Design Improvement of Machine Tools by Integration of Cutting Process Model into Finite Element Analysis

Gerhard KEHL
University of Applied Sciences, Faculty of Engineering Management
Flandernstr. 101, D-73732 Esslingen, GERMANY
gerhard.kehl@hs-esslingen.de

Abstract

In recent years, the use of simulation-aided methods has become well-established in machine tool development. Structural dynamics, for instance, are evaluated and optimized on the basis of simulated compliance frequency responses. This allows to compare alternative conceptual variants, however, it does not allow authoritative statements to be made in terms of process stability of specific cutting processes. To simulate the dynamic overall behavior and thus answer the crucial question "Will it cut or won't it?", it is necessary to couple machine model and process model. Precondition for this are confirmed machine and process models. The model of a machining centre, for instance, has to map the mechanical structure with the controlled drives and describe in detail the spindle system. The process model based on analytic model conceptions should be able to map all relevant effects of machining processes like turning, milling or drilling.

This article discusses the finite element (FE) modeling and simulation of machine tools from a machine tool manufacturers perspective as well as the stability analysis. The stability analysis is carried out in two different ways: By coupling of machine and analytical process model through compliance frequency responses and by FE simulation with integrated cutting process model.

Keywords: FE simulation, design, machine tool, cutting process, process stability, regenerative chatter

1 Introduction

A central field of activity in the development of a new machining centre before its launch into the market is the investigation and optimization of its process behavior, especially process stability and workpiece surface quality influenced by the regenerative chatter mechanism (**Fig. 1**).

Already during the design process some machine tool manufacturers apply methods of experiment and above all progressively simulation on digital models to investigate the expected process stability and achievable cutting depth. For this purpose, the focus is on the dynamic characteristics of the overall system resulting from the interaction of all relevant components involved (machine tool + cutting tool + fixture + workpiece) and the machining process under the influence of control technology.

Resulting from dynamic wave-on-wave cutting (**Fig. 2 left**) due to oscillating tool and/or workpiece regenerative chatter plays the key role in mechanisms limiting the productivity and leading to non-recallable portion of installed cutting performance. As a consequence the design goal is to noticeably expand the stable cutting area in stability charts of reference cutting processes (**Fig. 2 right**) [1].

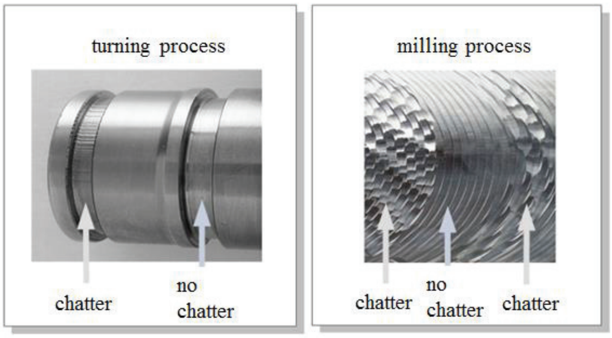

Fig. 1 Turning and milling workpiece surface quality with and without regenerative chatter

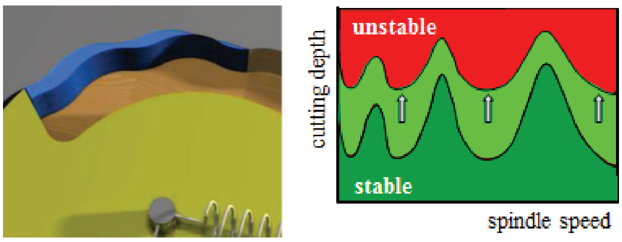

Fig. 2 Wave-on-wave cutting / design goal

2 Modeling and simulation of machine tool

In terms of the development process chain, structure-dynamic machine simulation differentiates between examination of individual components and examination of the overall system. As a result of dynamic process forces acting on tool and workpiece an important and established outcome of such examinations are compliance frequency responses.

Examinations of components are useful, if they can be isolated successfully and loads can be transferred to a model in a realistic way. However, in most cases the validity of such examinations is limited to a relative comparison between constructive variants.

Typical applications for component examinations are the cutting units of machining centers (comprising slide, main drive, milling spindle). **Figure 3** shows a direct driven machining unit with hollow-shaft motor (left) and a high-torque machining unit with spur gearing (right) together with simulated amplitudes of compliance frequency responses allowing evaluation and optimization during the design process.

