Simulation in design of high performance machine tools

HELLER

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1. Introduktion

Machine tools have been constructed and used for industrial applications for more than 100 years. Today, almost 100 large-sized companies and a number of smaller, specialized machine construction firms produce solutions for cutting applications all around the globe. Given these parameters, conventional innovations, introduced through the very latest technologies, would not actually seem possible. The number of revolutionary solutions with long-term effects is highly transparent in the development history of the machine tool. The introduction of NC technology and the introduction of solutions for multi-axis machining, e.g. 5-axis machining operations, are two examples. Consequently, development efforts are tending to focus on continuously improving product features for the customer. In nature, we would talk about evolutionary steps.

Over the last 30 years, the evolution of the machine tool has been characterised in particular by a productivity increase in the sense of faster solutions with shorter non-productive times. Although essential modifications to guides and bearings have helped make the axes or the tool spindles more dynamic, characteristics such as damping, for example, have often been reduced, contributing significantly to high stability in the machining process. Even given the current lively discussions regarding the efficient use of machines, it is astonishing to note that installed spindle capacities cannot always be converted into a corresponding machining capacity.

The combination of know-how and the latest simulation methods for development and re-coupling using distinct test series enables unprecedented torques and capacities to be installed and used, even in 5-axis machining operations on HSK 63 milling machines. For over a good decade, HELLER, supported by several research projects, has been expanding and intensifying FEM simulation such that every overall machine and every assembly in the development phase can be repeatedly "screened" and iteratively optimized through simulation.

The article uses a new 5-axis machine to demonstrate the methods and processes that are applied in development. It focuses on how overarching research activities enable the stability of the machining process to be simulated as part of the FEM environment. The use of these new methods in the development process considerably reduces expenditure in the test phase. Even the first prototype of the machine achieves cutting performance characteristics that have never been known before in this class.

For HELLER, innovation is the evolutionary advancement of the product characteristics of machine tools using new simulation methods, developed and evaluated in research projects in cooperation with universities and industrial partners.

2. The HELLER approach – Machining Competence in the global Market

HELLER supplies a wide range of industry sectors with machine tools and manufacturing processes. Therefore the customers' needs are addressed very specifically. For instance an automotive manufacturer has other individual requirements than a company that produces aerospace products and an energy supplier has another focus than a medical technology manufacturer. Moreover the customer's global location has to be considered, as usually the degree of automation is higher in countries with higher wages.

With its century-old experience HELLER's concern is to maximize the customer's perceived value of the products and services which are productivity, flexibility, cutting performance, automation as well as high competence in materials, processes and projects.

HELLER provides solutions for all requirements in a modern manufacturing plant. A maximum of productivity and optimal reliability are addressed with horizontal machining centers. HELLER's five-axis machining centers provide a maximum of flexibility synchronously with an outstanding cutting performance. The palette handling automation or the automation with robots ensure an optimum production process and maximize the added value.

3. Design Optimization

The global approach of HELLER is to be a synonym of high performance metal cutting, maximum productivity, high reliability and customer- orientated configuration. Regarding the feature of high performance cutting

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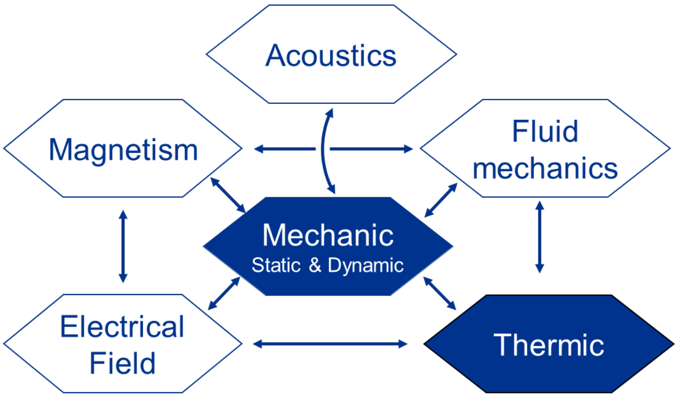
HELLER decided to invest in newest methods in design (method of finite elements) and testing (modal analysis and dynamic testing) over a decade ago. Since this investment the methodologies are continuously developed in cooperation with industrial partners, scientific institutes and universities.

