Study on an Interactive System for Conceptual and Basic Design of Machine Tool Structure*

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Abstract
This paper presents the improvement of design efficiency of machine tool structure in the conceptual and basic design stage. An interactive system has been developed for designing machine tool structure in this study. The key point in the interactive system is that a set of beam elements are assumed to compose the total structure of machine tool because it is easy to analyze the static, dynamic and thermal features. In this interactive system, a conversion procedure also has been developed. By using this conversion procedure, the selected beam structure of machine tool can be converted to an actual structure, completing conceptual and basic design. Consequently, using the interactive system allow, designers can complete the machine tool structure design in a shorter time with higher efficiency. The goal of the interactive system is to assist designers to quantitatively and quickly select a superior machine tool structure.

Key words: Machine Tool, Interactive System, Total Structure, Conceptual and Basic Design, Conversion Procedure

1. Introduction
In recent years, the static, dynamic, and thermal stiffness of a machine tool structure have improved. As a result, machining process achieves high speed, precision, and productivity dramatically. However, machine tools are still challenging the developments, especially in reducing time-to-market (1). In order to meet the goal, many researches have been done on structure and control system of machine tools. For example, Bianchi, G. and Paolucci, F. reduced the number of degrees of freedom (DOF) by compromising the static and dynamic analysis accuracy, leading to decrease the analysis time (2). Altintas, Y. and Brecher, C. et al. proposed a new design procedure with virtual prototypes that shorten design time (3). Zatarain, M. Lejardi, E. and Egana, F. cut calculating time in stiffness analysis using condensed mass and stiffness matrices instead of the huge matrices, which obtained by the finite element method (FEM) system (4). However, most researchers have considered the stiffness of the machine tools structures only in detail design stage.

Nowadays, designers can develop various machine tool structures by using the modular design system, which was proposed by Shinno,H. and Ito,Y. et al (5) - (11), or based on designers’ experiences. To analysis the static, dynamic and thermal stiffness of these proposed machine tool structures finite element method (FEM) is very useful. However, it takes long time to construct the structure analytic models and calculate the static, dynamic and thermal stiffness of these proposed machine tool structures, thus leading difficult to select the suitable structure in a short time. Therefore, developing a new design procedure to assist the designers reduce the machine tool structure design time is necessary.
In this study, an interactive system is proposed to efficiently accomplish conceptual structure design of machine tools. The key point in this interactive system is that all components of one machine tool structure are approximated into conceptual beam elements, with the polar moment of inertia of area, the moment of inertia of area, the cross-sectional area, and the beam length. DOF of the total structure are low because each beam has only two endpoints and twelve freedoms, leading to easily construct or modify the matrix data, for analyzing static, dynamic, and thermal stiffness. First order analysis (FOA) \(^{(12)}\) as a new type of computer-aided engineering (CAE) has been proposed, which assisted the designers to easily determine the automotive body in the concept design stage \(^{(13)}\). In FOA, components of one structure are generally considered to be composed beam elements and panel elements. In this interactive system, the structures are assumed only to consist of beam elements. Therefore, it can be considered as one of the FOA.

The lengths of conceptual beams in machine tool structures are decided based on the design requirements. Then, in the static analysis stage, all of the moments are calculated, by considering all of the cross-sectional areas as the same size. In the dynamic analysis stage, all of the cross-sectional areas are determined. After investigating the actual structures, the actual machine tool structures are formed from the structure consisting of conceptual beams depending on the polar moment of inertia of area, the moment of inertia of area, the cross-sectional area and the beam length. Finally, the appropriate structures are decided by analysis of the thermal stiffness.

Using this interactive system, the suitable machine tool structure with higher static, dynamic and thermal stiffness can be selected among several proposed structures. As a result, it is found that the system has the potential of utilizing as the design tool.

