. Introduction

Ultra-precision machining is considered as a key technology for the manufacturing of reflective optical components with high precision complex surfaces. Presently the performance of ultra-precision machining is still limited by small feed rates and small spindle rotation speeds compared with conventional machining [1]. This is due to the high precision and stability requirements on the process.

In order to improve the performance of ultra-precision machining without affecting the demanded precision in the nanometer range new machine and control concepts have to be developed. In particular, errors caused by increased dynamics such as unbalances of rotating components must be compensated reliably.

In this context conventional compensation of errors relying only on measured values proofs to be insufficient to maintain the precision in the nanometer range. Due to accessibility problems it is not always possible to place sensors at the positions of interest like the tool center point (TCP) during machining. Therefore a model of the machine is needed to predict errors at such positions. In the last years much research work has been conducted in the model-based compensation of dynamic errors for conventional systems [2-3]. For ultra-precision systems model-based methods for the compensation of geometric errors of precision and ultra-precision machine tools have been proposed in literature [4]. However predictive compensation of errors due to the dynamic compliance of ultra-precision machine tools has not been investigated so far. For this an accurate and real-time capable structural model of the ultra-precision system has to be built.

This paper begins with a description of an ultra-precision two axis workpiece table. Afterwards the system's model and the experimental analysis results are presented. Finally the offline adjustment of the model based on measurement data is shown. The parametrized model aims to compensate errors due to increased dynamics.

2. Ultra-precision demonstrator

The ultra-precision demonstrator shown in Figure 1 is a two-axis positioning system consisting of a linear axis with aerostatic bearings (Z-axis) and a novel linear axis with

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.054

electromagnetic bearings (X-axis) [5]. The electromagnetic guide provides the capability to compensate errors in five degrees of freedom in the range of ± 25µm. Furthermore it allows for damping of dynamic disturbance forces actively. On the contrary, the aerostatic guide is not actively controlled and consists of nine flat rectangular air bearing pads which are made up of porous media. The air gap is about 5µm for an input pressure of 4 bar.

Most of the system's components are made up of granite because of its good damping and thermal properties. In order to avoid tilting moments a box-in-box concept has been chosen. The cross table is mounted onto a support plate made up of granite which is installed on a steel frame. The TCP is located on the top of the electromagnetic slide. The travel of both axes is 100 mm.

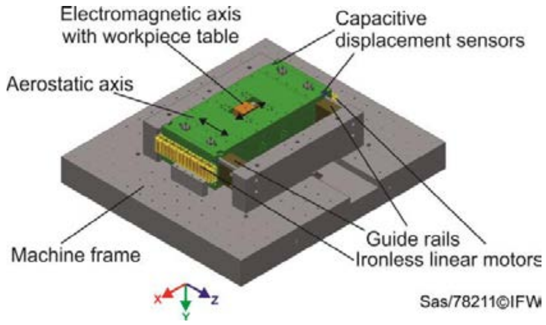

Figure 1: Ultra-precision demonstrator

Both axes are driven by two ironless linear motors in gantry configuration. The position feedback in the direction of motion is provided by linear encoders with a resolution of 1 nm. The deviations in the other two translational directions and the three angular deviations for the aerostatic axis are recorded by five capacitive sensors. For the electromagnetic axis twelve capacitive sensors are used. The installed displacement sensors allow for the online adjustment of the model by the use of an observer (kalman filter).

3. Model of the ultra-precision axis

The model of the positioning system is in state space representation (1). Here A is the system matrix, B the input matrix, C the output matrix, D the feedforward matrix, x the state vector and y the output vector.

$$\dot{x} = Ax + B\,u \\ y = Cx + Du \tag{1}$$

The model predicts the structural deviations at the tool center point based on the actuating forces as input. First the initial model's parameters have to be adjusted. The offline parametrized model calculates the deviations at the positions of the 17 capacitive sensors by the use of the output matrix C_{mes}. The determined values are compared with the measured values at the same positions. The discrepancy is used by the model-based kalman filter in order to adjust the model online. The adjusted model calculates the deviations at the TCP by the use of the second output matrix C_{TCP}. The measured geometric errors at the TCP are stored in a look up table and added to the calculated values. Figure 2 shows the principle of the model based observer. The resulting error at the TCP is then assigned to the appropriate system's actuators according to their direction, amplitude and frequency.

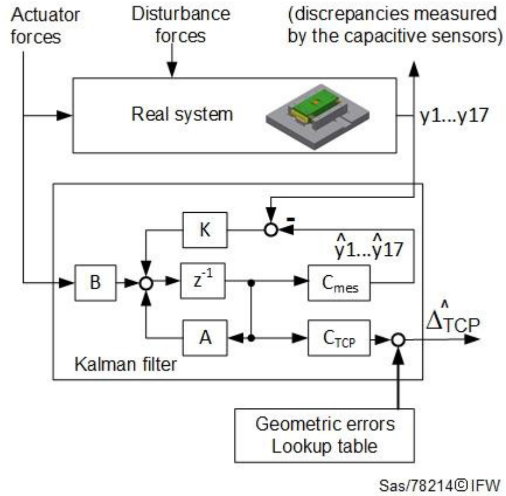

Figure 2: Model based Observer

A structural model of the 2-axis positioning system is built. The electromagnetic axis is not yet ready for operation regarding its control system. Thus, in this paper, the positioning system is modeled and analyzed assuming the magnetic guide to be rigid. Therefore the slide has been fixed.

3.1. Modeling method

In [6] two approaches for modeling the ultra-precision positioning system are presented and discussed. A top down method based on the detailed FE model has been chosen. A model order reduction is applied on the detailed structural model based on the modal superposition method. The reduction method describes the structure's response in terms of n eigenmodes. Here n is the number of the modes to be extracted. The result is a state space model with the system matrix A expressed as follows, where ω_i is the angular frequency of mode i, d_i is the effective modal damping of mode i and E is the unit matrix (2).

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{E} \\ \boldsymbol{\tau_1} & \boldsymbol{\tau_2} \end{bmatrix} \text{ with } \tau_1 = \begin{bmatrix} -\omega_1{}^2 & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & -\omega_n{}^2 \end{bmatrix} \text{ and } \tau_2 = \begin{bmatrix} -2d_1\omega_1 & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & -2d_n\omega_n \end{bmatrix} \tag{2}$$

Before applying the model order reduction method inputs and outputs have to be defined as nodes. Inputs are the application points of the driving forces. Outputs are the TCP and the centres of the measuring surfaces of the capacitive sensors. The next section describes the FE model and the parameters used.