Stiffness design of machine tools structures by topology management optimization approach

D M Dimitrov1,*, S D Slavov2 and K K Yordanov3

1 Technical University of Varna, Department of Manufacturing Technologies and Machine Tools, 9010 Varna, Bulgaria
2 Technical University of Varna, Department of Mechanics and Machine Elements, 9010 Varna, Bulgaria
3 Technical University of Varna, Department of Thermal Engineering, 9010 Varna, Bulgaria

Email: dm_dimitrov@tu-varna.bg

Abstract. The machine bodies are made as welded or cast parts, with relatively thin outer walls, reinforced with ribs that provide the necessary stiffness. Often, empirical formulas, which do not consider the load distribution in different areas of the body and that have an increased security factor, are used to calculate the thickness of the outer walls and the dimensions of the ribs. This approach does not meet modern design and production requirements, as it does not lead to optimal solutions. In the present work, a simulation, based on the finite element analysis methodology, is presented, using the capabilities of the COMSOL Multiphysics software, which allows the simultaneous determination of the magnitude and distribution of stresses from different load cases from machine operation. The topology optimization management algorithm is then used to remove unnecessary material from the machine body, based on the calculated stress distribution in the previous step. The results, achieved after the implementation of the topology optimization study, are shown and discussed. Conclusions about the applicability of the presented approach are made and objectives for its future development and improvement are also defined.

1. Introduction

Nowadays machine tool developers are forced to reduce energy consumption of their products, while increasing their productivity and accuracy. Lightweight design of machine tool structure is one of the important conditions to achieve energy efficiency [1, 2]. At the same time, however, they must have sufficient static and dynamic stiffness to withstand variations in the cutting force at high removal rates.

Increasing stiffness globally, while reducing or keeping the same component weights, is an important condition for avoiding overlapping the first natural frequencies of lightweight machine tool structure and the drivers [3]. Thus, the resulting stiffness and lightening weight are essential for improving the structural design of machine tools [4], and these conditions are particularly applied to the moving parts of the machine tool, such as columns, linear or rotary worktables, beams, etc.

Some studies are devoted to improving the performance of the metal cutting machines columns, their structure, constructive attributes and the materials from which they are made. The results obtained in [5] show that the dynamic characteristics of the column was improved by using composite-foam-resin concrete sandwich structures, or by implementing adhesively bonding glass fabric epoxy
composites laminates to the cast iron column [6]. In [7] steel fibre-reinforced concrete was used to develop a high precision grinding machine.

Another technique to obtain structural stiffness and to decrease material consumption in machine substructure elements is using stiffening ribs. The most widespread ribs distribution patterns are parallel, orthogonal or diagonal, usually with equal steps between adjacent ribs (see figure 1, a). However, when the ribs are designed this way (according to a conventional approach), based on general recommendations from books and the designer intuition, or following limitations of the manufacturing method (e.g. sand mould casting), there is no guarantee that an optimal solution will be obtained.

![Figure 1. Stiffening ribs distribution types: a) conventional ribs machine tools bed structure; b) bionic ribs machine tools bed structure [9]; c) topology optimized bed structure.](image)

An attempt to improve the outcome of the conventional design approach is given in literature [8, 9, 10], where a novel method for obtaining bionic structured ribs (see figure 1, b) in machine bed and column is described. Specially designed algorithms, which take into account the load of the machine column and arrangement of the stiffening ribs in manners, inspired by nature are used. In [11] a lot of such algorithms are described. The authors reported that this approach already have already been implemented in structural designs in robotics, aircrafts, watercrafts, etc. [12, 13]. To simplify the optimization algorithm, however, the shown examples of the application of this approach are mostly related to static column loads, which are not a common characteristic of all metal cutting machines of this type.

The purpose of the work is to present an approach of stiffening ribs design, based on the results from topology optimization (TO) method. Subject to that, combined optimization approach is the vertical support column from a grinding machine. The design criteria in terms of grinding machines are very similar to all other types of machine tools. They include high static and dynamic stiffness, low weight for moving parts, damping and fatigue strength, thermal and long-term stability, etc. [2].

