Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 52(3) (2020) 173-176
DOI: 10.22060/mej.2018.14793.5944

Improving the Milling Machine Stiffness by Optimizing the Internal Stiffeners Layout and the Wall Thickness Distribution of Column

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ABSTRACT: Machine tool static deflection due to the machining forces and thus the displacement of tool tip is the most important factor in reducing the dimensional accuracy of workpiece. Also, overlap of the operation frequency range with the machine natural frequencies causes an undesirable resonance phenomenon. Since the operating frequency range is lower than the first natural frequency, increasing the first natural frequency of milling machine and reducing the displacement of tool tip is a desirable modification that can be achieved by optimizing the wall thickness distribution and the internal stiffeners layout of column. This paper suggests a new method for the optimization of stiffeners layout for plate/shell structures. In each step of optimization, by establishing a loop of relationship between MATLAB and ABAQUS software and based on the sensitivity analysis, the most effective stiffeners on optimizing the objective function are added to design space. After optimizing the wall thickness distribution of the column using the ABAQUS software size optimization module, the suggested method is used to optimize the internal stiffeners layout. Ultimately, without increasing the column weight, the maximum displacement of machine tool is reduced by 6.9% and the first natural frequency is improved by 16.5%.

Review History:

Received: 8/7/2018
Revised: 10/26/2018
Accepted: 12/3/2018
Available Online: 12/19/2018

Keywords:

Static deflection
Resonance phenomenon
Optimizing the stiffeners layout
Sensitivity analysis
Milling machine column

1. Introduction

Machining is one of the most important manufacturing processes. The high machining forces results in the static deflection of the machine tool, and thus the displacement of the tool. The high static stiffness of the machine tool can lead to better resistance to tool displacement and increase the precision of the products. Also, overlap of the operation frequency range with the machine natural frequencies causes an undesirable resonance phenomenon. Therefore, increasing of static stiffness and operating frequency range is significant in design of machine tools. Innovative internal stiffeners layout can achieve this objective. Therefore, to solve the problem of stiffeners layout, many efforts have been made using topology optimization methods such as homogenization, density method and evolutionary structural optimization [1-4]. In these methods, less important material gradually are removed from the design space, and the residual material is considered as an initial design that the position and direction of the stiffeners are not clearly determined. To solve this problem, Ding inspired by the branching systems in nature, suggested a new and direct method to optimize the stiffeners layout for plate structures [5]. Based on this method Li developed an adaptive growth algorithm for 3D structures [6-8]. In the adaptive growth algorithm, unlike in old methods stiffeners grow in the design space and the optimization process directly leads to the final arrangement of the stiffeners. But in this method, the stiffeners layout depend on the number and position of the seed points, and in the early stages of optimization, only stiffeners near the seed points can grow in the design space. Also, the algorithm presented in these articles leads to complex layouts. Therefore, this paper suggests a new method for growth the stiffeners that there is no need to determine the starting point. Also, by group growth of stiffeners are prevented from complexity in the layout of them.

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2. The Method for Optimizing the Stiffeners Layout

For better explain of the method, a very simple example is solved. A square plate with the side of 100 mm and a thickness of 5 mm is assumed. All four sides of the plate are clamped and the plate is under a uniformly static pressure. The objective is to find the best stiffeners layout with a thickness of 5 and a height of 10 mm, to minimize the strain energy of the plate. Initially, the plate is discretized into 4-node shell elements and Stiffeners are discretized into 2-node beam elements and is prevented from relative movement between them.

At the start of the process, the beam elements cover the entire design space. But the height of the cross section of the beam elements is very small and has no effect on the analysis. In Fig. 1, the shell elements are shown in green and beam elements are shown in red.

After applying the load and the support conditions,

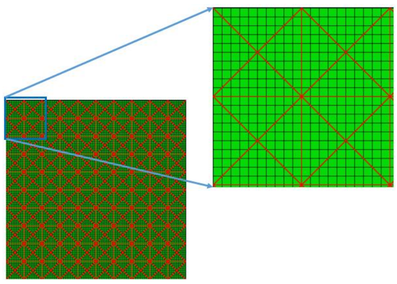

Fig. 1. Plate discretization into 4-node shell elements and the beam elements introduce the stiffeners.

