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Modelling and Validation of Position Dependant Structural Deformations of a Machine Tool Structure under Gravitational Loads

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Abstract
The structure of machine tools inevitably deforms under gravitational loads. Since the machine tool axes move during operation, the gravitational loads on the structure change, and with them varies the deformation of the structure.
This contribution addresses the efficient modelling and simulation of structural deformations due to gravitational loads and presents a comparison between simulation and measurement results.
The modelling approach is to use reduced order finite element models for an efficient calculation of the deformation at a multitude of axis positions. Two key elements for the successful modelling of this problem are the model order reduction technique applied and the modelling of moving interconnections between flexible bodies. A model order reduction technique, which allows an efficient model reduction with a predefined accuracy, is presented. Furthermore, a method for the modelling of moving interfaces on flexible bodies using a Fourier series approach is described briefly.
The test bench used for measurements is a stage with two cartesian axes. The X-axis is a gantry axis with a stroke of 0.5m. The Y-axis cosists of a carriage with an asymmetric mass distribution and a travel of 2.6m.
The roll and pitch angles of the carriage are repeatedly measured by means of two inclinometers for different Y-axis positions across the Y-axis travel range. The measurement results are compared with simulation results.
It is shown, that position dependencies of a machine tool structure can efficiently be modelled using the described techniques. Furthermore, not only the static behaviour can be simulated with these models, but also the dynamic properties can be analysed, e.g. by frequency response or modal analysis.

Coupled Finite Element Machine Modelling, Model Order Reduction, Position Dependency, Inclination Scale Measurements

1. Introduction

Machine tool structures deform under gravitational loads, leading to deviations at the tool centre point (TCP). These deviations strongly depend on the position of the moving axes and therefore lead to systematic errors, such as e.g. pitch and roll. These errors can be measured following the guidelines in [1], e.g. by using inclinometers.

During the machine tool design process an efficient prediction of these errors by simulation, will save time and costs.

For this application a new coupled reduced order finite element (FE) simulation environment named MORe (Model Order Reduction and More) [2] was developed. Model order reduction of each machine component is done by using a combination of modal condensation techniques [3] and moment matching methods using Krylov-subspaces [4]. Different to using a parabolic approach as e.g. proposed in [5], coupling of the reduced order machine components is realised by a new moving interface approach, based on Fourier series model inputs.

This modelling approach is applied to the structural components of a two axes linear stage with direct drives. The static angular component errors of the Y-axis EAY (pitch) and EBY (roll), have been simulated and compared to measurements performed with WYLER inclinometers (BlueLEVEL) for three different load cases.

2. Modelling Methodology

The methodology of modelling within the new modelling environment MORe is based on four different elements: components, interfaces, links and the composition.

2.1. Components

Components are linear elastic reduced order FE-Models of structural machine elements. Meshing and export of the components large scale stiffness and mass matrices is done using the software Ansys®.

In MORe the large scale stiffness and mass matrices of each component are reduced using modal condensation from the static value ($0\ \frac{rad}{s}$) up to a definable frequency ω_r in combination with a Krylov-subspace reduction with a single expansion point at the static value $\omega = 0\ \frac{rad}{s}$. The linear reduced order system is stated to be below a predictable error limit in frequency domain from (0 to $\frac{\omega_r}{\kappa}$), where κ is the frequency range restriction factor >1, which is needed because of possible resonance frequencies slightly above ω_r.

2.2. Interfaces

Interfaces are predefined regions on surfaces of components, where either a load is applied or a position, velocity or acceleration is measured. They are considered during the model order reduction as input and output matrices.

A Fourier series interface can be used for moving connection points as given for a linear guideway. The Fourier series interface allows to efficiently apply trapezoidal force and torque loads at a freely definable position along the interface, by adding a Fourier series of sine and cosine force inputs.

2.3. Links

Links are defined as connections between two interfaces of different components. Links are used to introduce damping or stiffness properties or to measure the relative displacements.

2.4. Composition

The composition consists of the assembly of all components, interfaces and links to overall mass, stiffness and damping matrices, representing the whole system.

3. Test Bench

3.1. Linear Gantry Stage

As a machine example a fully direct driven gantry stage is used. The stage consists of a linear gantry X-axis and a Y-axis moving on the bridge as shown in figure 1.

3.2. Measurement Setup

For the measurement of the pitch (EAY) and roll (EBY) angles on the tool plate, two high precision WYLER BlueLEVEL inclination scales have been placed as shown in figure 1.

