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Structural Optimization of Machine Tools including the static and dynamic Workspace Behavior

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Abstract
The use of topology optimization is helpful to obtain "systematic and proper" solution variants for a given static and dynamic design problem. Those solutions, which can be generated automatically provide the designer with new, previously unknown proposals of machine part structures. Up to now, the static and dynamic behaviour of the workspace was not recognized in such an optimization.

The paper introduces the topology optimization of machine tools applying the finite element method (FEM) coupled with the multi-body simulation (MBS). So parts of machine tools can be optimized while taking different critical workspace positions into account. Furthermore changes of the loads and the system behavior can be considered during the optimization process.

The potentials of this new optimization method will be shown on the example of a machine tool with hybrid kinematics.

Keywords:
Topology Optimization, Multi-body Simulation, Finite Element Method

1 INTRODUCTION

Competition permanently demands of machine tool manufacturers to improve the working accuracy and the dynamical behavior of their machines while reducing both product development time and costs. The development process, however, consists of several successive steps which lead to a time-, cost-, and functionally optimal product. The main steps are the selection of an appropriate machine concept, the simulation and optimization of the virtual prototypes and the validation of the simulation data using a physical prototype (Figure 1) .

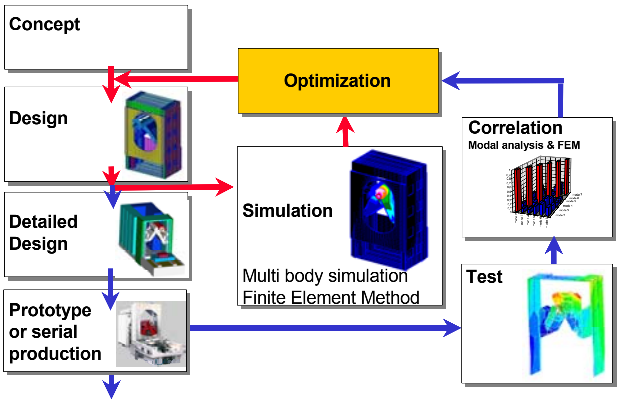

Figure 1: Simulation and optimization in the design process

How the use of different simulation and optimization methods supports the different steps of the product development process will be shown using the model of the new hybrid kinematics SPECHT Xperimental from Hüller Hille. This machine was developed in the BMBF project ACCOMAT as a welded construction was built [1, 2].

The static and dynamic behaviour of this kind of machine depends on the position in workspace. In this paper special attention has to be paid to topology optimization of the machine in consideration of the workspace position. These investigations are the current state-of-the-art at the Institute of Machine Design and the Institute of Machine Tools and Production Science. The research activities are promoted in the priority program “production machines with parallel kinematics” of the DFG (Deutsche Forschungsgemeinschaft).

2 SIMULATION OF MACHINE TOOLS

To simulate static and dynamic machine behaviour, mainly multi-body simulation systems and finite element simulation systems are used.

2.1 Multi-body simulation

The global machine structure and the kinematic behaviour can be simulated with a multi-body simulation system. Each individual element within multi-body system consists of rigid bodies coupled via spring and damper elements (Figure 2). One of the major benefits of the usage of multi-body system simulation for optimization is the easy generation of complex load cases including spatial acceleration fields for single components. The MBS makes it also very easy to visualize load histories of components and choose the appropriate ones for an optimization. However the flexibility and strain of single machine parts cannot be considered with the pure multi-body simulation.

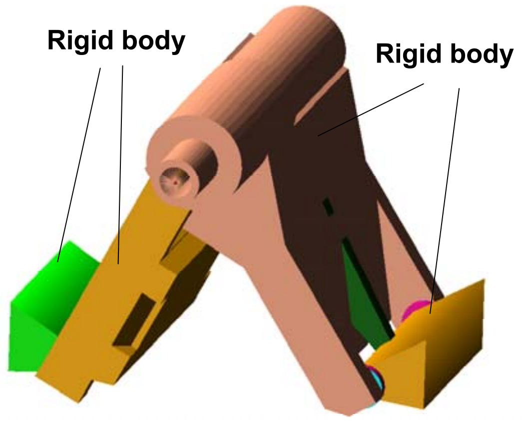

Figure 2: Multi-body model of the hybrid kinematic

2.2 Finite Element Simulation

For accurate static and dynamic simulation of machine behaviour the use of finite element simulation is required. Discrete components are modelled with finite elements and coupled via springs.

