Topology Optimisation of Rotating Automation Components for Machine Tools – Methodology, Cost Effectiveness and Examples

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Abstract: Light weight constructions possess a variety of general benefits in application, such as higher energy efficiency, increase of acceleration or payload. But especially the reduction of costs over the entire product life cycle is increasingly in the focus. By application of topology optimisation for rotating automation components a significant improvement is possible. On the other hand any simulation effort has to be judged as an entrepreneurial action for which a return on investment (ROI) has to be ensured. The simulation tasks, results and in conclusion the ROIs for some exemplary optimisations in the field of manufacturing machines are presented and assessed as success stories for the use of simulations in practice.

1 INTRODUCTION

The application of lightweight construction offers a variety of benefits, such as improved energy efficiency, acceleration and increased payloads. In addition to the use of lightweight raw materials and lightweight manufacturing methods, there is also potential in the area of structural design optimisation. This can be tapped by employing computer aided optimisation methods (Klein, 2013).

Some finite element software packages offer integrated topology optimisation functionality for this purpose. They are useful for the simulation of structural components during the concept development and design phases. ANSYS and ABAQUS e.g. support the consideration of static load cases to enable the development of load efficient structures.

Initially, it is important to understand the effects of different load cases in order to be able to optimise structural components that are used in machine tools (Brandenberger, 2004). Apart from the consideration of load bearing structural components (e.g. machine beds), the study of automation components such as tool changers, tool magazines and pallet changers might also be economically promising (Keller, 2005). If these components represent the unproductive secondary processing time and set-up time of machine tools, they promise improvements in movement in addition to the material and energy savings.

2 BASELINE INVESTIGATION

Firstly, topology optimisation is carried out and discussed for stationary 2D rectangular element models (according to the idea of Schumacher, 2005 and 2011), after which the observations will be extended to rotating 2D models. Then some practical applications are presented. The following boundary conditions apply for the 2D rectangular model:

- Design space: Height 100 mm, width 50 mm.
- The design space is discretised with about 30,000 8-node quadratic elements.
- The two lower corners each contain a fixed point.
- The force application point is 75% of the height.
- All forces are introduced in the plane, have the same value and each force is acting in the positive coordinate direction.
- As an optimisation constraint, the mass reduction is defined such that 20% of the design space should be filled with material.
- The end goal is to maximize the static rigidity.

Topology optimisation is carried out with the following load cases:

a) Horizontal force
b) Vertical force
c) Horizontal and vertical force applied simultaneously
d) Horizontal and vertical force applied sequentially with equal weighting to optimise the structure

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Figure 1 shows the obtained structures for all four optimisations which show many differences. The structures of a) and b) are plausible in view of load efficiency. It is also apparent that the structure d) clearly results from the superposition of a) and b). Interestingly, however, structure c) is asymmetrical and only suitable for the simultaneous occurrence of the horizontal and the vertical force in the assumed directions. However, the structure c) is not suitable for the exclusive occurrence of either the horizontal force or the vertical force, as well as for the case that one of the two forces is inverted.

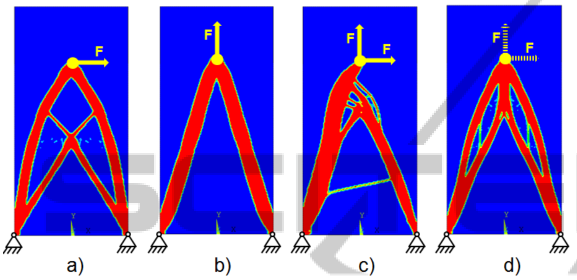

Figure 1: Topology optimisation for 2D rectangular models with different load cases.

From this baseline investigation, the important finding is that the optimised geometry has a high sensitivity to the load cases applied. However this could be overcome by providing the structure with some initial geometry constraints to ensure a sensible outcome. Furthermore, for a valid optimised structure a load case needs to be applied in which all loads are considered.