2. Structure Design Procedure

The structural design process in this study is divided into five steps: proposal, modeling, analysis, selection, and conversion. Figure 1 shows the flowchart of the five steps. In step 1, machine tool structures are proposed to be composed of beam elements. According to the requirements such as machining space, the original length of each beam can be determined. Of course, each structure has its special patterns, for example, the column is single type or double type. In step 2, mathematical models of each structure have to be established to analyze the static, dynamic and thermal stiffness and investigate the characteristics of each structure. The step 3 is analysis of the stiffness of all these structures, which proposed in the first step. Then, in step 4, the most suitable structure can been selected, based on the analysis results. In the last step, a conversion method has been proposed to convert the beam structure into the actual structure for realization of the integrity and practicality of this structural design system. Since the complex machine tool structure is considered as a simple model, which is composed of beams, it is easy to analyze the static, dynamic and thermal stiffness of beam structure. Researchers can quickly refine the beam structure based on the analysis results. Therefore, the efficiency of structural design in the conceptual and basic stage is expected to improve significantly.

2.1 Proposal of structure types

Requirements of machine tool design include three main aspects: production (machining capacity, high precision, high speed and so on), processing (shape and mass of work piece, etc), and environment (temperature humidity and vibration). Depending on the requirements, several structures can be proposed as candidates, based on designer’s experience or by the method that proposed by Shinno, H. and Ito, Y. et al. All these structures are considered to be composed of beam elements, and each beam serves as one part of machine tool structure. Therefore, according to the requirement of machining space, the length of each beam has been determined preliminarily, and then the whole structure
appears as the primary shape. During proposing of the structures, three principles have to be considered, that is, (1) The same machining spaces, (2) the same mass and (3) the same material of each structure. The number of proposed structure is arbitrarily decided.

2.2 Modeling of proposed structure types

Following proposing machine tool structures, it is necessary to establish mathematical model for investigating the static, dynamic, and thermal stiffness of proposed structures. Firstly, a Cartesian coordinate system on each structure is defined. Then, the coordinates of two endpoints of each beam can be determined, as shown in Fig. 2, where a machine tool structure is composed of beam elements. The structure has 13 endpoints and 14 beams. The points 1, 5, 9, 10 are considered as fixed-points. The stiffness matrix \([k]\) and the mass matrix \([m]\) of each beam can be set on the basis of the beam theory. According to the combination of circumstance of the structure and by using the coordinate transform system, the total stiffness matrix \([K]\) and the total mass matrix \([M]\) can be also prepared. Parameters of the two matrixes include the cross-sectional area, polar moment of inertia of area, the moment of inertia of area, Young’s modulus, Poisson’s ratio, density, and coefficient of thermal expansion.
In order to investigate the thermal stiffness, it is required to calculate thermal deformations, which caused by the temperature change in the surrounding environment and a machining operation.

Cutting forces loaded on machine tool structure during machining operation are very complex. Thus, it is difficult to set the cutting forces accurately. In this study, the cutting forces are proposed as a constant value in the all-machining spaces.

2.3 Analysis and selection suitable structure

By determining the force \( \{F\} \) loading on machine tool structure by the static analysis system, the static displacement \( \{x\} \) of the structure can be obtained based on Eq. (1). The natural frequencies can be calculated by another system, based on Eq. (2). The model of thermal conductivity is simple because the one-dimensional heat conduction, Equation (3), allows calculating the thermal displacements. It is impossible to analyze the thermal displacements at each point of the whole machining space because it has numerous points. Therefore, some typical points are selected for easy analysis. In general, twenty-seven points in the machining space are selected as analyzing locations. Here, eight corner points and one center point, as shown in Fig. 3, are chosen because they represent actives of the stiffness on the whole machining space.

Depending on the above three properties, the most suitable beam structure with good static, dynamic, and thermal stiffness can be selected.

\[
[K]\{x\} = \{F\} \\
[M]\{\ddot{x}\} + [K]\{x\} = \{0\} \\
\rho CA \frac{\partial T}{\partial t} + \lambda A \frac{\partial T}{\partial x} = -\lambda A \frac{\partial}{\partial x} (T + \frac{\partial T}{\partial x} dx) + \alpha S(T - T_0)
\]

Here, \( \rho \): Density of the material,
\( C \): Specific of the material,
\( A \): Cross-sectional area,
\( \lambda \): Traditional thermal conductivity,
\( \alpha \): Coefficient of thermal traditional,
\( T \): Temperature at one point in the beam,
\( T_0 \): Surrounding environment temperature,
\( S \): Circumference of the cross-section of the beam.