TO approach can be used for material layout optimization within a given design space, for a known set of loads, boundary conditions and constraints in order to minimise the mass of the object. Unlike size and shape optimization, the topology-optimized structures can attain completely different shape (see Figure 1, c) within the boundaries of the design space [14, 15]. TO algorithms also are integrated into many of the modern commercial and freeware CAD-CAE software products and can be used directly in the design process of machine tools parts.

## 2. Methodology of the optimization

### 2.1. Short description of the machine

The surface and profile grinding semiautomatic machine LSH-220, is designed for dimensional machining of grooves, as well as profiled surfaces of various parts, using the method of deep grinding [16]. The LSH 220 grinding machine is equipped with a rectangular table (with dimensions 800×400 mm and a horizontal spindle, which has working frequencies of the grinding wheel between 600 - 2000, rpm. The overall machine weight is 6700 kg. The processing accuracy is as follows: deviation from straightness of the grinded parts surface in the vertical and horizontal planes, not more than 10 μm; deviation from parallelism of the grinded sample surface to its base, not more than 10 μm; roughness of the grinded surface (Ra), not more than 0.63 μm.
This model was purposefully created for use in the grinding technology of turbine blades (for dimensional grinding of turbine blades groove). Because of its high accuracy and reliability, this machine is widely used in aircraft manufacturing enterprises. Pictures of the machine are shown on figure 2 a, b). To create FE simulations a CAD model of the machine is used, (see figure 2 c). One of the pieces, which can be optimized, is a column. It is fabricated of cast iron.

**Figure 2.** a) Front view of surface and profile grinding semiautomatic machine LSH-220 [16]; b) Image of vertical column with grinder spindle housing; c) 3D assembly model of the machine and d) 3D model of the vertical grinding machine headstock.

2.2. **Column design methodology**
Optimization of the column ribs is obtained by implementing the following steps (see figure 3):

Step 1. The stationary static problem is solved for the initial geometry of the column for each of the two load cases.

Step 2. The column design is simplified by removing the ribs, holes and some of the fillets. The stationary static problem is solved again for each of the two load cases. The total strain energy $W_{s0}$, used to define the objective function for topology optimization, is sum of the strain energies of each load case.

Step 3. The topology optimization problem is solved by taking into account all load cases.

Step 4. On the base of the solution from the optimization step, a new design of the rib is suggested.

**Figure 3.** Design process step by step. Initial Design - Simplification - Topology optimization - Final design.

**Figure 4.** Boundary conditions: a) fixing surfaces, b) loading when spindle head is in downward position c) loading when spindle head is in upward position.
2.3. FE modelling
To analyse stiffness of the machine column, the Single Module Method (SMM) is used [17]. The external forces are transformed to equivalent loads and applied to the contact areas. The fixing and load boundary conditions are shown on figure 4. The weight of the spindle head is transformed to an equivalent couple with a total force $F = 2500$ N. Since the spindle head can move up and down, two extreme load cases are defined, figure 3, b, c). The grinding forces are not taken into account as they produce the opposite couple and unload the column. The top surface of the column must support $Z$-axis drive system’s weight, so pointing down load $G = 1500$ N is applied on the roof of the column for each load case presented. A linear elastic model is chosen for the simulations, with the following properties of the material: Young’s modulus $E$ is set as 140 GPa, Poisson’s ratio $\mu$ is fixed at 0.25, and the density $\rho$ is defined as 7000 kg/m$^3$.

The Solid Isotropic Material with Penalization (SIMP) method, which is used in this paper, is a common approach, used by researchers in many engineering fields. The artificial density factor $10^{\theta}$ is introduced in order to modify the elastic coefficient:

$$E(u) = \theta(u)^p E_0,$$  \hspace{1cm} (1)

where: $E_0$ - elastic modulus of solid material; $p$ - penalization factor.

This type of optimization problem is called the MCWC (minimum compliance with a weight constraint) [18]. In particular, relative strain energy is used as an objective function.

$$\min_{\Omega} \int_{\Omega} \frac{W_s}{W_0} d\Omega, \text{ s.t. } \int_{\Omega} \theta(u) d\Omega \leq k,$$  \hspace{1cm} (2)

where $k$ - volume fraction, $u(x,y,z) \in \Omega$.

