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Efficient dynamic machine structure modelling for high performance dry grinding

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Abstract

Accurate finite element machine modelling is typically connected with high computational costs. For this reason, machine structures are usually simplified or analysed only partially. In this paper, an efficient machine modelling technique is presented. It makes use of modal condensation and Krylov subspace model order reduction techniques for Finite-Element-models and Fourier element coupling for moving interfaces. The resulting model is stated to be accurate statically and below a definable frequency. Especially the benefit of having an accurate low order static and dynamic machine model for grinding machine and process simulation is outlined. This enables a full size transient simulation without simplification or omission of potentially important machine components. The modelling methodology is applied to a large and complex test rig for high performance dry grinding. This test rig is used to emulate the railway grinding process, where low frequency deviations are acoustically most relevant. In order to be later used for transient grinding simulations, all test rig components are modelled and assembled. For the validation of the model, its modes and mode-shapes are compared to the results of an experimental modal analysis performed on the real test rig. TCP frequency response functions are further compared between measurement and simulation. The potential use of the model for surface roughness and waviness simulations is shortly implied.

Keywords: machine modelling ; model order reduction ; transient simulation ; grinding simulation

1. Introduction

Efficient modelling of machine structure dynamics is a crucial step towards a holistic process optimisation. This is valid especially for the stochastic grinding process, where potentially high process forces cause deformations and vibrations of the structure. Accurate modelling of these spatial micro-movements of the grinding machine allows a more precise prediction of the resulting workpiece geometry and process behaviour. Therefore a model of the structural dynamics of the grinding machine needs to be coupled with a model of the grinding process.

Coupling machine models with a grinding process model is often not successful, because of the high computational effort needed. According to Aurich et al.[1] two different groups of machine models can be distinguished: full and selective machine models. By the selective approach, only the machine parts with the highest impact on process stability are modelled in detail and the remaining parts are modelled approximatively. Only in full machine simulation, the whole machine structure is modelled. Further, full scale modelling is stated to be beneficial but expensive concerning the computational effort required. The usage of a new modelling strategy, based on reduced order FE-modelling is presented in this paper in order to reduce the computation time significantly, making full machine models applicable for grinding process simulation.

For this reason a grinding machine model was built in the modelling software MORe [2] and validated by an experimental modal analysis. The particularly used model order reduction (MOR) method, which is based on the projection of the FE-mass and -stiffness matrices into Krylov and modal subspaces, allows an efficient computation of the static and dynamic structural behaviour of the machine [3]. In a definable frequency range, the error caused by the MOR can be predicted. Using moving Fourier interfaces further allows to consider the position dependency of the structure dynamics [4].

Whereas this paper focuses on machine modelling only, also a variety of process models for a later coupling can be found in literature [5,6]. In [7] the choosing of two different grinding process models for high and low frequent contents are proposed.

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2. Experimental set-up

Within this paper the grinding machine test rig shown in *Fig. 1.* is analysed. The test rig is used for rail grinding experiments and therefore needs to be able to perform very high feed rates up to 480 m/min. It's main components are: a grinding unit (1) including the grinding wheel (2), the workpiece (3), a bridge (4), a laser distance sensor (5) and a clamping jaw (6). Using the notation of Schwerd [8] and the nomenclature t: tool, b: machine bed and w: workpiece, the configuration of the test rig can be described as: t-C1-B-Z-X-b-C2'-w.

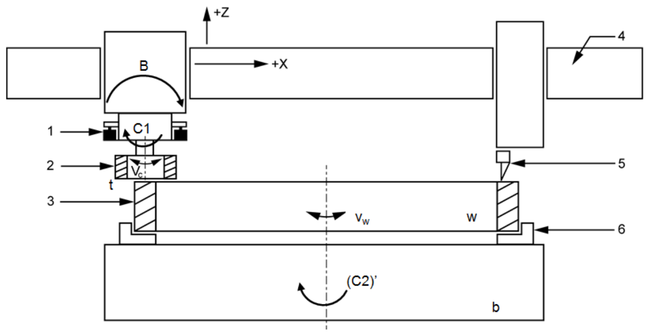

Fig. 1. Rail grinding test rig set-up, representing the vertical turning machine and the grinding spindle. All axes from the tool (t) to the work piece (w) are schematically shown.

3. Test rig modelling

Three steps are performed in order to develop a possibly low order but accurate dynamic and static structural test rig model: CAD modelling of the whole test rig, FE-modelling in ANSYS with mesh export and MOR in the MORe software.

3.1. CAD Modelling

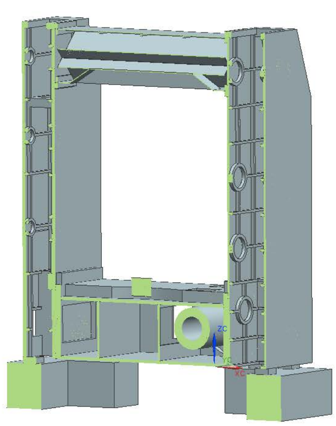

Fig. 2. Cross sectional view of the reconstructed CAD model of the test rig pillars.