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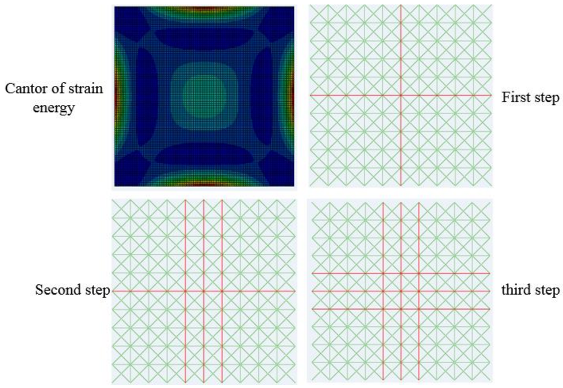

Fig. 2. Manner of adding the stiffeners to clamped plate

ABAQUS solver calculate the sensitivity of the objective function with respect to the height of each beam element. The sensitivity values of the elements of each group are gather and the groups with the highest sensitivity to weight ratio grow and their cross-sectional height reaches the desired amount of stiffeners (in this example, 10 mm). Then the elements that have grown in the first step of the design are coming out of competition. These changes are made in the model by the written program in MATLAB software, and the new model is sent to ABAQUS for analysis, and the finite element is retried again, and the steps are repeated. When the amount of grown elements reaches a specified value, the optimization process ends. Fig. 2 shows the cantor of strain energy with the three steps of optimizing the stiffeners layout connected to the plate.

3. Redesign of Column of a Vertical Milling Machine

In this section, the first objective is to reduce the strain energy of column of a vertical milling machine and thus reduce the displacement of the tool. Since the operating frequency range is lower than the first natural frequency, increasing the first natural frequency of milling machine is second objective. So at first, size optimization module of the ABAQUS software, is employed to optimize the wall thickness distribution of column. The initial column has a uniform thickness of 22 mm. after optimization, the thickness in the lower parts is changed to the maximum possible value of 30 mm and in the upper parts to the lowest possible value of 15 mm, as shown in Fig. 3.

The next step is to find the best internal stiffeners layout in the column with a new thickness distribution using the method presented in the second part of the paper. The original and optimal stiffeners layout is shown respectively in Figs 4 and 5.

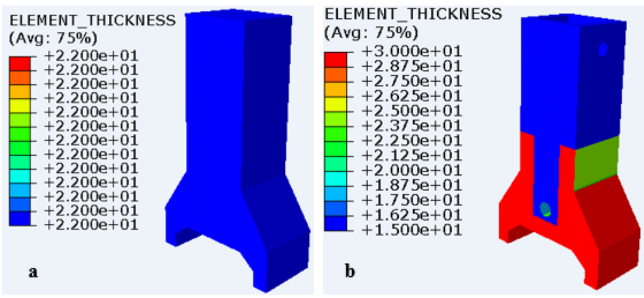

Fig. 3. a) Original column with uniform thickness, b) column with optimal thickness distribution

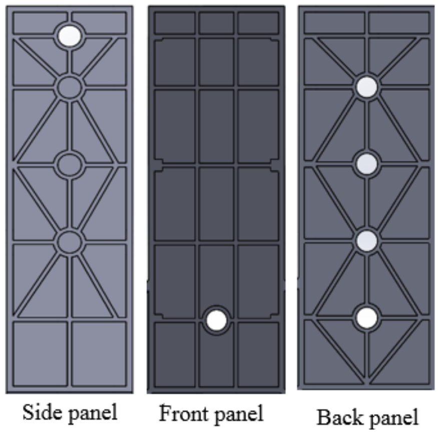

Fig. 4. Stiffeners layout in the original column

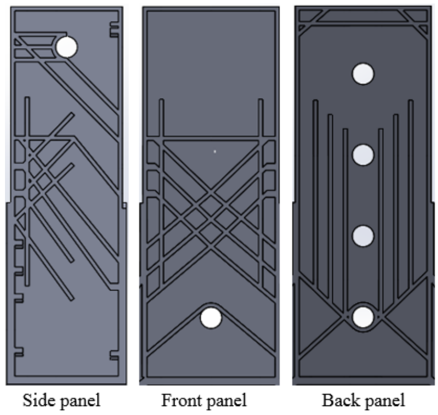

Fig. 5. Stiffeners layout in the optimal column

Table 1. Comparison of the mechanical properties.

Column	Weight, kg	Max displacement, µm	First frequency, Hz
Original	740.9	231	50.2
Optimal	737.5	215	58.5
Variation (%)	- 0.5	- 6.9	16.5

As shown in Table 1, after two optimization steps, without increasing the column weight the maximum displacement of the milling machine is reduced by 6.9% and the first natural frequency is improved by 16.5%.

4. Conclusions

This paper suggests a new optimization method for stiffeners layout for plate/shell structures. After optimizing the wall thickness distribution of column of a vertical milling machine, the internal stiffeners layout of the column is optimized using the suggested method. Finally, with minor changes in the column, the intended characteristics of the milling machine are improved

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