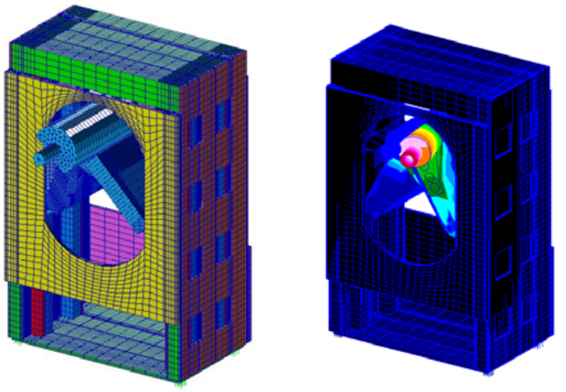

Figure 3: FE-model and static simulation of the hybrid kinematic

With this method it is complicated to simulate the motion and the resulting strain within workspace. If another position in workspace has to be calculated with this method, all components have to be moved by hand and a new calculation has to be started.

2.3 Coupled Simulation

The advantages of both methods can be combined by integrating flexible bodies in the multi-body system.

The integration is done by replacing the rigid bodies in the multi-body system with flexible bodies using the Craig-Bampton method. Displacements of the flexible bodies in the multi-body system can be described by this method using different modes. These modes are constraint modes and fixed-boundary normal modes. Constrained modes are static shapes obtained by giving each boundary degree of freedom a unit displacement, while holding each other boundary degree of freedom fixed. Fixed-boundary normal modes are obtained by fixing the boundary degree of freedom and computing the eigenvectors. After solving the Craig-Bampton modes, the modes have to be orthogonalized by a mathematical operation and the flexible bodies can be integrated [3].

After integration of flexible bodies in the multi-body system and connecting the flexible and rigid bodies, an ordinary multi-body simulation with applied force over the workspace can be done.

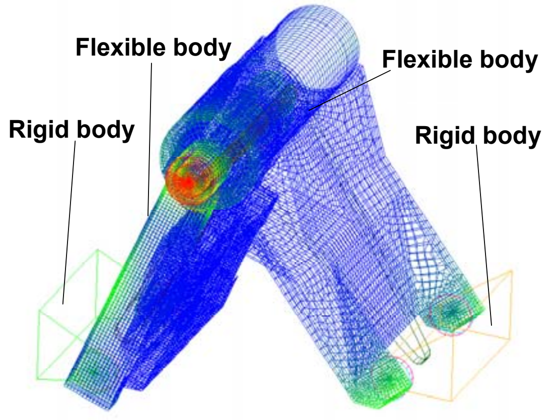

Figure 4: Multi-body model with stressed flexible bodies

Therefore, an exchange of forces and load cases between the two different software applications can be realized, and structural optimization of the single parts under “realistic” stress conditions from movements and time variant forces can be achieved (Figure 4).

3 STRUCTURAL OPTIMIZATION

Based on the FE-simulation, different optimization techniques can be applied to optimize machine tools. Figure 5 illustrates three different types of the optimization methods.

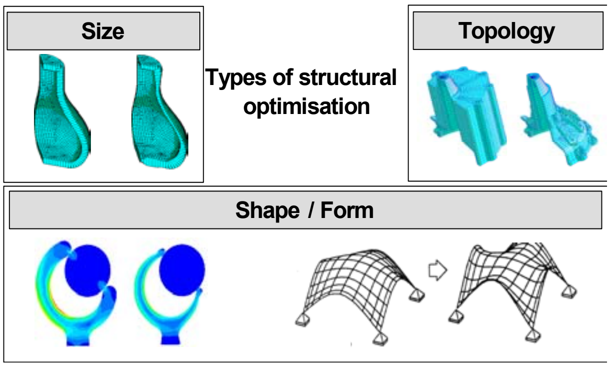

Figure 5: Types of structural optimizations.

While sizing and shape optimization rely on an already existing initial design proposal for the component, topology optimization tries to compute an optimum design of a structure in an available design space.

This article focuses on the topology optimization in the context of multi-body systems with flexible bodies on finite element basis.