As basis for the later FE-modelling CAD data of each machine component (moving body / axis) are derived. As no test rig CAD data was available from the manufacturer, it is reconstructed by measurements of the components. For the static and dynamic deviations, only the large machine parts are stated to be relevant. Therefore many small parts and geometrical features such as small screws, coolant and lubricant aggregates, single electric drives, small holes, chamfers and edge fillets are neglected. As an example CAD part, a cross sectional view trough the reconstructed ribbed test rig pillar is shown in *Fig. 2.*.

3.2. FE-modelling

In the second step a linear elastic FE-model of each test rig component is built. Each component has 6 free rigid body modes at 0 Hz, corresponding to the 3 translations and 3 rotations of a rigid body. Aluminium is used as material for the grinding wheel, because of its similar damping values to resin bonded corundum. Structural steel is further used as material for all the other test rig components.

The components are meshed in ANSYS®. The mesh is refined at locations of interest, in this case in the region around the grinding wheel. Counting all the components of the whole test rig, the full FE-model consists of 91'155 elements and 566'800 DOFs in total. The large model size makes transient simulation impossible.

3.3. Model Order Reduction (MOR)

The software framework MORe introduced in [3] and presented also in [4] is used for the model order reduction, as well as for the assembly of the overall mass and stiffness matrices. Combining modal condensation [9] with rational interpolation [10] leads to models with high and predictable static and dynamic accuracy in combination with minimal order. In the modal reduction all natural frequencies from the static value at 0 rad up to a definable frequency ω_r are considered. All higher modes are not represented by this reduced model.

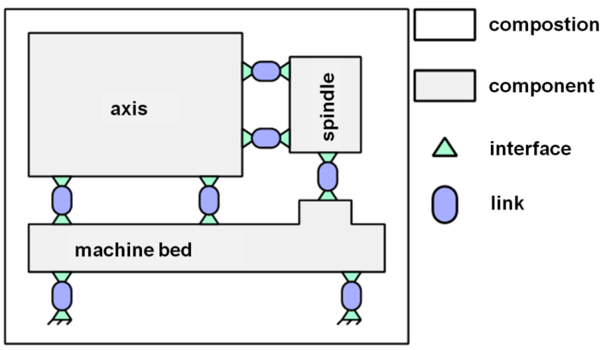

Fig. 3. MORe model elements - adopted from [3].

As schematically shown in *Fig. 3.* MORe models contain following elements:

- Components: Linear elastic reduced order FE-models of each structural component.
- Interfaces: Areas on the components where either a force shall be applied (input) or the position, velocity or acceleration shall be read out (output). The interfaces can be

stationary on a component or moving (Fourier-interface). Interface definition at the TCP and on the workpiece is needed for the interaction with a process model.
- Links: Links are connections between interfaces. They are used e.g. for linear elastic couplings (inputs) or relative interface motion estimation between two interfaces.
- Composition: Representation of the whole assembled reduced order FE-model with all defined in- and outputs and couplings.

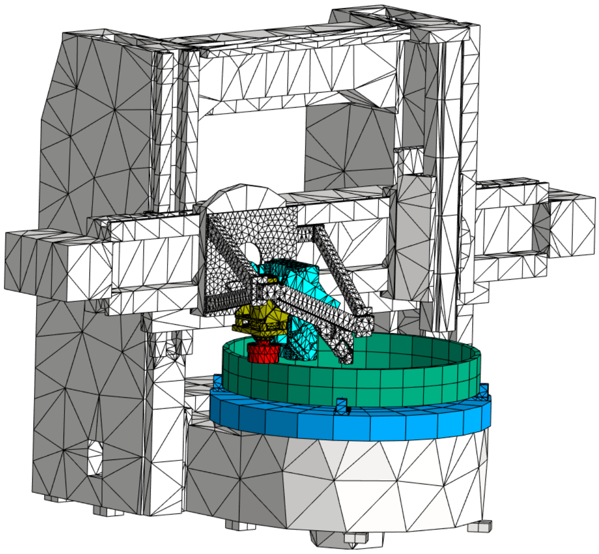

Fig. 4. Assembled test rig components inside MORe. The components are indicated as grey: machine support, red: spindle rotor, yellow: spindle stator, cyan: spindle support, blue: turn table and green: work piece.

Fig. 4. schematically shows the assembled test rig (composition) with its components in MORe. The spindle support is connected to the basement by six supported bearings. The spindle stator with the integrated force measuring platform is supported on the two pneumatic slides at four points with a low axial stiffness. The grinding spindle with the grinding wheel is supported by a fixed bearing at the bottom and by a floating bearing at the top. For the table support a friction bearing is used. The metal workpiece is clamped by four clamping jaws to the table.