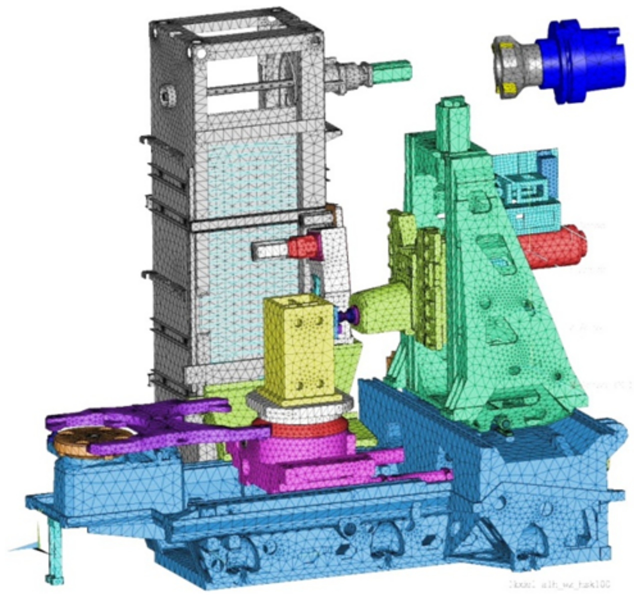


A wide range of physical simulation fields and even their influence on each other is covered by the Finite Element Method (see figure). However, HELLER focuses on two main fields which are structural and thermal simulations.

Machine tools are always exposed to temperature changes, e.g. due to day-night or due to seasonal bulk temperature changes. But also the machine tool itself as a heat source influences the temperature field. Thermal simulation results are temperature fields which allow calculating thermal strains. Thermal expansions can reduce the machining accuracy as they can cause unwanted relative displacements between tool and workpiece. It is still a challenge to compensate these effects by the numeric control system.

To increase the product quality and to meet the required technical requirements structural analyses are carried out with the Finite Element Method (FE, FEM). Here the software ANSYS is applied which is supplemented by a long list of HELLER-written macros.

Most FE-simulation models are built up based on 3D-CAD geometry and completed with specific properties and parameters. A remarkable feature is, that the simulation models represent entire machine tools. Here all machine parts of considerable relevance for the dynamical behavior are included and tied together by hundreds of local spring and damping elements.



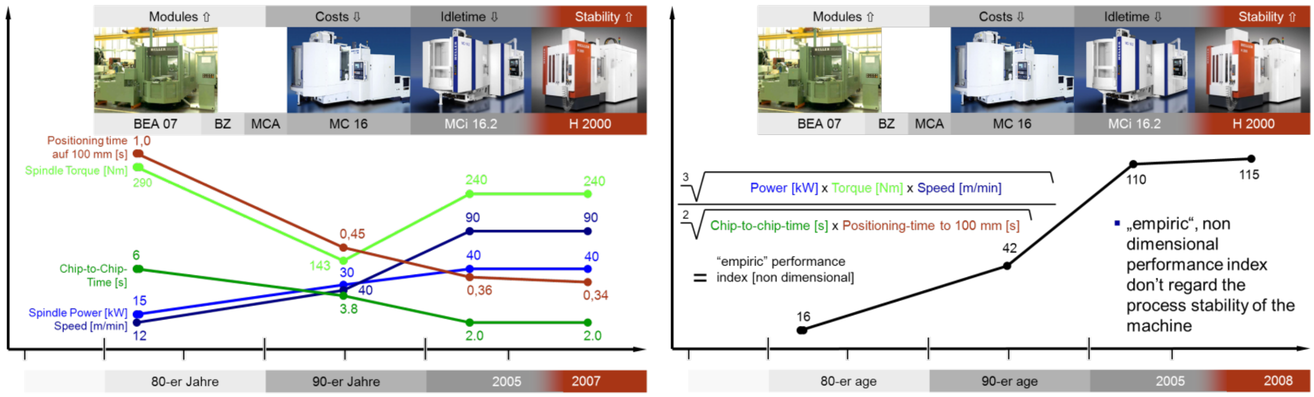
The parameters of these discrete elements are based on measurements and experience-based estimations. In cooperation with universities in Germany and based on projects financed direct by industrial partners or founded by the German ministry of science different projects were attended to collect these specific parameters, e. g. the stiffness and damping coefficients for linear guides, bearings, leveling elements.

Structural simulations include static and dynamic force- or displacement-driven deformations. The results are evaluated with respect to static compliance, accuracy, oscillation behavior and in-service-strength-durability. Weak regions in the machine structure can be identified and eliminated at an early design stage, where changes remain quite cheap. Overall the FE-based structural simulations help to master the balancing act between those properties needed for fast positioning movements and those needed for a high cutting performance.