3.1 Topology Optimization

In the planning phase, a fundamental structure of the object can be found using topology optimization. Starting from known loads and boundary conditions and the maximum design space available, a design concept can be found which is as light as possible while meeting all requirements on, e.g., stiffness and durability. Areas that are not needed are removed from the given design space. The new structure shows an indication of the optimal energy flow. The result of the topology optimization serves as a design draft for the creation of a new FE model for the subsequent simulation calculation.

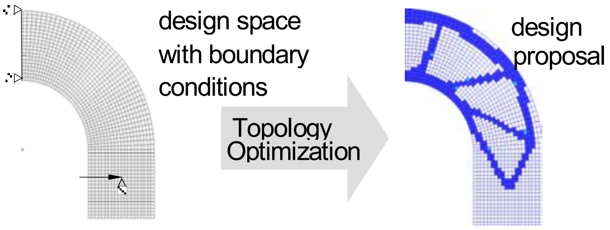

Figure 6: Topology optimization

The optimization is an iterative procedure where the bodies' geometrical structure is changed until a user defined objective is met (Figure 7).

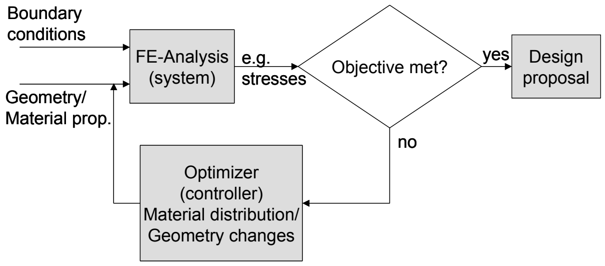

Figure 7: Optimizer as a "controller" of a component

3.2 Topology optimization in the flexible multi-body system

For statically loaded structural components, loads and boundary conditions can be defined in a straightforward manner. Things get more complicated when dynamically loaded bodies and different positions in the workspace are considered.

For example fast moving machinery parts can be subject to complex inertia loads that cannot be modelled by hand in general. Furthermore, in traditional finite element based optimization the applied loads do not change during the iterations. Since the optimiser makes changes to the body's spatial mass distribution, especially in the case of topology optimization the loads due to the body's inertia will change during the optimization process. This change in the bodies mass distribution and inertia can lead to a completely different system overall behaviour which can then again effect the loads on the body.

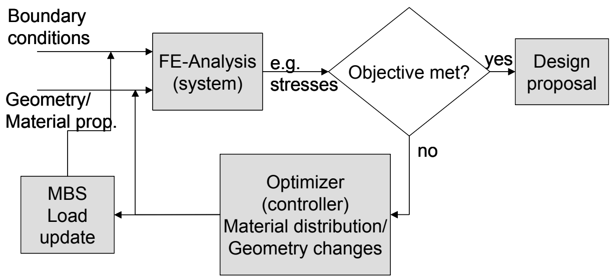

Figure 8: Optimizing flowchart with integrated multi-body system simulation (MBS)

To overcome the above mentioned difficulties a coupled approach has been developed at the Institute of Machine Design with a hybrid multi-body system for the automatic derivation of iteration dependent, complex loads on a flexible body. This was realized by the introduction of the multi-body system simulation into the optimization loop with the developed software mkl-sysopt. A first study of coupled topology optimization was presented in [4, 5, 6], using tripod models as an example for a parallel kinematic. Here, the coupled topology optimization of the platform showed significant improvements of the mechanical properties.

For the optimization the software TOSCA from the company FE-Design is used. As FE solver MSC.Nastran is used and the multi-body system simulation is covered by ADAMS.

4 OPTIMIZATION OF THE HYBRID KINEMATIC

For the investigations on coupled topology optimization for machine tools, the right coupler was chosen. Figure 9 shows the design space.

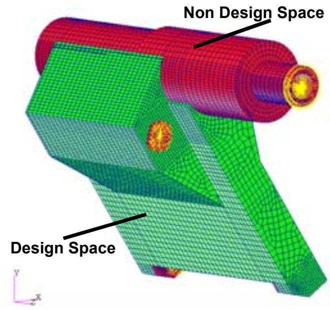

Figure 9: Design space of the right coupler

In the multi-body system, the left and right coupler are considered flexible, the other parts are rigid. The connecting parts are bushings with damping and spring elements.