3 STUDIES WITH ROTATING SYSTEMS

Topology optimisations are performed and then discussed for 2D circular discs with point masses. The technical data is based on practical implementation and the following boundary conditions apply:

- Design space: Homogeneous, massless disc with a diameter of 500 mm.
- The design space is discretised with about 30,000 8-node quadratic elements.
- The disc centre is modelled as rigidly fixed.
- The four identical point masses (m = 1 kg) are arranged symmetrically on the periphery of the disc at 90 ° intervals.
- Also as previously, as an optimisation constraint, the mass reduction is defined such that 20% of the design space should be filled with material.
- As before the final aim is to maximize the static rigidity.

Topology optimisation is carried out with the following load cases:

a) Linear acceleration with 2g horizontally
b) Linear acceleration with 2g vertically
c) Angular acceleration $\alpha = 720°/s^2$
d) Angular speed $\omega = 360°/s$
e) Combined load case of: a), b), c) and d) with a load case weighting vector of (2,2,1,1)

Figure 2 shows the differences between the optimised structures obtained for the given load cases of the rotating disc.

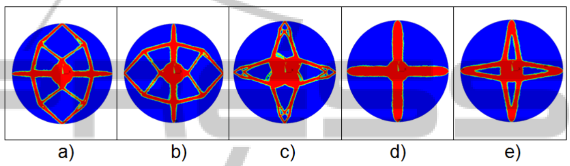

Figure 2: Topology optimisation with homogenous 2D circular discs with four equally spaced point masses at the extremities.

The structures for a) to d) are plausible in view of load efficiency. Structure b) is simply a 90 degree phase change from structure a). Structure e) is created by superposition of the structures a) to d) and is optimal with reference to the given laod cases and weighting.

Such optimisation results can often be implemented in practical structural design. An initial presentation of the methodology in more detail follows below. This will then be applied to examples from the machine tool industry with respect to rotating automation components such as tool changers, tool magazines and pallet changers, where this method in particular might be economically promising.

4 METHODOLOGY FOR TOPOLOGY OPTIMISATION

Topology optimisations with combined load cases are useful when dealing with real problems, with the ultimate aim being practical application of the solutions found. For this purpose, the following procedure has proven itself:

1. In machine tools, a variety of tools and work piece pallets with standardised mechanical interfaces can be used. The central basic body

of the rotational automated moving component normally comprises of regular geometric repetitions. The aim is to keep the analytical model small and thus shorten the optimisation procedure. The first thing to consider is the ability to use the symmetry conditions (mirror symmetry, axial symmetry and cyclic symmetry). It should be noted that the symmetry always relates simultaneously to geometry and loads.

2. The next step is to determine whether a simulation by 2D or 3D model is appropriate. A 2D model can significantly shorten the calculation process. 3D models should be applied to the topology optimisation only when absolutely necessary. This happens for example, if forces are not applied within the plane considered, but in a parallel plane some distance away or perpendicular to the plane.
3. Static load cases should be solved individually to determine whether loads and boundary conditions are reasonably defined. Stresses and deformations have to be determined and compared for each load case. If there are load cases that do not contribute significantly to a combined load case, these load cases may be neglected in the topology optimisation.
4. Next, the topology optimisation is performed with each load case. Is the optimised topology solution sensible with respect to the loads applied in the load case?
5. Based on the previous results, the weighting of the load cases for the combined load case is to be determined. The default could be an equal weighting of all load cases, but the weight function should at least be reasonably varied for trial purposes.
6. Even if the target mass for the optimised component is known exactly, it is recommended that the mass reduction be changed for testing purposes. This could lead to significantly different structures that provide more ideas for the design implementation of the results in practice.
7. If possible, topology optimisations should be performed with different optimisation algorithms for comparison (with ANSYS: OC and SPC).

5 COST-EFFECTIVENESS OF TOPOLOGY OPTIMISATION

Overall, this approach has been applied in a number of topology-optimised components to reduce costs and improve the characteristics of the component such as weight, inertia and stiffness. Subsequently, three components will be presented. The examples of the successful application for 2D or 3D optimisation of rotating automation components for machine tools are:

- Double gripper arm of a tool changer for a grinding machine (2D)
- Tool magazine for a grinding machine (3D)
- Double gripper arm for a tool changer of a machining centre (3D)

For the overall goal of reducing costs in the context of the entire product life cycle (Nyhuis, 2009 and Wiendahl, 2010), Figure 3 shows the effectiveness of the topology optimisation of various machine tool components with regard to the usual types of costs considered (Witt, 2006). This proves to be critical to the assessment of the soundness of topology optimisation when involving machine utilization by the user.

