Optimal Design of Machine Tool Bed by Load Bearing Topology Identification with Weight Distribution Criterion

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Abstract

This paper attempts to develop a simple and practical procedure for the optimal design of machine tool bed. In this research, a simplified model is first defined to characterize the bed structure. The load bearing topology of the bed structure is then identified to represent the optimal layout of the inner stiffener plates. Subsequently, detailed sizing optimization is conducted by using a novel criterion which describes the best solution in terms of weight distribution of both the outer supporting panels and inner stiffener plates. Finally, calculation results are elaborated to demonstrate the effectiveness of the proposed method.

Keywords: Machine tool bed; Optimal design; Weight distribution

1. Introduction

Precision is a guideline for machine tool design, which is influenced by many factors including the stiffness error caused by structural deformation, assembly error of the sub-components on tool position, system dynamic responses under excitation of the operational forces, etc [1]. Among these factors, component stiffness is one of the most important factors. In a machine tool system, the bed is among the most critical components which possesses the complicated mechanical structure coupled with the sophisticated load bearing conditions. With the ever-increasing demand in higher machine precision, the requirement for bed’s stiffness is also increasing. In addition, lightweight design is also being pursued for bed structure which is important for a lower cost of material. However, it is difficult to obtain such a successful design due to the intricacy involved, including the diversity of layout pattern, the complexity of structural features as well as the variability of design parameters. So, when the engineers carry out a new design project, it is a common practice for them to depend on the similitude principle and their own engineering experiences to find similar past designs as a starting point, and once the design is accomplished, it is more difficult to modify the bed structure by adjusting dimensions and consequently, engineers cannot determine why the design does or does not work. Therefore, it is looked forward to searching for a novel and effective optimal design approach for machine tool bed.

It is known that the machine tool bed is usually a box structure with inner sub-components (i.e. stiffener plates) located horizontally and perpendicularly. Before getting into the actual design, the question about the layout pattern of inner stiffener plates arises. Actually, the layout optimization is a particularly interesting problem, because the stiffness, strength and dynamic characteristics of the bed structure are dependent on the layout pattern to a major degree. However, it is also a difficult problem, especially when the number of stiffener plates is large and the structure is subjected to a complicated operational (mechanical and thermal) load. Although great effort has been devoted to investigate the stiffener plates layout, most of these studies have been
carried out mainly based on the designer’s experiences, and major focuses have been limited to optimal design of the spacing distances and geometrical dimensions of the stiffener plates under the precondition that their layout pattern has been given in advance [2–4].

In recent years, the development in topology optimization technique has provided a great potential for designers to find not only a proper but an optimal layout solution at the early design stage. However, the full three-dimensional topology optimization is prohibitively expensive, especially for a complicated component such as a machine tool bed. Moreover, due to the bitmap-like calculation results, it is difficult to distinguish the real structural layout pattern including both the location and orientation of the stiffener plates. Therefore, a simple and practical method for the layout optimization is still lacking and needed to be explored.

To the best of the author’s knowledge, this paper suggests a simple and practical procedure for the optimal design of machine tool bed, which involves three major steps, namely, model simplification, layout optimization and detailed sizing optimization. In the first step, a simplified fiber model composed of shell and matrix elements is developed to handle the complications of mechanical structure and boundary conditions considered in the numerical simulation. The next step is the layout optimization, where the concept of load path is introduced to define a topological plot that will facilitate to represent the optimal layout pattern of inner stiffener plates. In the third step, a concise mathematical explanation for the weight distribution law of the bed structure is derived based on the well-known Lagrange conditions, leading to a novel optimality criterion for detailed sizing optimization. In this criterion, the optimal solution is described as an ideal ‘balanced point’ among the main design parameters in terms of weight distribution of both the outer supporting plates and inner stiffener plates. A typical grinding machine tool bed is selected as a design case, and the result confirms the effectiveness of the proposed method.

2. Model simplification

A cylindrical machine tool is illustrated in Fig. 1a, where the bed structure provides a foundation for all other components. The bed structure is depicted in Fig. 1b, which is composed of two parts, one is the front bed and the other is the rear bed. Both are composed of outer supporting panels with inner stiffener plates.

It is known that the grinding process consists in a grinding wheel rotating in parallel to the work piece. The longitudinal feed is produced by driving the worktable longitudinally where the work piece rests. In this end, the loads acting on the bed structure may be grouped into two categories: namely, (1) the inertial loads including the self-weight of the bed and the weight of all other components resting on it; (2) the operational loads such as the moving load of worktable caused by the grinding force. These loads will lead to a complicated deformation combining torsion, bending and compression effects. To ensure the grinding precision, the deformation of the bed structure subjected to either the inertial loads or the operational loads must be controlled to a minimum.
rotations about the nodal x, y, and z axes. There are three options to use the matrix27 to define coefficients, and in this research, we use the symmetric form which is shown in Fig. 2.

