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METHODOLOGY FOR PREDICTING DYNAMIC BEHAVIOUR OF MACHINE TOOLS BASED ON A VIRTUAL MODEL

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Abstract: *This paper focuses on methodology for predicting dynamic behaviour of a machine tool based on a virtual model. The conventional approach based on a Finite Element Method is improved by including advanced modelling techniques, such as component mode synthesis, dynamic system identification and state-space transformation. Up to date, one of the available approaches to suppress the unstable behaviour during an operation is based on compensation of insufficient characteristics of the existing machine, however the goal is to optimize crucial parameters before the machine is manufactured. Presented method enable an effective prediction of unstable behaviour due to insufficient dynamic stiffness during an early stage of the product pre-production phase. In this paper, the theoretical foundation of virtual modelling of machine tools is set and a basic principle of the implemented techniques is discussed. Their application is a subject of an ongoing research.*

Keywords: Machine Tool, Dynamics, Virtual Model, Simulation, FEM.

1. Introduction

The aim of the present manufacturing industry is to produce parts in the most cost-effective way, matching required standards, and in the shortest time possible. The increasing product complexity makes testing and optimization of physical prototypes rather difficult. Therefore, the design process slowly shifts away from using economically ineffective physical prototypes and employs virtual prototyping to reduce the cost and time necessary for testing and optimization of the final product during the pre-production phase.

To increase the precision and effectivity of machine tools, various steps are being made to compensate geometric errors of the machine tool (Holub et al., 2015; Holub et al., 2016). However, it is also important to focus on describing dynamic behaviour during the operation, which might involve unstable phenomena, such as chatter vibrations. Up to date, description of the unstable behaviour has been mostly based on operational measurements of cutting forces and simplified analytical models (Siddhpura & Paurobally 2012). However, the goal is to predict it in the pre-production phase, where time-effective optimization of the machine tool takes place. For that reason, a complex virtual model of the machine tool is assembled (Altintas et al., 2005), that should substitute the real machine in the fields of interest (e.g. statics, dynamics etc.). The accuracy of predicting unstable operational behaviour is directly conditioned on the precision of the virtual model. Although the whole structure of the machine tool should be considered, current analytical models used for predicting chatter vibrations are usually concentrated into a 2D system of a workpiece and a tool (Yue et al., 2016). The dynamic stiffness is usually modelled as a spring-damper element, whose parameters are identified by impact hammer measurements with a relatively high estimation error. Due to the stochastic character of chatter, the inaccurate dynamic stiffness estimation may lead to incorrect results, which might distinctly differ from reality. The Moreover, the dynamic stiffness also changes as the tool moves along the path during operation, resulting

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in position-dependent stability of the cutting process (Law et al., 2013; Luo et al., 2014). Facts such as these should be considered when creating a virtual model of a machine tool.

2. Methods

The proposed methodology for creating a functional virtual model of a machine tool for predicting dynamic behaviour combines multiple modelling techniques. Firstly, Computer Aided Design (CAD) of the machine tool geometry is used, followed by flexible Multi-Body System (MBS) and Finite Element Method (FEM) modelling is used. The large order FEM model should be reduced using sub-structuring by component mode synthesis (CMS) (Craig et al., 2011). Secondly, transformation into state-space is made and transfer function (TF) is obtained (Fig. 1). Meanwhile, experimental data are subjected to dynamic system identification (Ljung 2007), resulting in estimated TF of the real system (Brezina et al., 2012). Finally, time and frequency domain responses are simulated and the virtual model is validated.

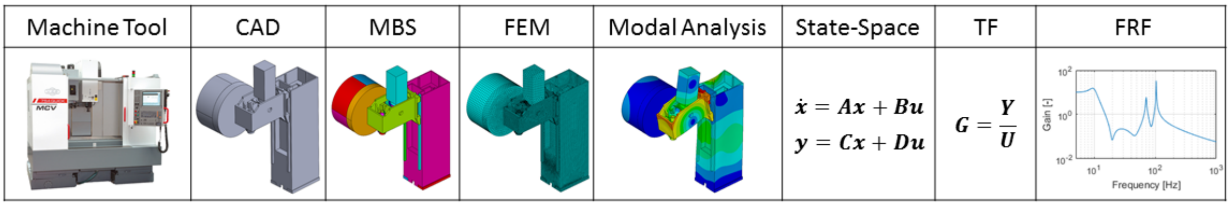

Fig. 1: Procedure of creating virtual model of a machine tool.

In the following part, highlighted steps in the modelling process as well as the thorough principle of the individual methods are described.

Finite Element Method (FEM)

In this step, CAD models are imported into ANSYS where the Finite Element Analysis (FEA) takes place. The quality of the mesh directly affects the accuracy of the results. The meshing process differs substantially for static and dynamic analyses; there are different rules for suitable types, shapes and dimensions of the elements. Based on these rules, the mesh should be kept as uniform as possible and emphasis should be put on creating regular mesh (i.e. mapped or swept) in locations where either joints or external loads are present. In contrast, the refinement around stress concentrators usual for static analyses should be avoided.

The individual flexible components of the MBS are connected by flexible connectors. In the concept of machine tools, three general types of flexible connectors are to be considered: bearings, linear guides and ball screws. Different modelling techniques are used for each of these connector types.