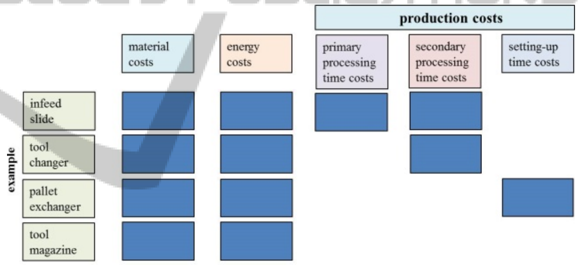

Figure 3: Effectiveness of the topology optimisation with regards to the type of costs.

A topology optimisation on a tool changer with the aim of reducing mass can influence material costs, but also the operating energy costs. Furthermore the production costs of a machining centre with this weight-reduced tool changer are favourably influenced by more rapid tool changes.

In the topology optimisation of a tool magazine however, there is usually no reduction in production costs to be substantiated, because the tool magazine movement happens isochronical to machining processes.

6 DOUBLE GRIPPER ARM OF A TOOL CHANGER FOR A GRINDING MACHINE

In this case the tool changer arm conducts rotary as well as linear movements for every tool change.

Therefore, a part with reduced mass and reduced mass moment of inertia reduces the secondary processing time.

As all relevant forces lay within the plane considered, a 2D topology optimisation was sufficient. The topology optimisation was conducted with a combined load case containing the following load cases:

a) Linear acceleration (1g horizontally)
b) Gravitational force (1g vertically)
c) Angular acceleration $\alpha = 180°/ s^2$
d) Angular speed $\omega = 90°/s$

The *optimisation result* obtained from the *design room* was used as the basis for an *optimised geometry*. Final calculations showed about 35% increased stiffness for the same mass compared to the *original geometry* of the grinding wheel changer (Figure 4).

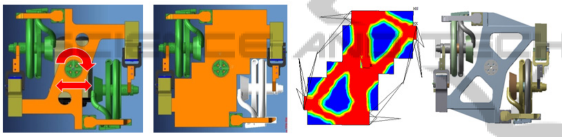

Figure 4: Topology optimisation of a tool changer of a grinding machine.

Although a stiffening is advantageous, another alternative was examined. This provided the same stiffness with a 27% lower mass and a 32% lower moment of inertia. This made increased linear and rotational accelerations possible, while using the same drive equipment. A detailed cost-benefit analysis was made for this topology optimisation. This was judged as an entrepreneurial action, for which a ROI (return on investment) can be determined. The analysis yielded the following results:

The grinding machine manufacturer had to invest an initial one-off € 834 development costs (including staff for analysis and design, software, hardware, equipment costs) for the topology optimisation of this component. The machine manufacturers benefits initially by the reduction of material costs by € 33 per grinding machine. Furthermore the machine user registers a productivity gain of € 152 per grinding machine for a duration of 10 years. Thus, from a macroeconomic point of view, the payback of this amount is received with five machines. However, for this type of machine, a total of 1000 units are planned, this topology optimisation provides a surplus of approximately € 184,166 in the long term. The majority of the profit goes to the users of these grinding machines (€ 152,000), but the machine manufacturer gains a profit as well (€ 32,166).

While it remains uncertain whether the machine user is ready to pay in advance for the productivity growth through an investment, an increase in efficiency of the grinding machine due to this optimisation would strengthen the market position of the machine manufacturer over the competitor's (Jickeli, 2014).

7 TOOL MAGAZINE FOR A GRINDING MACHINE

The disc-shaped tool magazine shown in Figure 5 supplies six different grinding wheels for a grinding machine controlled by a forward timing device. Due to the placement of the tool magazine disc in the vertical plane and projecting tool holders with grinding wheels, gravity loads apply in a plane parallel off-set to the disc plane such that a 3D model is required. The calculation expense can be reduced by neglecting the load case "angular acceleration" by symmetry conditions (6 x 60 °). Even a reduction to a 30° segment would have been possible. Using topology optimisation load-oriented grooves in the disc and material savings on the outer contour, an increase in the stiffness-to-mass ratio of 29% was realised. Manufacturing as a cast part thus shows reduced material costs. The mass moment of inertia was reduced by 24%. A reduction in the chip-to-chip time was not found in practice however, as the motion of the tool magazine can be performed simultaneously during machining. However, the reduced driving torque required results in energy savings during operation.