Static topology optimization is carried out for machine parts to obtain an optimum relation between material investment and structural stiffness. The iterative topology optimization process leads to an advantageous material distribution within a predefined design space. The mathematical background is to minimize the overall deformation energy with respect to a given configuration of loads and boundary conditions. It is remarkable, that topology optimization results often resemble on structures that can be found in nature. Moreover these results often lead to the conclusion, that traditionally developed machine structures are more complicated than necessary.

4. Results to Product Features

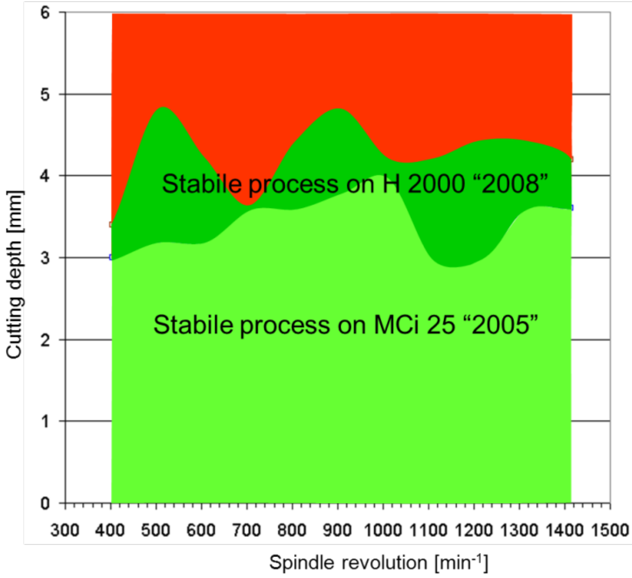
Due to an empiric, not scientific, performance index the machining performance has increased by more than 700% since the 1980s. The figure relates the cube root of the product of spindle performance, spindle torque and rapid feed speed to the square root of the product of chip-to-chip-time and positioning time for a distance of 100 mm.



However, in this figures limitations due to instable cutting processes are neglected. This is imported to understand, because otherwise it is inapprehensible, that there seemed to be no evaluation in the classical technical data of a machining center, like spindle torque and power, chip-to-chip-time, etc. in the last ten years. Additional items, normally not documented in marketing oriented brochures, are necessary to explain the machine ability and the evaluation.

HELLER's machines are designed to avoid cutting instabilities (chattering) as far as possible, because chattering leads to reduced workpiece quality, increased tool wear, tool fraction, machine damage and overall to a loss of productivity. Process stability is traditionally expressed by a so-called stability diagram, where the cutting depth is displayed over the spindle revolution.

- Material:
  - C45
- Tool:
  - 75°- cutting head
  - Z = 6
  - Ø 63 mm
  - L = 140 mm,
  - f_z = 0,15 mm
  - a_e = 54 mm



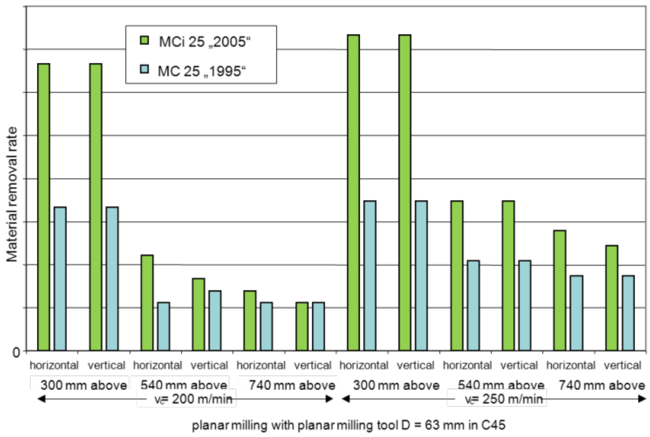
Here the curves represent the border between the stable and instable domains i.e. the curve shows the maximum cutting depth, which still lead to a stable cutting process. It is important to mention, that stability curves are very specific, as they strongly depend on the machining system and its stroke position, the tool's geometry and on the work piece's geometry, material and fixation. The figure demonstrates also the development steps in machine tool design and performance.

The curve defined between the green and the dark green areas describe the process stability of on older machine type (offered to the market in 2005). All machining operations, which can be located in the green and dark green area are stabile on the machine, presented to the market in 2008. So, with the new designed type the process stability can increased up to 60%. The increase in productivity can be reached by using the experience of design experts and newest simulation technologies, developed in research projects founded by the german government. However it is necessary to understand the history of this optimization to valuing the results of the evaluation.

5. Process Stability Prediction – History of Research Work

Dynamical FEM simulations can be extended to predict the stability of predefined cutting processes. The results contribute directly to machine structure optimizations.