In *Table 1.* the test rig model components together with their original and reduced order DOFs are shown. The modal reduction is performed up to a frequency of $f_r = \frac{\omega_r}{2\pi} = 500\,\text{Hz}$, leading to a reduction factor of over 900.

4. Model Validation

For the model identification and validation an experimental modal analysis (EMA) of the test rig is performed.

4.1. EMA measurement set-up and procedure

The machine structure is excited with a hammer impact, while measuring the impact force signal of the hammer pulse and the acceleration signals at defined positions on the structure. Using mode fitting algorithms, allowes identifying the resonance frequencies and the corresponding mode shapes.

Component	DOFs-original	DOFs-reduced
basement and traverse (rails, table, and pillars) - grey	341’577	277
machine table - blue	6’609	42
workpiece - green	1’890	177
spindle support - cyan	51’231	69
spindle stator - yellow	96’102	27
spindle rotor - red	9’027	21
Total	**566’800**	**613**

Table 1. Test rig FE-model components and their original and reduced model order (DOF numbers). Modal reduction limit frequency $f_r = 500\,\text{Hz}$.

For the mode fitting and visualisation the software ME’Scope is used. *Fig. 5.* shows the ME’Scope model with the 132 measurement points.

As the most important modes are supposed to be at low frequencies, the hammer is equipped with a rubber tip, leading to a low frequent structural excitation. The results confirm this assumption. The excitation point was chosen to be possibly close to the grinding process and close to the grinding wheel. The excitation was performed in x-,y- and z-directions.

4.2. EMA results

Overall 38 different modes an frequencies are found in the measurements, where 14 of them are identified as critical for the machining precision. Therefore these 14 critical modes have been used for the fit of the model parameters.

4.3. Model validation results

After the parameter identification, the compliance frequency response function (FRF) at important points are compared between model and measurement. *Fig. 6.* e.g. shows the comparison between the compliance FRFs calculated and measured directly on the grinding wheel.

5. Conclusion

In this paper a reduced order coupled FE-model of a full size high performance dry grinding test rig was investigated. Using model order reduction and novel coupling techniques, it was possible to derive a model with a total order below 613 DOFs. The low model order allows an efficient coupling of the full machine FE-model with an arbitrary process model, overcoming the limitation that only selective or significantly simplified machine models could be used before. Also transient simulation is possible with the order reduced model.

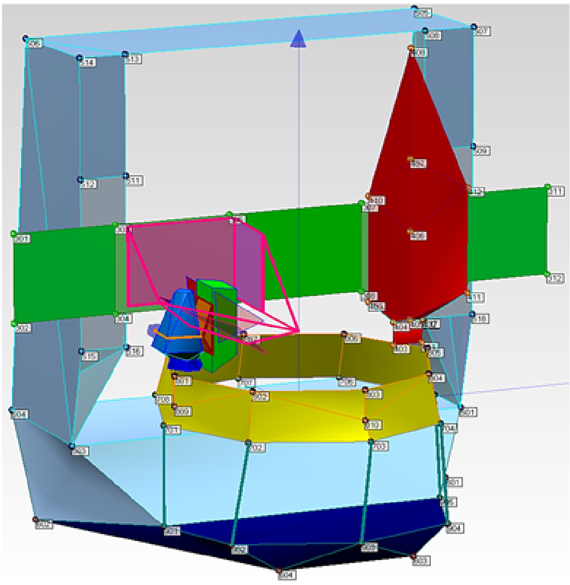

Fig. 5. ME'Scope [11] visualisation of the measurement points used for the EMA.

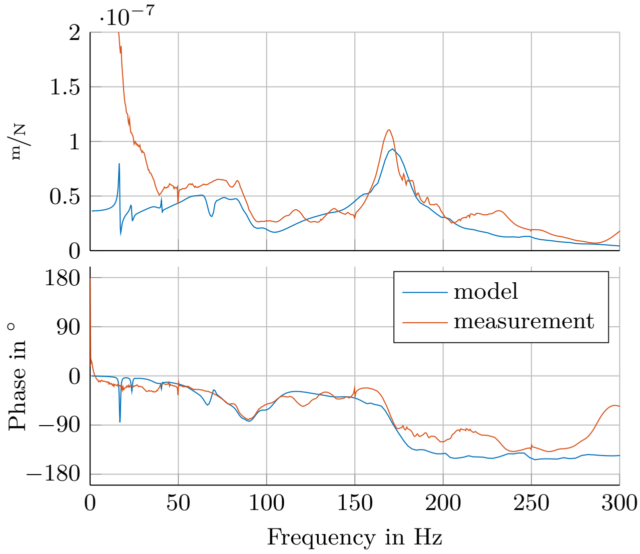

Fig. 6. Example compliance frequency response comparison between model (blue) and measurment (red) directly on the grinding wheel.

Estimating the model parameters and comparing the results of the model with an EMA showed good correlation in the interesting frequency range.

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