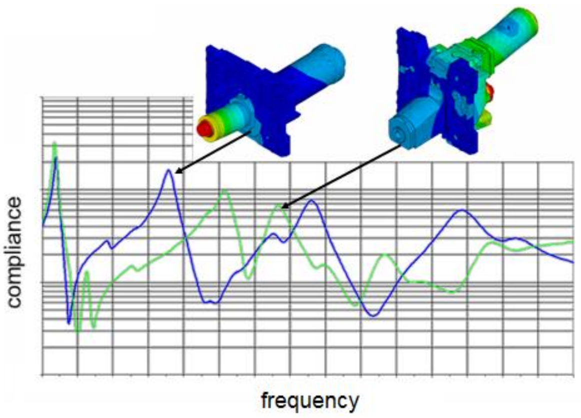

Fig. 3 Compliance responses of cutting units

Examinations of this kind are purposely not conducted on the complete machine model to permit evaluation on component-level.

Detailed 3D CAD models are required already for component examination and a large number of details (spindle bearing, bolted joints, couplings) have to be included for FE modeling.

To begin with, topology optimization of major structural parts (guide slide, spindle neck) is conducted as an integral part of component development. Additionally, sensitivity of coupling points (spindle bearing, couplings, clamping system) can be analyzed and subsequently optimized [2].

Examination of the complete system (if necessary with tool, fixture and workpiece) is useful to obtain more precise responses to be used for further investigations. By means of the software used for modeling the machining process (separate or FEA integrated), the compliance frequency responses of the virtual machine allow to determine in how far a specific operation can be performed under stable conditions and which process conditions may cause instability.

Complete machine models are also used to examine axis dynamics, since the relevant parameters for the axis dynamics of the machine tool (control parameters, jerk, pre-control) cannot be indefinitely increased, but are limited by instabilities of the machine in terms of reference and disturbance response. Without simulations of this kind it is not possible to make predictions about the expected productivity of the machine.

Experience has shown that the modeling of drive trains in the controlled system is one of the greatest challenges in conjunction with the complete machine model. For modeling drive trains incorporating ball screw drives or rack and pinion drives, typically a spatial oscillator chain with translatory and/or rotary degrees of freedom is employed. To ensure correct representation of natural modes including bending, the ball screw is mapped as a volume model. All axial and radial bearings of the ball screw drive are included in the model. To ensure high efficiency in model generation the models of the ball screw drives can be generated fully automatically via macros.

Examination of the reference and disturbance response in the frequency and time domain is made possible by a control toolbox (for example in ANSYS [3]). This additional macro allows the implementation of machine tool usual control structures like P-position-PI-velocity feedback control for each axis integrated into FEA, whereas mechatronic simulations on large models require prior model reduction by component mode synthesis (CMS). Typical criteria evaluated in such simulations regarding the dynamics of machine tools are:

<u>Frequency domain</u>

- reference frequency responses of the velocity and position control loop
- compliance frequency responses relative between tool and workpiece.

<u>Time domain</u>

- behavior for jerk-limited positioning
- circularity behavior
- behavior in case of disturbance force jumps.

Compared to frequently used co-simulations between FEA and Matlab to represent mechatronic systems, the method of integrated FE modeling and simulation has clear advantages in terms of

- integration into the development process chain
- applicability for complex systems with coupled axes
- flexibility regarding alternative control structures
- 3D visualization of results.

An advantage for a machine tool manufacturer creating the models as mentioned is that many of the machines are very similar in terms of axis configuration, components used in drives, linear guideways, structural parts and foundation elements. Main differences in machine design often are just based on:

- axis strokes
- cutting units (different speeds and torques)
- work piece flow (integrated pallet changer or direct loading).

A classical problem of FE modeling of machine tools is the damping. Since damping coefficients of components are as yet incomplete, local damping approaches are currently used only for foundation elements, linear guideways, bearings, ball screws, couplings e.g. The data base is currently being completed for selected machine model ranges in cooperation with component manufacturers. However, due to the complexity of the damping mechanisms, results cannot be expected in the short run. As a result, application of machine simulation in everyday practice can unfortunately not yet work without the use of modal damping whose correlation with the design of the machine is unknown. At present detailed FE models usually allocate not more than 50% of the system damping in local damping effects, remaining the rest in modal damping. Further improvement can be expected with incorporated bolted, welded and glued connections in the FE model.

3 Coupling of machine and process by compliance frequency response

One fundamental possibility for coupling the machine tool with an analytical process model (e.g. Cutpro [4]) are the compliance frequency responses gained from simulations on the FEA machine model (or from experiments on the already existing real machine).

This is essential, because solutions linking process simulation with FEA software packages directly are as yet commercially unavailable.