2.4 Converting beam structure to actual structure

Since the selected beam structure is not an actual structure, it is necessary to convert the beam structure into an actual structure. In order to obtain the ratio relation among the moment of inertia of area \( I_y \) and \( I_z \), the torsion constant \( J \), and the cross-sectional area \( A \) of
actual structure cross-sections, the existing machine tool structures are investigated.

The underlying idea of the proposed converting method is to find proper ratio coefficients among the moment of inertia of area $I_y$ and $I_z$, the torsion constant $J$, and the cross-sectional area $A$. Figure 4 shows the flowchart of conversion procedure. The first step is to find a ratio coefficient $\alpha_i$ among the beams. Then, ratio coefficient $\beta_{ij}$ can be found among $I_y$, $I_z$, and $J$. The best ratio coefficients $I_{yi}$, $I_{zi}$, and $J_i$ are calculated by Eq. (4). Accordingly, the correlative part structure of the machine tool with a suitable cross-section shape can be selected. Finally, according to the design requirements, the detailed size of the cross-section shape can be determined. Thereby, the converting from the beam structure into actual structure is realized.

$$
\begin{align*}
I_{yi} & \leftarrow I_{yi} \times \alpha_i \times \beta_{i1} \\
I_{zi} & \leftarrow I_{zi} \times \alpha_i \times \beta_{i2} \\
J_i & \leftarrow J_i \times \beta_{i3}
\end{align*}
$$

3. Case Study: Structural Design of Three-Axis Control Machining Center

Various machine tool structures can be proposed in the conceptual and basic design stage. The emphasis of this study is to discuss the effect of type on the stiffness of structure with the same size level, thus the size of machine tool in the case study is not a critical fact. In order to prove the usefulness of the interactive system, eight typically comparable beam structures, as shown in Fig. 5, have been selected as the proposed original structures. The beam with arrows means movable parts of the structure. The movable direction and ranges such as $X$, $Y$, and $Z$ denoted by the arrows, standing for the machining space, which represent cubic of each beam structure. Each structure has the same machining space $500 \times 500 \times 500$ mm$^3$. Determine all the structures in the same mass, the cross-sectional areas are considered to have different sizes, due to total length of each structure are different. The lengths and cross-sectional areas of these structures are listed in Table 1. In Table 1, the number of beam is the total one composing the structure, the total length is the length of all beams, and the section is the beam cross-section of each beam of the structure.
Table 1  Total length of individual structure

<table>
<thead>
<tr>
<th>Structure</th>
<th>Number of beam</th>
<th>Total length(mm)</th>
<th>Section(mm×mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>15</td>
<td>8000</td>
<td>100 x 100</td>
</tr>
<tr>
<td>II</td>
<td>15</td>
<td>8000</td>
<td>100 x 100</td>
</tr>
<tr>
<td>III</td>
<td>15</td>
<td>8000</td>
<td>100 x 100</td>
</tr>
<tr>
<td>IV</td>
<td>15</td>
<td>8000</td>
<td>100 x 100</td>
</tr>
<tr>
<td>V</td>
<td>16</td>
<td>8500</td>
<td>97.01 x 97.01</td>
</tr>
<tr>
<td>VI</td>
<td>16</td>
<td>8500</td>
<td>97.01 x 97.01</td>
</tr>
<tr>
<td>VII</td>
<td>16</td>
<td>7500</td>
<td>103.3 x 103.3</td>
</tr>
<tr>
<td>VIII</td>
<td>16</td>
<td>9500</td>
<td>94.28 x 94.28</td>
</tr>
</tbody>
</table>

In addition, the same Yong’s modulus $E \times 10^{11}$ Pa, Poisson ratio $\gamma$ 0.33, density $\rho$ 7850 kg/m$^3$, and linear expansion coefficient $1.2\times 10^{-5}$ °C$^{-1}$ for each structure have been supposed.
Cutting forces loading on machine tools are supposed to $F_x$ 1000 N, $F_y$ 1000 N, $F_z$ 1000 N for each structure. Moreover, in order to investigate the thermal stiffness of these structures, the surrounding temperature is proposed to change from 0 to 20°C.