The optimization problem is implemented in COMSOL Multiphysics [19]. An MMA optimization algorithm with a limited number of iterations is chosen. To avoid mesh dependency and checkerboards the Helmholtz type filter [19] with radius $R$ equal to the maximum size mesh element and hyperbolic tangent projection are applied. The penalisation factor is set to $p = 3$, and projection factor to $\beta = 1$. The volume factor is set to $k = 0.5$. The Von Mises stress from static solution is normalised and used for the initial value of the design variable $\theta$. In this way, the number of iterations can be minimized.

3. Results and discussion
The results from the optimization step are shown on figure 5. Since the design of the front beam and the lower part with fixture bolts cannot be changed, the optimization domain includes only the side, top and back walls of the column.

Figure 5. Results from the TO: a) filtered density factor $\theta > 0.40$; b) filtered density factor $\theta > 0.95$.

Figure 5, b) clears the load path. The ribs inside were designed, inspired by the structural bionic method. A dendritic-like structure is chosen with an inclined main rib and branches, figure 5, b). The weight of the initial column is 865 kg, the optimized design weight is 719 kg, so as a result the optimized column is 17% lighter than the initial one. Finally, a comparison of the stress distribution,
strain energy and displacements at key points is made. The stress distribution and the deformed geometry from the upward load case are presented on figure 6.

The strain energy and point “A” (see figure 6) displacements are summarised in table 1. It is clearly visible that the compliance of the optimized column is about 30% higher, especially in upward load case. Comparing the higher displacement in $Y$ direction, it can be seen that it increases with about 10%. Knowing that the weight reduction is about 17%, the optimized design can be accepted.

![Figure 6. Von Mises stress distribution and deformed shape for the upward load case: a) initial design; b) optimized design.](image)

![Table 1. Total strain energy and displacement field in Point “A” (see figure 2) of initial and optimized design](table)

| Design | Load case | Total strain energy, J*10^-3 | Point “A” Displacement field, μm |
|--------|-----------|------------------------------|---------------------------------|
|        | 2         | 13.72                        | X 0.87                          |
| Initial| 1         | 8.03                         | Y 8.75                          |
|        |           |                              | Z 2.58                          |
|        | 2         | 17.69                        | X 0.58                          |
| Optimized| 1       | 8.73                         | Y 6.17                          |
|        |           |                              | Z 1.53                          |

4. Conclusions
The present work demonstrates the possibilities of combining the advantages of the topology optimization method with another relatively new approach, based on the use of nature-inspired designs in building elements of metal cutting machines. In the methodology described above and the case-study, the topology optimization algorithm was initially used to reduce the column material (without ribs) of the flat grinding machine by removing it into excess areas that did not contribute significantly to its stiffness. Then, the topologically optimized design was used as a template for reconstruction of the original column construction. Bionic type grids with stiffening ribs were added only in those areas where the material was not removed after the topology optimization process. While in other such studies the column load is set at a single fixed vertical position of the machine spindle, in the case considered herein the topology optimized structure of the column is the result of the joint action of the two load cases 1 and 2, thus taking into account the load in the two end positions (the lowest and the highest) of the grinding machine's spindle unit.
Thus, a reduction in the mass of the column from the initial 865 kg to 719 kg was achieved, or a decrease of 17%. From the results, shown in Table 1 for the calculated displacements in the three directions $X$, $Y$ and $Z$ for the initial and the optimized column constructions, it is seen that they slightly increase. The largest increase in displacement is observed in the direction of the $Y$ axis under load case 1, which is 1.55 µm. The values of all other displacements are within 0.5 µm greater than those of the original design. Consequently, it can be concluded that the optimized design of the column will be 16% lighter than the initial one, while retaining the stiffness of the structure near to the original one.

The work presented in this paper should not be deemed to be finally completed. Future work will be focused in several directions, as follows: adding important boundary conditions in the model, such as taking into account deformations due to temperature changes from machine operation, the influence of the natural frequencies on the optimization of the construction, etc. Future work also will include continuous methodology refinement, and automation of the algorithm for optimal and nature-borne ribbing of parts, such as columns, beds, work tables and other similar elements of the machine-tool construction.

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