Using the "known" technology of topology optimization for a machine column (together with some other improvements) the machining performance can be increased up to 100% regarding the step from 1995 to 2005.

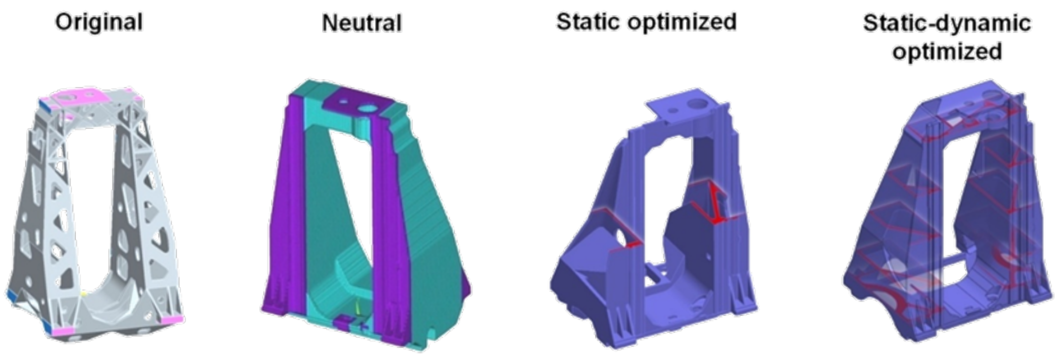


The figure compares the process stability, defined by the chip removal rate, of a machine offered to the market in 1995 to the redesigned machine of 2005. As mentioned above a lot of parameters influence the process stability of a machine. The figure shows also, that the chip removal rate can be increased, if the spindle of a horizontal machining center is moved to a lower vertical position in the working area.

An additional consequence of the optimization was the significantly improvement of the positioning behavior, caused by an increased stiffness of the driven axis in direction of the feed drive. This was remarkable, as the underlying static optimization neglected dynamic effects. Also the influence of the surrounding machine parts was neglected. With the good experience from this first step in the optimization of the stability, a second topology optimization was carried out to increase the process performance and to simplify the column structure.

A “totally new designed” column (see figure) was integrated in a machine. Surprisingly the tests were disappointing, because the process stability had decreased. The conclusion from this experience was that a topology optimization on dynamically loaded parts must include deformations due to oscillations, additionally to the purely static load configuration.

In a scientific work a method was developed at HELLER to include dynamic effects as well as the influence of the surrounding machine parts. The comparison between the purely static optimized structure and the static-dynamic optimized structure reveals significant differences. Due to estimations based on frequency response analyses the machining performance could increase by about 20% with the new column.

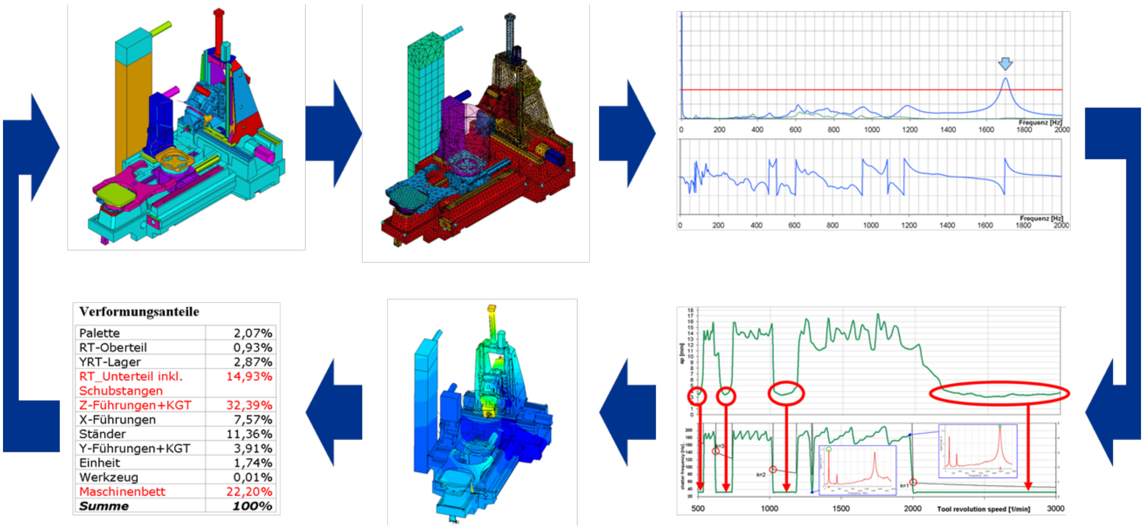


A general parameter optimization provides the opportunity to strive for desired properties by variation of discrete parameter values within a limited range. Here the challenge is to avoid trivial solutions and to find suppliers providing the machine components with the desired properties.