4. Discussion of the Case Study

When the proposed cutting forces are loaded to these structures at one analyzing point, the static deformations take place. Figure 6 shows the example of static deformations of structure VIII from analytic points A to I, corresponding analytic points in the machining space A to I as shown in Fig. 3. All static deformations in 27 analytic points form the static error space, which are errors corresponding analytical points caused in machining space. The obtained results of static stiffness show as error spaces of the proposed eight structures, shown in Fig. 7. It is obvious that the static stiffness of structure I to IV is weaker than structures V-VIII. Therefore, the last four structures have been selected as candidates.

Natural frequency is an evaluation index of the structure dynamic stiffness. Thus, all these natural frequencies of eight structures are calculated, and the correlative dynamic deformation also is obtained. As an example, the parts of the dynamic deformations with their correlative natural frequency are shown in Fig. 8. Three lowest natural frequencies of eight structures are listed in Table 2. In general, the lowest natural frequency attracts attention because the amplitude with the lowest natural frequency is largest. Therefore, the structures V, VI and VIII have been selected as candidates because they have higher lowest natural frequency than others.

Fig. 6  Static deformations of structure VIII

Thermal stiffness is another important evaluation index of a machine tool structure, because a machine tool is not always surrounded at the same temperature. Thermal deformations of the eight structures are evaluated by raising the temperature from 0 to 20 °C. Figures 9 and 10 show examples of thermal deformations of structure VIII and all eight thermal error spaces of proposed machine tool structure respectively. Thermal displacements of structures I-VI are almost at the same level, while those of structures VII and VIII are slightly small. Thus, the structures VII and VIII are selected as candidates for their higher thermal stiffness.
Fig. 7  Error spaces of static deformations of eight beam structures

Fig. 8  Natural frequencies and its vibration modes of structure VIII
Fig. 9  Thermal deformations of structure VIII

Fig. 10  Error spaces of thermal deformation of eight beam structures
Table 2  Lowest three natural frequencies of structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural frequency (Hz)</td>
<td>1st</td>
<td>57.14</td>
<td>57.64</td>
<td>57.36</td>
<td>58.09</td>
<td>77.75</td>
<td>76.68</td>
<td>67.41</td>
</tr>
<tr>
<td>2nd</td>
<td>96.55</td>
<td>98.12</td>
<td>96.55</td>
<td>90.78</td>
<td>143.8</td>
<td>138.2</td>
<td>78.59</td>
<td>110.5</td>
</tr>
<tr>
<td>3rd</td>
<td>136.9</td>
<td>111.5</td>
<td>151.0</td>
<td>125.8</td>
<td>149.6</td>
<td>164.6</td>
<td>152.1</td>
<td>135.0</td>
</tr>
</tbody>
</table>

Considered in a comprehensive way, structure VIII is selected as a suitable structure among the eight proposed structures from the viewpoint of the static, dynamic and thermal stiffness. If the force is changed, static deformations will be changed proportionally, but the selection result will not changed. The change in the temperature is as same as the force loading on machine tool. The selected structure VIII obtained in this study is a beam structure. Conversion that beam structure to an actual structure is now processing, and the result will be reported in next paper.

5. Concluding Remarks

This method is applicable to design a structure in the stage of conceptual and basic of machine tool design. The interactive system, whose key idea is considered the total structure as a combination, which is composed of a finite number of conceptual beam elements, is presented to improve the effective design of machine tool structure. The whole design process does not build the huge data of the total structure that usually analyzes the stiffness of one structure, easily completing the total structure design. Therefore, a suitable structure can be designed in a short time. In other words, a preliminary of the interactive system have been established. Simulation results show this method works more effectively in machine tool structure design. The interactive system has the potential application in other mechanism structure designs. The main results of the study are as follows:

1. The structure of machine tool is proposed to be composed of beams. The interactive system for conceptual and basic design of machine tool structure has been established. By proposed machine tool structure as beams, the whole analysis process is turned to easy, simple, and can be finished in a short time.

2. The analysis method of the static, dynamic, and thermal stiffness of the proposed machine tool structure is developed.

References


