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FE-SIMULATION OF MACHINE TOOL WITH INTEGRATED CUTTING PROCESS TO ANSWER THE CRUCIAL QUESTION: "WILL IT CUT OR WON'T IT ?"

Gerhard KEHL[1]

[1)] Prof. Dr.-Ing., University of Applied Sciences, Faculty of Engineering Management, Esslingen, Germany

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 machining processes. To simulate the dynamic overall behavior and thus answer the above-mentioned question, it is necessary to couple machine model and process model. Precondition for this are qualified machine and process models. The machine model of a machining centre must on the one hand map the mechanical structure with the integrated drives and controls, and on the other hand 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 following points from a machine tool manufacturers perspective: FE modeling and simulation of the machine tool; coupling of machine model and process model by compliance frequency response; stability analysis by FE simulation with integrated cutting process model; experiences and limitations regarding the forecasting capability of this simulation; future steps for further development.*

Key words: *FE simulation, design, machine tool, cutting process, process stability, cutting depth, 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].

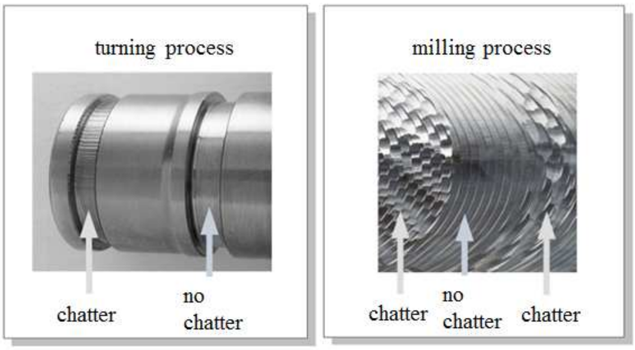

Fig. 1. Turning and milling workpiece surface quality with and without regenerative chatter.

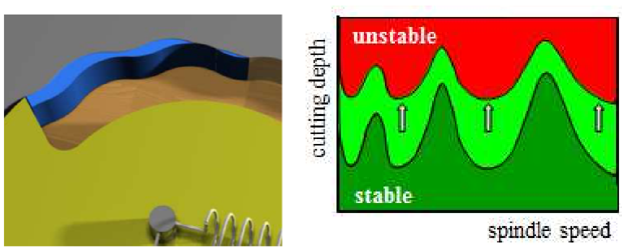

Fig. 2. Wave-on-wave cutting / design goal in stability chart.

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

Corresponding author: Prof. Dr.-Ing. Gerhard Kehl
Hochschule Esslingen, Flandernstr. 101, D-73732 Esslingen
Tel.: 0049-711-397-4309
E-mail address: *gerhard.kehl@hs-esslingen.de*

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 components can be successfully isolated and static and dynamic load types 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 (> 1000 Nm) with spur gearing (right) together with simulated amplitudes of compliance frequency responses allowing evaluation and optimization during the design process. 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 [2]. Additionally, sensitivity of coupling points (spindle bearing, couplings, clamping system) can be analyzed and subsequently optimized [3].

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.

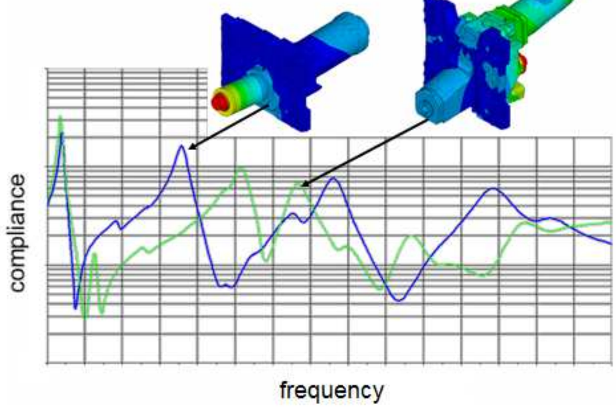

Fig. 3. Cutting units and compliance frequency responses.

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 [4]). 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:

Frequency domain

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

Time domain

- 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;
- 3D visualization of results;
- flexibility regarding alternative control structures.

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 components and foundation parts. Main differences in design often are:

- axes strokes;
- cutting units;
- work piece flow (integrated pallet changer or direct loading).

A classic problem of FE modeling of machine tools is the damping. Since damping coefficients are as yet incomplete, local damping approaches are currently used only for foundation elements, linear guideways, bearings, ball screws and viscous couplings. 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 do without the use of modal damping whose correlation with the design of the machine is difficult to interpret. 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 main interface for coupling the machine tool with an analytical process model is the compliance frequency response gained from simulations on the FEA machine model (or from experiments on the already existing real machine).

In order to obtain statements allowing for prognoses regarding process stability of reference processes, the FEA machine model needs to be coupled e.g. to Cutpro [5], since solutions linking process simulation and FEA software package are as yet commercially unavailable.

A bidirectional interface implemented by the BMBF (Federal Ministry of Education and Research) for the “SimCAT” project automates export of the force-time characteristic from the analytic 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 shows the result of a coupling by means of a stability chart. The chart also shows the chatter frequencies determined by simulation and three experimental samples of process stability.

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 tools [3].

Applicability of the coupled models (FEA and process) for wide areas of cutting technology is only guaranteed when the forecasting capability of the process simulation is substantially verifiable.

4. STABILITY ANALYSIS BY FE-SIMULATION WITH INTEGRATED CUTTING PROCESS

A further development has been initiated to directly allow the comparison of alternative conceptual variants during the design process. For this purpose analytical process models for turning and milling have been integrated in the FEA software packages ANSYS and PERMAS during the funded research 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]:

- cutting process: turning or milling;
- 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) ;
- sampling time, number of analysed tool rotations.