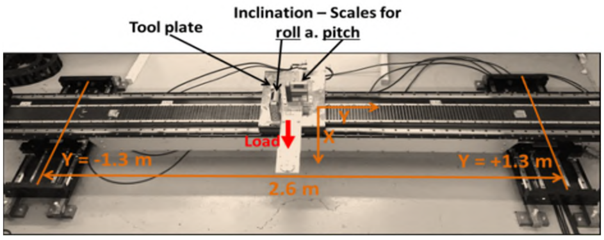

Figure 1. Test bench and measurement set up at Y-centre position

3.3. Test Bench Model

Using the modelling environment MORe, a reduced order FE-model of the test bench was built, as shown in figure 2. It contains 4 components: bodies X1 and X2, X-bridge and the Y-slide. Bodies X1 and X2 are connected by a stiffness link to the ground. The guideways between bodies X1 and X2 and the moving X-bridge, as well as between the Y-slide and the X-bridge have been implemented as Fourier interfaces.

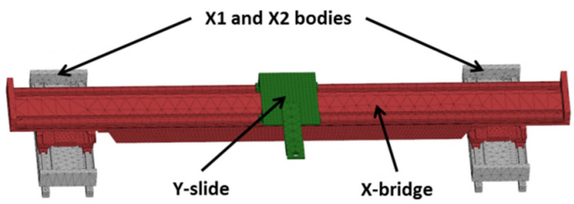

Figure 2. Structural bodies of reduced order FE test bench model.

4. Simulation and Measurement

4.1. Simulation and Measurement Procedure

Using the simulation model described in chapter 3.3 and the measurement setup described in chapter 3.2, roll and pitch angles of the tool plate along the Y-axis have been measured and simulated in steps of 5 cm from Y position -1.3 m to +1.3 m using no, 18 kg and 58 kg of additional load at the indicated point on figure 1. The X-axis was at position 0 m for all evaluations.

4.2. Simulation and Measurement Results

In figure 3, the resulting roll and pitch angles for the three load cases are shown for the simulation and measurements. Measurements with no additional load have been used as reference, to eliminate geometric effects caused by, e.g. guideways straightness, which are in a comparable order of magnitude as the structural deformations. The maximum absolute deviations between simulation and measurements are 0.16 mrad for pitch and 0.26 mrad for roll. Figure 4 shows a visualisation of the machine deformation at the Y-axis position of +0.5 m with a scaling factor of 500.

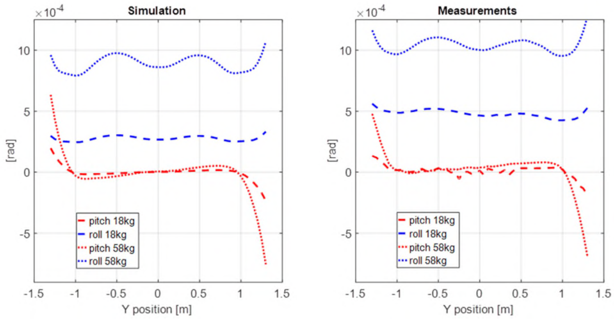

Figure 3. Simulation (left) and measurement results (right) of Y-axis roll and pitch evaluation.

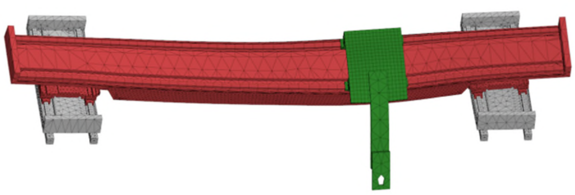

Figure 4. Scaled (x500) model deformation at Y = +0.5 m.

4.3. Conclusion

Simulation and measurement results in figure 3, show that reduced order simulation is able to predict roll and pitch angles of the Y-axis well and can be used for efficient simulations of these effects. Deviations between measurements and simulation may come from non-linear bearing stiffness values.

5. Summary and Outlook

A simulation approach using reduced order FE-models of machine components with a Fourier series coupling is applied for the evaluation of position dependant roll and pitch angles of a linear gantry stage Y-axis, coming from gravitational deformation of the machine structure. Measurements using WYLER inclinometers show good agreement with Simulation results.

The same modelling approach can also be used for the efficient position dependant simulation of the machine dynamic behaviour such as natural frequencies, mode shapes, and frequency response function analysis.

References

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