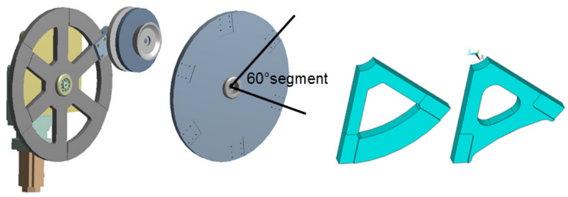

Figure 5: Topology optimisation of a tool magazine of a grinding machine.

The cost-benefit analysis for this component yielded the following results: For the topology optimisation of this component € 549 development costs (including staff for analysis and design, software, hardware, equipment costs) were assumed. This can be compared with a material cost reduction of € 47 per grinding machine. Surprisingly, the energy savings due to reduced mass moment of inertia is calculated as less than € 1, despite taking 10 years of operation into account. One reason for that is, that the inertia of the drive itself is a multiple of the inertia of the optimised tool magazine. Nevertheless, this measure makes sense economically from a quantity of twelve units, even if the payback time due to lack of relevance for chip-to-chip time clearly occurs later, compared to double gripper arm of the tool changer. It is still indisputable, based on the planned sales, that this optimisation is the right decision from an entrepreneurial point of view (Schietinger, 2014).

8 DOUBLE GRIPPER ARM OF A TOOL CHANGER FOR A MACHINE CENTRE

The double gripper arm in Figure 6 provides the automated exchange of cutting tools between a tool magazine and spindle within a machining centre, via rapid linear and rotary movements. The machine by Gebr. Heller Maschinenfabrik GmbH (HELLER MCH 280C) can handle very heavy tools of up to 35 kg during a tool change and reaches a chip-to-chip time of approximately 6.8 seconds.

The aim was to investigate how to further reduce the chip-to-chip time, but above all to increase the reliability of the tool change, so that jamming of tools in the spindle or in the tool supply position is ruled out under all operating conditions.

Therefore, a topology optimisation of the geometry has been applied with cyclic symmetry (2 x 180°), so that only the half models of the double gripper arm are shown. 3D models were considered, since in addition to the already known load cases of gravitational force and rotational movement, there are also significant extraction forces from the tool interface of the clamping system. These forces apply in axial direction of the tool and are therefore out of plane.

As a result of the topology optimisation and redesign, the component on the bottom right of Figure 6 shows increased stiffness-to-mass ratio of 21% for typical operating loads compared to the original component (top right). Additionally, there was a 19% increase in fatigue resistance, thus increasing the reliability of the tool change.

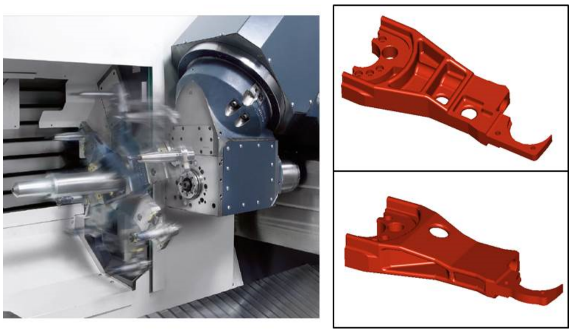

Figure 6: Double gripper arm: Function and half models of the original / optimised component.

9 CONCLUSIONS

Rotational motion components in machine tools often occur in automation solutions for tools and work piece flow. Systematic topology optimisation is a way to improve their technical and economic characteristics. However, they have to be justified as economical business decisions in advance. A means for this is the consideration of the amortisation of topology optimisations. This can occur at different unit numbers for various components due to the influence of cost types. Experience has shown that the optimisation of components for reduced primary processing times, secondary processing times, and set-up times often turns out to be commercially successful, even in small quantities.

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