Fig. 2. Symmetric form of matrix27 element.

Based on this, the FEA spring model of the front bed structure is constructed, as shown in Fig. 3. The outer supporting panels are divided into shell elements, in which the top panel and the bottom panel should exactly have the same grids. Matrix elements inside the box structure are created by connecting the corresponding nodes between the top and bottom panels.

Fig. 3. Model simplification of the machine tool bed.

3. Layout optimization by load bearing topology identification

To truly get an effective optimization scheme for layout pattern of the inner stiffener plates, attention should be given to the load bearing topology of the outer supporting panel. In fact, the identification of load bearing topology is a particularly interesting problem in structural design, because the stiffness, strength and dynamic characteristics of the bed structure are dependent on the layout pattern of the inner stiffener plates to a great extent. However, it is also a difficult problem, especially when the amount of stiffener plates is large and the layout pattern is intricate. Such a condition is not uncommon when the bed structure is subjected to a combined load with torsion, bending and compression effects. One promising approach to this problem is the load path concept introduced by Kelly [6, 7]. In this concept, the load path is used to define a topological plot that will facilitate to represent the load bearing topology of the component.

Fig. 4. Flowchart of the layout optimization

Figure 4 illustrates the flowchart of layout optimization of the inner stiffener plates, which involves five major steps:

Step 1: A hollow box structure is constructed according to the principal dimension of the bed structure. The outer supporting panels are divided into shell elements. The top and bottom panels have a corresponding relationship between their nodes;

Step 2: The spring model is constructed in which matrix elements are created by connecting the corresponding nodes between the top and bottom panels;

Step 3: The boundary conditions including inertial loads and operational loads are applied on the spring model. Particularly, the torsion effect is simulated by a pair of concentrated moving loads acting along opposite directions at the guiding rail;

Step 4: The upper panel is set to be the design area. A load path-based topology optimization algorithm is utilized to define the optimal material distribution, for algorithm details see literature [8]. Based on this, the load bearing topology of the upper panel is clearly identified;

Step 5: By connecting the springs whose ends in the upper panel are inside the high material density area, a layout pattern of the inner stiffener plates can be determined, as shown in Figure 5.
4. Detailed optimization using weight distribution criterion

Once the layout pattern of the inner stiffener plates is obtained, detailed sizing optimization of the bed structure should be carried out to determine the thickness of its key components including the outer supporting panels and inner stiffener plates. As mentioned earlier, the stiffness error caused by the transverse deformation of the guiding rail installed on the front bed is the most important factor to cause the reduction of the overall grinding precision. In this end, the design objective is to maximize the transverse stiffness \( K_T \) of the bed structure, consequently to minimize the transverse compliance \( C_T \) of the bed structure. \( C_T \) is formulated as follows:

\[
C_T = \left( \sum_{j=1}^{J} u_j^T \right) / F_x
\]  

where \( u_j^T \) is the transverse displacement of node \( j \), \( J \) is the total number of nodes aligned on the guiding rail.

A general formulation of the optimization problem is expressed as follows:

\[
\begin{align*}
\text{Find:} & \quad x = [x_1, x_2, \ldots, x_N]^T \in R^N, \\
\text{Min:} & \quad f(x), \\
\text{Subject to:} & \quad W(x) - W_s = \sum_{i=1}^{N} W_i(x) - W_s = 0,  \\
& \quad x^U_i > x_i > x^L_i, i = 1, 2, \ldots, N
\end{align*}
\]  

where \( x \) is the design vector, \( x_i \) is the thickness of the \( i \)th key component, \( x^U_i \) and \( x^L_i \) are the upper and lower bounds of the design variable \( x_i \); \( f(x) \) and \( W(x) \) are the objective and constraint functions, respectively, in terms of transverse compliance and component weight.

Before the analysis continues, several assumptions concerning both the objective and constraint functions are made as follows:

1. The objective function \( f(x) \) is a continuous derivable function;
2. The constraint function \( W_i(x) \) can be expressed as \( W_i = x_i A_i \rho \). Where \( A_i \) and \( \rho \) are the surface area \( (m^2) \) and material density \( (kg \ m^{-3}) \) of the \( i \)th key component, respectively.

The necessary conditions for a local minimum solution are the Lagrange conditions [9]:

\[
\frac{\partial f}{\partial x_i} + \lambda \cdot \frac{\partial W}{\partial x_i} = 0 \quad (i = 1, \ldots, N)  
\]  

Multiplying the numerator and denominator in Eq. (3) by \( W_i / A_i \rho \), it can be expressed as follows:

\[
-\frac{\partial f}{\partial x_i} / \frac{\partial W}{\partial x_i} = \left( \frac{W_i}{A_i \rho} \right) \frac{\partial f}{\partial x_i} / \left( \frac{W_i}{A_i \rho} \right) \cdot \frac{\partial W}{\partial x_i} = \lambda  
\]  

i.e.