In FEM environment, they can be modelled with massless spring-damper elements. Before the elements can be added, coupling of the joint areas should be done. Coupling means that the areas that are functional for the contact are concentrated into one single point, which represents the displacement of the contact area in the characteristic direction. In other words, the contact area (i.e. all elements and their nodes) behaves in that particular direction as a single entity.

FE Model Order Reduction

Large-scale machine tools consisting of several parts result in large order FEM models. The computational time needed for dynamic analyses, such as modal, harmonic, and transient, depends exponentially on the amount of degrees of freedom (DOF). Therefore, it is necessary to reduce the amount of DOF to an acceptable amount by sub-structuring via a component mode synthesis (CMS) technique, which is frequently used in the field of dynamic analyses. An example of CMS may be the Craig-Bampton method, which considers the interface as fixed (Bampton et al., 1968).

State-Space Transformation

In this step, a FE model is transformed into state-space using modal transformation. It is used for time-effective simulations of behaviour of the structure in time or frequency domain using software like Matlab/Simulink and implement other systems that contribute to the behaviour during operation (e.g.

control systems). Depending on the number of input and output variables, we can represent the system either a Single-Input-Single-Output (SISO) or Multiple-Input-Multiple-Output (MIMO).

As a part of this step, state-space matrices are assembled with the use of a reduction method based on a modal transformation. The input and output vectors of the system have to be defined. In case of ANSYS, these are DOF in which either input or output variable (i.e. displacement, velocity, acceleration, and/or force) is required. Mathematical description in a state-space represents a Linear Time-Invariant (LTI) model of a machine tool (Hadas et al., 2012).

The transformation of state-space system into transfer function matrix is given by the equation (1), where $\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}, \boldsymbol{D}$ are state-space matrices and $\boldsymbol{I}$ is an identity matrix.

$$\boldsymbol{G}(s) = \frac{\boldsymbol{Y}(s)}{\boldsymbol{U}(s)} = \boldsymbol{C}(s\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{B} + \boldsymbol{D} \quad (1)$$

The transfer function directly represents the dynamic stiffness of the system, the main benefit is an easy implementation into a multi-domain co-simulation and its suitability for time and frequency domain response simulations.

Measurements of Static and Dynamic Parameters

Experiments and measurements have an important role in the virtual model creation. As mentioned above, many of the input parameters for the virtual model of machine tool are based on experiments. Furthermore, it is necessary to verify the validity of the virtual model by measuring key static and dynamic parameters and comparing them with simulated results. The sequence of necessary measurements follows the previous steps in virtual model assembly.

For static stiffness measurements, chosen location is subjected to a static force, generated by accurate hydraulic actuator. The applied force is measured with a force transducer with an implemented strain gauge. Deflection of the part can be measured with different sensors such as laser interferometer, capacitive displacement sensor, inductive displacement sensor, mechanical displacement gauge or contact linear gauge. This type of measurement might be also used for simulation of a cutting process to empirically determine conditions for stable operation (Knobloch et al., 2015).

For dynamic response measurement, a combination of an impact hammer and piezoelectric accelerometers are used. The accelerometer is mounted in the location that corresponds with the output of the virtual model. The impact hammer is used as a source of impact force in a location, which corresponds with the input of the virtual model. When dynamic behaviour during operation is measured, usually a set of accelerometers is used and based on their position on the structure, they are considered either as input or output. Due to complexity of the structure, it is crucial to avoid placing sensors into nodes of individual mode shapes (i.e. places, where the displacement is nearly zero). Proper sensor placement based on simulated modal analysis is recommended.

Dynamic System Identification

The response function of the real system is obtained via dynamic system identification (Ljung, 2007). This technique is a mathematical operation that for the given set of input and output data and a chosen mathematical model (e.g. transfer function, state-space system) quantifies the parameters of the model in such way that the response of the mathematical model corresponds with the response determined by the measurement. However, the order of the mathematical model should be set with care, as higher order does not guarantee better accuracy and may lead to controversial results. Various least-squares methods for minimizing the difference between the two responses can be used.

Virtual Model Validation

Although several theoretical approaches are available for the verification of the dynamic response of the virtual model, their suitability is based on the type of measured data. If the input data have a stochastic character (e.g. vibrations of a base during operation), the corresponding response of the virtual model would be obtained only if it is excited by the same signal. That would lead to a transient analysis of a structural FEM model, which is very time-consuming and may lead to problems with a convergence.

The proposed approach is based on an impulse response of two transfer function matrices, where the first one represents the virtual model and the second one represents the real system. They are compared based on an impulse response in frequency domain, also called Frequency Response Function (FRF). Furthermore, the FRF may be used for adjustments of some fuzzy parameters (e.g. damping) of the virtual model.

3. Conclusions

As the complexity of the products and the demands for machine tool precision are increasing, constant improvement of machining process is required. The structure of a machine tool is being subjected to various types of optimization and steps to compensate certain undesired deviations are being made. The aim of this study is to propose an approach based on a virtual model of the machine tool that would be used for predicting its dynamic properties in the pre-production phase. Presented methods utilize the benefits of a state-space system, such as direct transformation into a transfer function and its use for time-effective response simulations. Implementation of experimental data is done via dynamic system identification technique, which enables accurate validation of the virtual model and adjustments of its fuzzy parameters. However, some of these methods have not been originally used for virtual modelling of machine tools and further development is necessary. The application of proposed techniques for a real machine tool is a subject of an ongoing research.

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