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Low-dimensional time-discrete models for high dynamic machine tools

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Abstract
The coupling of real and virtual machine tool components in a hardware-in-the-loop environment is commonly used by state-of-the-art engineering tools as well as automated test procedures to verify the system behaviour. Time deterministic models are necessary to provide simulation results in a predictable time frame. This leads to efficient development procedures. This article presents a method and results of an automated engineering tool that uses time discrete deterministic order-reduced systems for the calculation of the dynamic machine tool behaviour. An innovative model-order-reduction (MOR) procedure was developed that provides a low-dimensional approximation of the original model with associated error estimation as well as inherent system characteristics, like passivity and steady-state accuracy, for a defined time step width. The validation of the calculation model, based on the new MOR procedure, was carried out on a three-axes test stand. It is representative for high dynamic machine tools and equipped with an integrated real-time control environment. The real-time settings as well as stiffness K, damping D, and mass M can be adjusted. Various low-dimensional time discrete models were implemented for demonstrative application and experimental validation of the MOR procedure. The results show high potential for the use in engineering processes. A reduction from a secondary order system with 19,932 unknowns to a first order system with 80 unknowns was realized. Furthermore, the difference between calculated and measured deviation of the test stand's x-axes was achieved with a value of e_{XMax} = 750 nm.

Keywords: Micro-milling tools, dynamic Simulation, model reduction

1. Introduction

In modern engineering tools and automated tests machine tool components are coupled in a hardware-in-the-loop setup [1]. To get simulation data in an adequate time, time-discrete systems and model-order-reduction MOR methods are necessary. Hereby, models can be used more efficient in the development of a product and the models are able to be applied in a real-time-control system. Compared to the real system characteristics a high accuracy of the simulated models can be reached.

To optimise a machine tool, different modelling methods like Finite-Element-Method FEM or Multiple-Body Simulation MBS are used. Model-Reduction-Methods are required to get time-discrete and deterministic reduced model-order systems. For example, modal decomposition, Padé approximation or the balanced truncation are state of the art, but typically they are not designed for time-discrete approximation.

Therefore, a new model-order-reduction method using fixed time steps was developed. Furthermore, the inherent system properties (passivity, steady-state accuracy) are maintained.

2. Modelling

Different investigations on FEM-models were performed to get automated and application-adapted models for time-discrete deterministic reduced systems. The FEM-models were created with high input forces for high dynamic machine tools and were produced with ANSYS workbench and mechanical.

Herewith, some studies were carried out. The resolution of the mesh was changed, various contacts between machine tool components and areas were proofed, various materials with different properties were considered, some investigation of different meshes, nodes and contacts were done, and the complexity of the machine tool was simplified. Moreover, only single parts and components of the machine tool were modelled and coupled with other components of the machine tool. For example, the x-axis was modelled and coupled with the modelled y-axis.

For all variants modal analyses and harmonic analyses were carried out to get the eigenfrequencies f_n, eigenvectors u_n, eigenforms $A_n(u_{xyz})$, transmission behaviour, mass matrices M, stiffness matrices K, and damping matrices D. The received matrices were unsorted and unreduced. An example of one FEM-model is illustrated in figure 1.

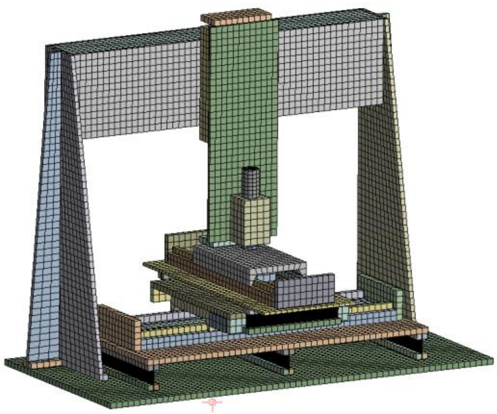

Figure 1. One FEM-Model of the used machine tool

To validate the FEM-models and get more information about the damping δ of the systems experimental modal analyses were carried out and various setups of the three-axes-test stand were investigated. For example the damping δ and the stiffness k were modified. The setup for the experimental modal analysis is shown in figure 2.

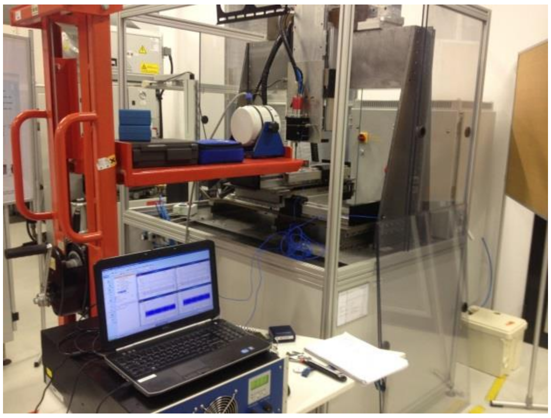

Figure 2. Experimental Setup for validation of the FEM-Models

The received information about the models in mathematical form was transferred between ANSYS and MATLAB with a proofed interface.