\[
-\frac{W_i \cdot \frac{\partial f}{\partial W_i}}{\frac{\partial W}{\partial W_i}} \cdot \frac{\partial W}{\partial W_s} = \lambda  
\]  

Because

\[
W(x) - W_s = \sum_{i=1}^{N} W_i - W_s = 0  
\]  

Then

\[
\frac{\partial W}{\partial W_i} = \frac{\partial}{\partial W_i} \left( \sum_{i=1}^{N} W_i \right) = 1  
\]  

Substituting Eq. (7) into Eq. (5) yields:
Substituting Eq. (8) into Eq. (6), the Lagrange multiplier \( \lambda \) can be written as:

\[
\frac{1}{\lambda} = \frac{W_o}{\sum_{i=1}^{N} \left( -W_i \frac{\partial f}{\partial W_i} \right)}
\]  

(9)

Substituting Eq. (9) into Eq. (8), the weight of the \( i \)th key component can be determined as:

\[
W_i = \left( -W_i \frac{\partial f}{\partial W_i} \right) \left/ \sum_{i=1}^{N} \left( -W_i \frac{\partial f}{\partial W_i} \right) \right. \cdot W_o
\]  

(10)

Noticing that:

\[
W_i \cdot \frac{\partial f}{\partial W_i} = A_i \rho x_i \cdot \frac{\partial f}{\partial (A_i \rho x_i)} = x_i \cdot \frac{\partial f}{\partial x_i}
\]  

(11)

Then

\[
W_i = \left( -x_i \cdot \frac{\partial f}{\partial x_i} \right) \left/ \sum_{i=1}^{N} \left( -x_i \cdot \frac{\partial f}{\partial x_i} \right) \right. \cdot W_o
\]  

(12)

Let

\[
D_i = \left( -x_i \cdot \frac{\partial f}{\partial x_i} \right) (i = 1,...,N)
\]  

(13)

\[
D_o = \sum_{i=1}^{N} \left( -x_i \cdot \frac{\partial f}{\partial x_i} \right) (i = 1,...N)
\]  

(14)

From Eq. (12), (13) and (14), the weight of the \( i \)th key component can be expressed in simplified form:

\[
W_i = \frac{D_i}{D_o} \cdot W_o \quad (i = 1,...,N)
\]  

(15)

By combining Eq. (9) and (15), we have the following relationship:

\[
\frac{D_1}{W_1} = \frac{D_2}{W_2} = \ldots = \frac{D_i}{W_i} = \ldots = \frac{D_N}{W_N} = \lambda \quad (i = 1,...,N)
\]  

(16)

From Eq. (16), it can be found that in an optimal bed structure, the actual weight of the \( i \)th key component \( W_i \) is proportional to the value of \( D_i \). In the case that \( x_i \) is the thickness of the key component, a set of the weight distribution criterion equations can be further established in the following way:

\[
x_i = \frac{W_o}{A_i \rho} \cdot \frac{D_i}{D_o} \quad (i = 1,...,N)
\]  

(17)

It can be seen that Eq. (17) provides an opportunity to search for the optimal solution in terms of weight distribution of different key components.

The recursion formulas can be solved by an iteration method, and in order to improve the convergence of the calculation process, a relaxation factor \( \alpha \) is introduced into the equations:

\[
x_i^{(k+1)} = \alpha \cdot \frac{W_o}{A_i \rho} \left( \frac{D_i}{D_o} \right)^{x_i^{(k)}} + (1 - \alpha) \cdot x_i^{(k)} \quad (i = 1,...,N)
\]  

(18)

In the original design, the thickness of the outer supporting panel is 20mm, and the thickness of the inner stiffener plates is 18mm. By using the weight distribution criterion, the detailed sizing optimization of both the outer supporting panels and inner stiffener plates are implemented. In the optimal design, the thickness of the outer supporting panel is 21.6mm, the thicknesses of the inner stiffener plates are 15.5mm, 16.2mm, 17.5mm, 17.8mm, 17.5mm, 16.7mm and 16.2mm, respectively. Figure 6 demonstrates the comparison of the maximum deformation between the original and optimal designs. It is found that the maximum deformation is reduced by 19.0%, and the transverse stiffness is improved by 7.82%.
5. Conclusion

This paper attempts to develop a novel and practical optimization approach to provide an eco-efficient bed structure in order to meet increasingly stringent stiffness requirement, whilst meeting customer expectations and minimizing the weight of machine tool system. The proposed approach involves a three-phase procedure. Firstly, a simplified spring model composed of shell and matrix elements is developed to simulate the real bed structure. With this model, the finite element method can be easily and economically employed to identify the load bearing topology of the bed structure under actual operation conditions. After characterizing the layout pattern of the inner stiffener plates, an analytically based weight distribution criteria is presented to determine the thickness of both the outer supporting panels and inner stiffener plates. Optimization results are finally elaborated to demonstrate the effectiveness of the proposed method.

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