Fig. 5 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 cutting process different loops with basically transient sub-simulations have to be conducted:

- increasing tool rotation;
- different cutting depth;
- different spindle speed.

Fig. 6 shows a stability chart gained from FE simulation with integrated cutting process using the time-dependant chip-thickness modulation determined by spatial movement of tool centre and workpiece as a stability criteria.

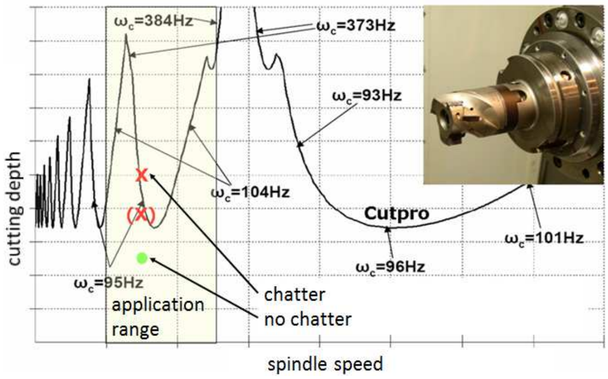

Fig. 4. Predicted stability chart on the basis of compliance frequency responses from FEA simulation.

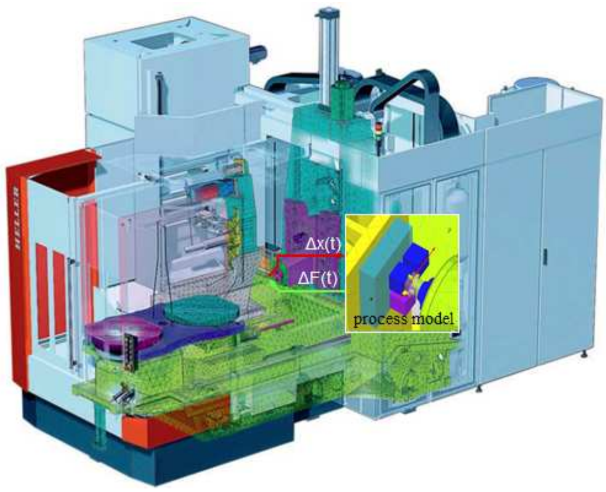

Fig. 5. FE simulation of Heller H5000 with integrated cutting process for the prediction of stability charts.

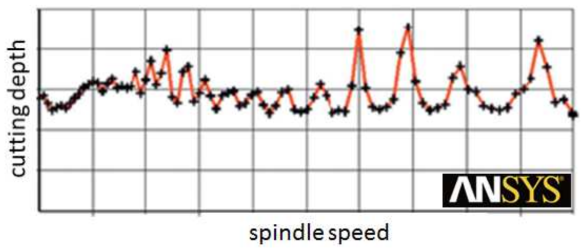

Fig. 6. Stability chart gained from FE simulation with integrated cutting process.

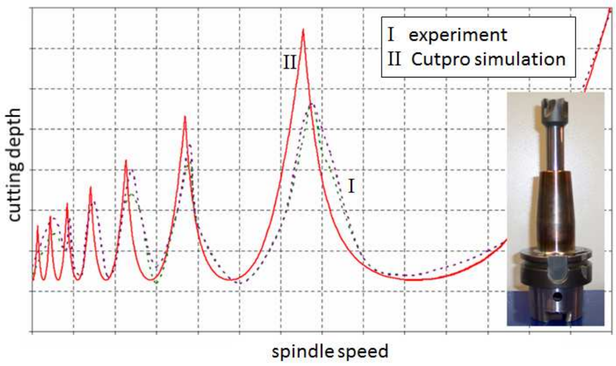

Fig. 7. High speed cutting of aluminum (Heller MCi 16.2 using PCD face milling cutter ∅24mm, $z = 4$, AlMg4.5Mn, grooves).

This method has entered the development process chain of some machine tool manufacturers to evaluate `1machine designs with respect to process stability and to compare alternative conceptual variants before manufacturing any part of a new machine. Actual experiences are rare but will be expected after ongoing product design processes are concluded.

5. FORECASTING CAPABILITY OF CUTTING PROCESS SIMULATION

Stability charts are prepared for selected reference processes over the tool speed range and compared to each other. Compared are

I stability charts from experimental milling trials

II stability charts from the analytic process model (Cutpro) on the basis of compliance frequency responses determined by experiment.

Stability charts on the basis of the analytic process model are prepared as follows:

- The relative compliance frequency responses of the machine with cutting tool, fixture and workpiece are measured by means of hammer or shaker excitation.
- 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 (incl. reproduction of compliance frequency responses, input of process and geometry data) are prepared.

Stability charts obtained in I and II are compared in Fig. 7 by the example of aluminum HSC-machining showing a close agreement. In case I, experimental evaluation of chatter was made on the basis of criteria of acceleration amplitudes and also by means of acoustic evaluation. The deviations at low spindle speed can be explained by missing measuring points.

However, analysis of high performance cutting (HPC) in the range of $k = 5\ldots8$ 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. depth of basic cut (level)
- relevant chatter frequency.

Due to the process characteristics of HSC, the negative experience gained so far indicates that there are obviously effects that the applied process model does not account for [5]. Explainations for imperfectness in the forecasting capability have been sought for and agreed to be caused by process damping [7].

6. CONCLUSIONS AND FUTURE STEPS

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 *system behavior*

- rotary degrees of freedom on the cutting edge, torsional vibrations of the spindle, inconstant spindle speed;
- change of dynamic compliances in rotational condition;
- imbalance excitation;

and *process behavior*

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

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. Furthermore it supplies novel opportunities to reach the customers expectations in higher productivity.

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