The flexible bodies are made up of hexahedron elements and contain nine rigid bar elements. Eight of these are used to couple the so called interface nodes, which connect the flexible body with the multi-body system.

As machining forces, three components are applied (F_X=1000 N, F_Y=1000, N F_Z=1000 N) to ninth rigid bar element located at the tool center point.

To investigate the influences of different workspace positions, two optimizations have been conducted and compared: In the first optimization the tool center point was moved over the workspace from the left to right position (Figure 10). In the second optimization the couplers stand still (Figure 11). The second method is similar to conventional topology optimization approaches where configurations of FE-Models can not be changed without further effort. Both couplers have the same mass after the optimization.

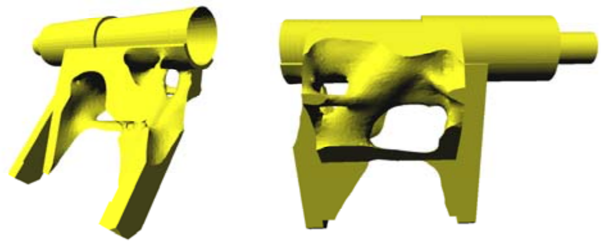

Figure 10: Results of the optimization with motion over the workspace

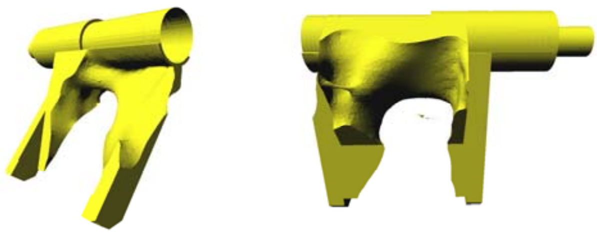

Figure 11: Results of the optimization without motion

The main difference in the resulting topologies is the remaining of a connection in the bottom part of the structure optimized with motion. This structure is not generally stiffer than the one optimized in the center position, but deformation is more homogenous when moving across workspace with loads applied (Figure 12).

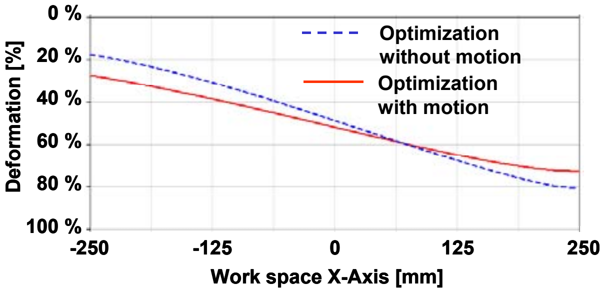

Figure 12: Deformation of the optimized structure with and without respect of motion during optimization

5 SUMMARY

Two different approaches of optimizing a FE-Structure in combination with a multi-body system have been shown. The optimization using motion and automatic calculation of loads in different workspace positions showed its usefulness resulting in a more evenly distributed stiffness behaviour over the workspace. Generating loads within a multi-body system allows to take a great variety of system configurations into consideration without having to incorporate the time consuming changes using conventional FE-Models.

6 REFERENCES

[1] Horn, W., Konold, T., 2000, Parallelkinematiken für die Metallbearbeitung in der Automobil-Massenproduktion, 2. Chemnitz Parallel Kinematic Seminar

[2] Stengele, G., 2002, CROSS HÜLLER SPECHT Xperimental A machine Center with New hybrid Kinematics, 3. Chemnitz Parallel Kinematic Seminar

[3] N.N., 2002, ADAMS user manual, Appendix D, Theoretical Background

[4] Müller, O., Häußler, P. et al., November 17-19, 1999. Berlin, Automated Coupling of MDI/ADAMS and MSC.Construct for the Topology and Shape Optimization of Flexible Mechanical Systems, 1999 International ADAMS Users' Conference., Germany.

[5] Häußler, P., Emmrich, D. et al., November 14-15, 2001, Automated Topology Optimization of Flexible Components in Hybrid Finite Element Multibody Systems using ADAMS/Flex and MSC.Construct, 2001 European ADAMS Users' Conference.. Berchtesgaden, Germany.

[6] Weule, H., Albers, A., Haberkern, A., Neithardt, W., Emmrich, D., 2002, Computer Aided Optimization of the Static and Dynamic Properties of Parallel Kinematics, 3. Chemnitzer Parallelkinematikseminar