A bidirectional interface initiated by the BMBF (German Federal Ministry of Education and Research) in the project "SimCAT" automates export of the force-time characteristic from the analytical process model for utilization in FEA as well as import of the compliance frequency responses determined in FEA for direct application in the analytical process model. **Fig. 4** therefor shows an exemplary result by means of a stability chart. The chart also shows the chatter frequencies determined by simulation and three experimental samples of process stability.

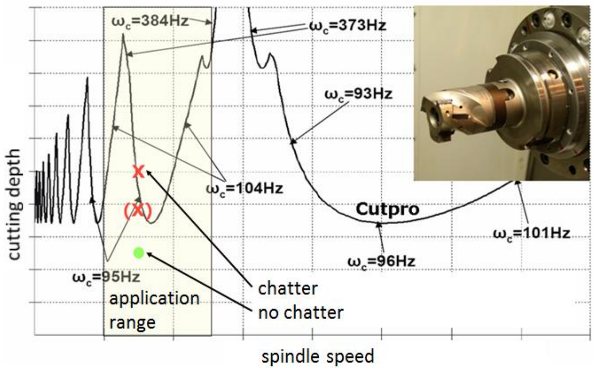

Fig. 4 Predicted stability chart on the basis of compliance responses from FE simulation

The implemented interface also allows conducting sensitivity analyses (dependency of stability charts on parameters of the machine model) and running optimization loops with the aim to improve process stability by means of topology and parameter optimization on the machine tool [2].

Applicability of the mentioned workflow for wide areas of cutting technology is guaranteed only if the forecasting capability of this simulation is substantially verifiable in everyday practice.

For this purpose stability charts have been prepared for selected milling processes over the tool speed range and compared to each other. Comparisons are drawn for

I stability charts from experimental milling trials

II stability charts from the analytical process model on the basis of compliance frequency responses determined from experiments on already existing machines.

In case I experimental evaluation of chatter was made on the basis of criteria of acceleration amplitudes and also by means of acoustic evaluation. In contrast to this stability charts in case II are prepared as follows:

- The relative compliance frequency responses of the overall system are measured by means of hammer or shaker excitation and subsequently represented by oscillator models [1].
- The cutting force coefficients of each process are determined by means of a force measuring platform (several cutting depths).
- Stability charts for the reference processes are analytically calculated.

Stability charts obtained in I and II are compared in **Fig. 5** by the example of aluminum HSC-machining showing a close agreement. The deviations at low spindle speed can be explained by missing measuring points.

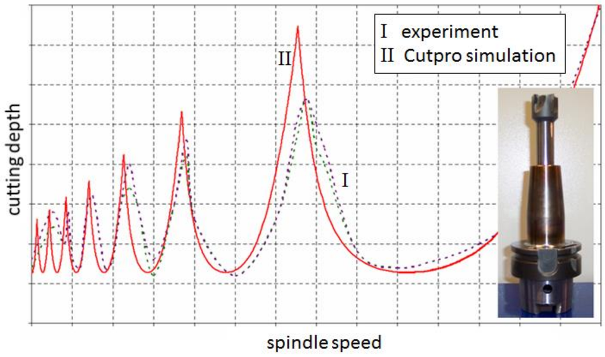

Fig. 5 High speed cutting of AlMg4,5Mn (Heller MCi 16.2, PCD face milling cutter ∅24mm, z = 4)

However, in contrast to this, further experience of high performance cutting (HPC) in the range of $k > 5$ with

k = chatter frequency / edge engagement frequency

showed much less agreement of curves. In the case of insufficient forecasting reliability, it is only possible to derive the following statements from II:

- approx. minimum depth of cut (basic level)
- relevant chatter frequency.

The negative experience in forecasting the stability and cutting depth of HPC machining processes gained so far indicates that there are obviously effects that the applied process model does not account for [4]. Explainations for imperfectness in the forecasting capability have been sought for and agreed to be caused by process damping [5]. Sufficient solutions for modeling those damping effects are just on the same level as for the damping in the machine model itself.

After analysis of the applied process model, some effects were discussed that will be systematically examined by way of experiment and simulation in terms of their relevance for determining process stability. Although the list of effects of unknown impact is certainly incomplete, a classification can be made in

<u>system behavior</u>

- inconstant spindle speed
- torsional vibrations of tool or spindle

- change of compliance responses under operational condition
- imbalance excitation.

process behavior
- material behavior depending on cutting speed
- notable process damping in cases of $k > 5$.

4 Stability analysis by FE simulation with integrated cutting process

Apart from the listed difficulties a further development has been initiated to directly allow the comparison of alternative conceptual variants regarding the process stability during the design process. For this purpose analytical process models for turning and milling have been implemented for use in the FEA software packages ANSYS and PERMAS during the BMBF project “VispaB”.