The simplest optimization strategy requires the biggest manual effort, because all iterations require a new geometry model. The interpretation of the simulation results and the improvement proposals are managed manually.

Traditionally during the R&D-Process the few most innovative machine tool manufacturers consider the system’s frequency response behavior which is obtained by simulations or measurements to evaluate several dynamical system properties. However, to derive the machine’s process stability fitness from frequency response curves, a lot of experience-based interpretation has to be done and many uncertainties still remain. In contrast to this procedure a stability curve provides much more clarity, as process-specific influences are considered and the values directly address the customer's questions with regard to productivity.

Of course, stability charts can be generated due to tests. This is a very time-consuming and cost-intensive procedure and the real prototype of a new machine must be physically available. As a participant in a bunch of recent scientific projects, HELLER has developed the ability to do a simulation based process stability prediction with the Finite Element Method. This opportunity provides HELLER to optimize the desired machine properties in a very early design stage.

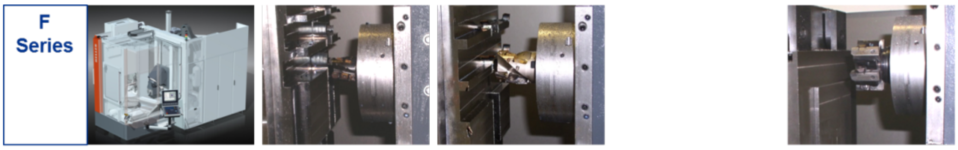


In the figure the FEM integrated PSP (Process Stability Prediction) is described I a few steps. The 3D model represents the actual design status. It is modeled in that way, that all necessary geometry can be extracted on an automatic way to the FEM preprocessing step. In the FEM preprocessing the model will be meshed and all additional parameters (see chapter 2) are added. HELLER expanded the functionality of the preprocessing with additional functionality to increase the automation of the process step in simulation.

In the first simulation run a frequency response analysis will be done, to identify the typical dynamic property of the complete machine system. In the next step the simulated NFGs are used for a transient simulation to predict the stability loops of the machine. The region of leak stability can be now analysed in detail to identify the relevant frequencies and eigenmodes, which influence the stability. Using the visualization of eigenmodes the simulation and design experts can identify interfaces, components, etc., which should be optimized to increase the dynamic behavior of the system. As a support of this engineering activity the simulation experts can create a so called kinematic analysis. This tool defines the relevant movements in the force chain from the tool to the workpiece in a predefined eigenmode and help to locate the "leakest" components, which should be modified. After the designer changes the geometry, the parameters of components, e. g. by using bearings with higher stiffness, etc. the PSP can be started again. It is then up to the experts to identify the maximum of optimization regarding the process stability of the machine, the control behavior of the axis, the basic tolerances and accuracy, etc.

The PSP is a helpful tool to optimize the machine tool. In the past HELLER used frequency response analysis, eigenmode analysis, modal analysis, simulation of static displacements, etc. All these methods are helpful and will be also used in future to optimize the machine. However with the FEM integrated PSP it is possible for the first time to predict the machine behavior, the customer is mainly interested in. Machine tools are designed to mill and bore metal components and the customers are always interested to increase the quality of the parts and to decrease the cycle time. The process stability for a few reference processes can now be simulated in a very early design phase of the machine and in iterative steps an optimized design can be developed.

HELLER developed the methodology in different research projects, funded by the government of Germany and supported by research universities in Germany and competent software partners. The methods help HELLER to develop the branding to be best-in-class in machining on horizontal and 5-axis-machining centers. The cooperation of simulation experts, using the described simulation tools, and design experts lead to a new designed 5-axis-maching center, which is now best-in-class solution regarding to the installed torque of spindle and process stability in the range of HSK 63 machines (see some process examples in figure below).



Workpiece	C45N	C45N	C45N	EN-GJL-250
Tool	HM WP	HM WP	45°-PMK	PMK
L [mm]	40	50	63	80
Ø [mm]	90	110	90	113
Z	2 + 2	3	5	6
Cutting Parameters				
v_c [m/min]	125	167	200	750
fz [mm]	0,15	0,19	0,4	0,17
S	995	1064	1010	3000
F	300	612	2020	3000
Stability				
a_e [mm]			55	64
ap [mm]	30	20	6	8
Used power [%]	70	95	100	100
M [Nm]	170	230	240	147
P_c [kW]	18	27	24	44

For HELLER the cooperation in research projects helps to design unique seeling points.