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The Effect of Linear Guide Representation for Topology Optimization of a Five-axis Milling Machine

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Abstract

Topology optimization is a countermeasure to obtain lightweight and stiff structures for machine tools. Topology optimizations are applied at component level due to computational limitations, therefore linear guides' rolling elements are underestimated in most of the cases. Stiffness of the entire assembly depends on the least stiff components which are identified as linear guides in the current literature. In this study, effects of linear guide's representation in virtual environment are investigated at assembly level by focusing on topology optimization. Two different contact models are employed for rolling elements in the linear guides. Reliability of the contact models are verified with experiments. After the verification, heavy duty cutting conditions are considered for the system and topology optimization is performed for two different contact models to reduce the mass of the structure. The difference caused by the representation of rolling elements is demonstrated for the same topology algorithm and the optimization results are compared for the models. Lastly, the effect of using more stiff linear guides in the five-axis milling machine is investigated by increasing the stiffness of the contact elements.

Keywords: FEM, Topology Optimization, Stiffness, Linear Guides ;

1. Introduction

Competition in the market is steadily forcing machine tool developers to increase productivity while reducing machine costs by creating a descending trend in the machine tools energy consumption. Today, lightweight design of machine tool structures is mainstreamed for energy efficiency, but it is also important to note that the ability to reach the upper limits of servo drivers is another major contributor while developing efficient machine tools. However, to be able to design such a machine tool is not an easy task. Lightweight machine tool structures provide extended working bandwidths for servo drivers compared to the massive ones due to mass reduction. Also, these lightweight structures push the low modes to higher frequencies allowing higher gains to be used in the control loops. The first natural frequencies of lightweight machine tool structures and the drivers are in a similar bandwidth. Therefore, a greater risk may occur during design stage for overlapped modes at low frequencies [1]. In order to overcome the mentioned drawbacks, the everlasting objective should be increasing stiffness globally while reducing or keeping the same component weights [2]. However, entire machine structure stiffness depends on the weakest components of assembly which are usually linear guides and bearings [3, 4].

Topology optimization is one of the most powerful tools for designing lightweight and stiff structures at the early design stage; however, it has its own drawbacks. A typical topology optimization application is carried out in virtual environment by employing FE models of the machine. These models have proved their suitability and significance for subsystem level design analyses such as modeling of ball-screw feed-drive systems [5], spindles [6] and full machine assembly design analyses. However, FE analyses of full machine models are computationally costly. For instance, an FE model of typical machine assembly has one million degrees of freedom (DOF) or more [7]. In order to reduce DOF and model complexity, most of the FE models ignore contact elements and connection parameters. In reducing computational cost, two approaches are

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common. The first one is to define critical structural components and optimize topology for these components separately. The second is to use the full assembly model for topology optimization with co-FEM or Model Order Reduction techniques [5, 7].

The first approach -defining critical parts and optimizing them- has generally been applied when different considerations are taken into account for topology optimization. In a machine tool structural optimization problem, the objective might not only be the static stiffness; the end user may also care about chatter and surface quality of the workpiece. Hence, the problem statement must also include dynamic rigidity concerns, and therefore employing a soft-kill BESO method [8] proposed for the component or sub-assembly level. For most practical design problems, 'self –weight' and 'design depended loading' issues drive the objective as minimizing mass while satisfying stress constraints. Due to stress singularity in the computational process reaching a global optimum for a stress-based topology optimization is not guaranteed, therefore it is applied locally [9]. Additionally, it is well known that continuous topology optimization problem forms like SIMP and RAMP methods tend to offer composite material structure in terms of element density [2, 10]. At this point manufacturability is the greatest obstacle for the stiffness objective, although most dominant topology optimization software has casting, drawing and extrusion constraints with the help of MMA methods [11]. Manufacturing constraints pose innumerable computational effort therefore, these constraints strictly limits the assembly optimization initiatives [12].

The second approach- entire assembly optimization - gives superior results while simulating real behavior of the machine tool structure, by representing the contact interfaces. However, simulation of full FE model, is a really time consuming process and is inefficient for a FE solver [7]. Therefore, CMS and Model Order Reduction techniques are applied together [13]. Also co-FEM methods like Multi Body Simulation techniques are coupled with topology optimization to decrease the computational cost [3, 14].

The rolling elements of linear guides have rarely been simulated in a FE model of milling machine assembly until now, due to the computational limitations. Besides, the design tendency for stiff structures have directed designers to create massive structures without considering the least stiff components of the machine tool assembly. This study is aimed to reveal significance of the contact elements. Especially, the linear guides are considered in the given entire machine tool assembly. The optimized topologies are compared with respect to their static and dynamic behaviors. For this purpose, two different linear guide representations of a five-axis milling machine are plugged in the entire assembly of an FE model, and then the reliability of these sub FE models are verified with experiments. Rolling elements of the linear guides are represented as surface contacts in the first equivalent contact model, while the same components are represented as springs in the second equivalent contact model. Furthermore, linear guide's stiffness is increased and its effects on mass reduction are demonstrated within this study.

The paper is organized as follows; two different representation of linear guides based on FE models of the entire assembly are presented, the reliability of these FE models are verified with static experiments and then, the loading conditions are explained for topology optimization in Section 2. In Section 3, topology objectives and constraints are stated then, the results of topology optimization are compared for two different linear guide's representation. Furthermore, linear guides' stiffness is increased and resultant topologies are demonstrated in Section 3. Conclusions are shared in Section 4.

2. FE simulation of machine tool structures

A competitive five –axis machine in the market must have superior design features. To design a lightweight, fast and precise five-axis machine tool, FE simulations and topology optimizations are vital. These methods provide predictions about precision and accuracy limits of the machine tool at early design stages. In order to obtain the best reliable results from topology optimization, the FE models of machine tools and the simulation conditions should be close to real ones. However, computational limitations drive machine tool designers to made simplifications on the machine tools and analyze them in component level. Therefore, all contact surfaces are neglected or underestimated. In this part, different representation of linear guides based on FE models of the entire assembly are presented. Two approaches are employed for the rolling contact elements at the assembly level. Reliability of these FE models are verified with static tests. For topology optimization, loading conditions are explained. The results of the loading conditions are used as constraints in Section 3.

2.1. FE models

Five-axis milling machine FE models are generated by using its respective CAD models. Each structural component of the model is meshed with tetra elements, with total of ~ $4x10^6$ elements and ~$1x10^6$ nodes, after a convergence test. Three material properties, for steel and cast iron assigned to different components of the model are given in Table 1.

Table 1. Material properties assigned to components

Material	Elasticity Modulus	Density	Poisson Ratio
Steel	210 GPa	7850 kg/m^3	0.3
Cast Iron	140 GPa	7200 kg/ m^3	0.3

The crucial part of the modeling is the representation of the rolling elements within ball grooves of the linear guide components, which is significant to obtain a realistic machine tool structure.

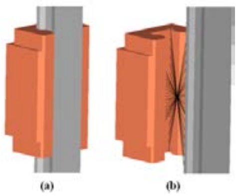

Fig. 1. (a) Model 1 surface contacts for rollers elements, (b) Model 2 springs for roller elements

These roller elements are modelled as surface contact in Model 1. For Model 2 non-linear spring elements are employed. The