Extensive cutting tests have been realized to attain sufficient information on cutting force coefficients and suitable stability criteria. The following parameters are necessary to describe stationary cutting conditions for e.g. groove milling and to carry out an integated cutting process stability calculation [6]:
- tool geometry: number of teeth, tooth pitch angle
- workpiece material
- cutting force model (linear or exponential)
- stability criteria
- cutting depth, tooth feed, spindle speed (constant speed or sinusoidal speed variation)
- number of analysed tool rotations.

Figure 6 shows the applied method for a H5000 type horizontal machining centre of Gebr. Heller Maschinenfabrik GmbH, Nürtingen.

To gain all data for a complete stability chart of a reference milling process different loops with basically transient sub-simulations have to be conducted:
- increasing tool rotation
- different cutting depth
- different spindle speed.

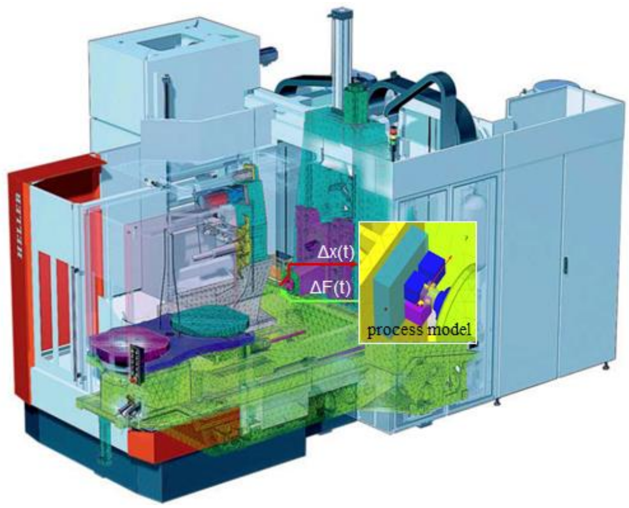

Fig. 6 FE simulation of Heller H5000 with integrated cutting process for the prediction of stability charts

Figure 7 shows a stability chart gained from FE simulation with integrated cutting process using the time-dependent chip-thickness modulation (**Fig. 2** left) determined by spatial movement of tool centre and workpiece as a stability criteria.

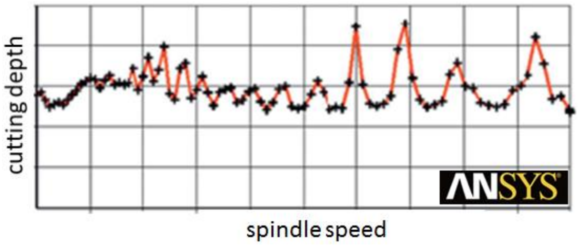

Fig. 7 Stability chart gained from FE simulation with integrated cutting process

This method has entered the development process chain of a few german machine tool manufacturers to evaluate machine designs with respect to process stability and to compare alternative conceptual variants in achievable cutting depth before manufacturing any part of a new machine. Actual experiences are rare but will be expected after ongoing product design processes are concluded.

5 Conclusions

However, in summary the evaluation of process stability during the development process of machine tools is of high importance for fast introduction of new products into the market and for less design expenses. Furthermore it supplies novel opportunities to reach the machine tool users expectations in higher productivity.

References

[1] T. Surmann, D. Biermann, G. Kehl, “Oscillator Model of Machine Tools for the Simulation of Self Excited Vibrations in Machining Processes”, Proceedings of the 1st International Conference on Process Machine Interactions, (2008), Hannover.

[2] A. Broos, J. Will, A. Melchinger, G. Kehl, S. Röck, “Sensitivitätsstudien und Parameteroptimierung bei der virtuellen Produktentwicklung von Werkzeugmaschinen“ (Sensitivity Study and Parameter Optimization in the Virtual Product Development of Machine Tools), 3. Weimarer Optimierungs- und Stochastiktage (2006), Weimar.

[3] R. Alber, “Systemsimulation in ANSYS integriert” (ANSYS Integrated Systems Simulation), CADFEM-Infoplaner, No. 2, (2006), pp. 22-23.

[4] Y. Altintas, M. Weck, Chatter Stability of Metal Cutting and Grinding”, Annals of CIRP, Key Note Paper of STC-M, (2004), Vol. 53/2, pp. 619-642.

[5] L.T. Tunc, E. Budak, “Identification and Modeling of Process Damping in Milling”, Journal of Manufacturing Science and Engineering 135(2), (2013).

[6] R. Rauch, “Damit es weniger rattert“ (For less Chatter), CADFEM-Infoplaner, No. 1, (2012), pp. 16-19.

Received on August 20, 2013
Accepted on February 3, 20