The generated matrices were used for the transfer function of the system $G(s) = C(Ms^2 + Ds + K)^{-1}F$ and Rayleigh damping was supposed. The approach leads to the new MOR method.

The new method is characterised by the following steps as an example for the x-axis. The damping matrix D is given by the Raleigh damping with $D = aM + bK$, whereby a and b is chosen by the damping of the resonances from the first eigenfrequency f_1 of $M\ddot{x} + Kx = 0$ and the cut-off frequency of the sample is $\xi \leq 0{,}005$.

The next step is to interpolate the transfer function by rational Krylov-spaces to get a matrix V.

That is used to get the reduced form of the used matrices $M_r = V^TMV$, $D_r = V^TDV$, $K_r = V^TKV$, $C_r = CV$, $F_r = V^TF$ [2]. For the interpolation of the eigenvalues $M\ddot{x} + D\dot{x} + Kx = 0$ were defined and comply the cut-off frequencies.

To improve the time of simulation of the reduced models, the systems were transferred in first order state space models and a time discretisation by Zero-Order-Hold was realised.

The reduced matrices were implemented in a new state space model. The state space models were created by use of MATLAB and SIMULINK. A Linux kernel was necessary to use the models in real-time. The basic framework of the applied machine control is explained in [3]. To use the reduced matrices in the real-time setup, it was necessary to adapt the outputs of the state space model for the control loop. Most outputs were filled with zeros. Not at least, by implementations of the models the focus was on time synchronous calculability.

3. Results

The transferfunction of the reduced model was compared with the transferfunction of the validated structure of figure 2. More precise, the part of the $\mathcal{H}_2$ Norm in the frequency range of $0 \leq 60{,}000$ Hz is $\left(\frac{1}{2\pi}\int_{-\omega_c}^{\omega_c}|G_r(\iota\omega)\text{-}G(\iota\omega)|^2\right)^{0.5} = 7 \cdot 10^{-14}$. The positive definiteness is transferred of the matrices M_r and K_r, so the reduced system is also a passive mechanical system.

Moreover, a reduction of second order system with 19,932 unknowns to a first order system with 80 unknowns could be achieved.

Next, a constant error by means of interferometry could be determined. The interferometer was directly integrated in the machine control. Therefore, the interface between interferometer and the machine control has to be configured. The results are shown in table 1.

Table 1. Measured constant error by means of interferometry

n = 10	v_f = 0.0167 m/s = 1 m/min			
travel range [mm]	10		20	
axis	X	Y	X	Y
maximum Dislocation [nm]	333	336	342	346
minimum Dislocation [nm]	323	316	323	3265
relative Error [%]+	0.00334	0.00336	0.00171	0.00173
relative Error [%]-	0.00323	0.00316	0.00162	0.00163
n = 10	v_f = 0.0333 m/s = 2 m/min			
travel range [mm]	10		20	
axis	X	Y	X	Y
maximum Dislocation [nm]	337	338	343	346
minimum Dislocation [nm]	326	317	326	328
relative Error [%]+	0.00337	0.00338	0.00172	0.00173
relative Error [%]-	0.00326	0.00317	0.00163	0.00164
n = 10	v_f = 0.0666 m/s = 4 m/min			
travel range [mm]	10		20	
axis	X	Y	X	Y
maximum Dislocation [nm]	339	340	346	347
minimum Dislocation [nm]	329	322	329	330
relative Error [%]+	0.00340	0.00340	0.00173	0.00173
relative Error [%]-	0.00330	0.00332	0.00164	0.00165

As shown, the constant error increases with an increase of the feed velocity v_f but is nearly independent from the travel range of the axes. Furthermore, the maximum feed velocity v_f of the system was tested on a travel range x = 10 mm. It was identified with v_f = 19 m/min. Above this velocity the control loop of the three-axes-test stand gets instable. The maximum error under this conditions achieved a value e_{XMax} = 750 nm, which also represents the stop criterion for the models.

4. Conclusions

The results of the research project show initial approaches to direct generate time discrete and low-dimensional models for a high dynamic machine tool. The new MOR method achieved a stable, passive, time-discrete, low-dimensional model with high accuracy. In further investigations the transferability to machine types with more axes has to be proofed and the usability for not open sources machine controls has to be evaluated.

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