DEVELOPMENT OF A DESIGN TOOL SUPPORTING DESIGN REVIEWING
OF MACHINE TOOLS

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ABSTRACT

Since processes of machine tool design are rather experience basis, the design procedures of machine tools need to be more effective and helpful to shorten the time-to-market. It is said that design review at the early stage is the key issue to make the design effective. The series of the research including this paper is trying to propose and verify a new design tool which can support the decision making of a machine tool designer by providing a method of design review. This paper applied a design tool which was proposed by the author to a new machine tool design procedure having wide range of design variations. The tool combined the form-shaping theory which is a well-known mathematical expression method of cutting motions of machine tools, to the Taguchi method which is also a well-known robust design tool. The tool was effective in identifying the effects of machine tool structures, design parameters and error sources on machine performance. Since the tool can identify which factors are critical to machine tool performance and which are not, machine tool designer can tighten critical tolerance of machine components and loosen non-effective tolerance. The paper applied the procedure to example designs of milling machines, and clarified characteristics of two different design concepts. One is a single column milling machine and the other is a gantry type milling machine. The design tool can compare the overall performance of the two machines. It was also possible to clarify which design parameter is the most critical one for the performance of each machine respectively, and what is the key component to be tightened its tolerance to improve accuracy of the machine tool. By these information, the paper concludes that the design tool is useful in design review of machine tools.

1. INTRODUCTION

Machine tool design has been a rather time-consuming and experience-based procedure. However, the products machined by those machine tools tend to have more varieties and quantity deviation. In response to the situation, not only the products design, but also the machine tool structure. By this extension, the design tool can handle not only component errors, but also the structural deformations.

2. DESIGN EVALUATION METHOD

Since there are many sources of error in a machine tool, a design evaluation method needs to take the errors into consideration. This design evaluation method divides errors to two “components errors” and “structural deformation”. “Component errors” are the errors caused by geometric inaccuracies or motion errors of the machine components. On the other hand, “structural deformations” are the errors caused by deformation of the machine structure such as bases, columns, beams, and so on. Most simulation software calculates these errors. The form-shaping theory focuses on component errors to clarify how the kinematic relation of each motion axis of the overall performance of the two machines. It was also possible to clarify which design parameter is the most critical one for the performance of each machine respectively, and what is the key component to be tightened its tolerance to improve accuracy of the machine tool. By these information, the paper concludes that the design tool is useful in design review of machine tools.

A machine tool structure is a chain of directly linked rigid components. An orthogonal coordinate system \( S_i \) corresponding to element \( i \) \((i=0 \text{ to } k)\) is defined. The transformation from \( S_i \) to \( S_{i+1} \) represents a coordinate transformation between components. Form-shaping theory \[8\] represents these respective coordinate transformations by homogeneous transformation matrices (HTM) \[9\]; \( A_i \).

When the homogeneous transformation matrices \( A_i \) are represented by the transformations \( J_i \), \((i=1 \text{ to } 6)\), and the amounts of motions are represented by \( l_i \), we define \( A(i)(j)(k)(l) \) as the expressions of the matrices. Vector \( \bar{r} \) represents the relative displacement between the product and the tool, and the tool shape vector \( \bar{r} \) is also defined. The relation between \( \bar{r} \) and \( \bar{r} \) is given by eq. (1), and \( \bar{r} \) is the definition of the form-shaping function. \( A_i \) is another homogeneous transformation matrix to generally represent transformation errors between elements. By inserting the error matrix \( A_1 \) between \( A(i)(j)(k)(l) \) and \( A(i+1)(j)(k)(l) \) in equation (1), the form-shaping function including errors, \( \bar{r} \) is written as equation (2).

The form-shaping error function \( \Delta r_0 \), expressing the error amount, is defined as the difference between the form-shaping function not containing errors and that containing the errors, as equation (3). The form-shaping error function \( \Delta r_0 \) is a 4 dimensional vector which has error length in the \( x, y, z \) directions for the first three elements.

\[
\begin{align*}
\bar{r}_0 &= A(0)(j_0)(l_0) \cdot A(i)(j_1)(l_1) \cdot A(i+1)(j_2)(l_2) \cdots A(k-1)(j_{k-1})(l_{k-1}) \bar{r} \\
\bar{r} &= A(0)(j_0)(l_0)A_{x0} \cdot A(i)(j_1)(l_1)A_{x} \cdot A(i+1)(j_2)(l_2)A_{x} \cdots A(k-1)(j_{k-1})(l_{k-1})A_{x} \cdot \bar{r} 
\end{align*}
\]

\[
\bar{r} - \bar{r}_0 = A(0)(j_0)(l_0)A_{x0} \cdot A(i)(j_1)(l_1)A_{x} \cdot A(i+1)(j_2)(l_2)A_{x} \cdots A(k-1)(j_{k-1})(l_{k-1})A_{x} \cdot \bar{r} - A(0)(j_0)(l_0) \cdot A(i)(j_1)(l_1) \cdots A(k-1)(j_{k-1})(l_{k-1}) \bar{r} = \sum_{j=0}^{k-1} A_{x} (j+1) (l+1) (j+1) (l+1) \bar{r} 
\]

\[
\begin{align*}
\Delta r_0 &= A(0)(j_0)(l_0) \cdot A(i)(j_1)(l_1) \cdot A(i+1)(j_2)(l_2) \cdots A(k-1)(j_{k-1})(l_{k-1}) \bar{r} \\
\Delta r &= A(0)(j_0)(l_0)A_{x0} \cdot A(i)(j_1)(l_1)A_{x} \cdot A(i+1)(j_2)(l_2)A_{x} \cdots A(k-1)(j_{k-1})(l_{k-1})A_{x} \cdot \bar{r} 
\end{align*}
\]
As shown in the former page, transformation between two local coordinate systems can be expressed by the HTM. Since all the elements of the transformation matrices are target value of the motions plus errors, the errors themselves represent one of the 6 motions. So, every error of a machine tool can be expressed by one of the six errors shown in Table 1, or its combination. Using the component errors, HTM expressing the transformation errors can be written as equation (4). It means that a form-shaping error function shown in equation (2) is an equation having an error matrix (equation (4)) attached to every transformation matrix shown in equation (1).

$$\Delta r_0 = r_{e0} - r_0$$  \hspace{1cm} (3)

Although the original form-shaping theory does not handle structural deformations, those have significant effects on machine tool performance. Therefore, most CAE tools try to calculate the deformations. However, CAE tools are not very efficient in handling component errors such as straightness errors of slides, etc. Since they based on a modeling of macroscopic shape of the machine structure, it is difficult to simulate errors caused by meso/microscopic behaviors of components, such as repetitive deviation of ball slides caused by slight differences of ball diameter, and so on. Of course it can be possible, but focusing on meso/microscopic behaviors results enormous effort in simulating overall machine structure. And it is not a practical choice in design review of machine tools in its early design stage. Because of that, the paper proposed a method to combine form-shaping theory with simplified calculation of structural deformation. For example, deformations caused by static force are simulated as following. As shown in the former section, form-shaping theory based on consecutive transformation between two local coordinate systems assigned to machine tool structural components. In the original form-shaping theory, each component is assumed to be rigid. But, by dividing the components to small and rigid sub-components and assign sub coordinate system to each, it is possible to handle the inner deformation of the structure by the transformation between the first sub-component and the last sub-component in the component. Fig. 1 below shows the sub-components and local coordinate systems assigned to each of the sub-components respectively. By assuming local deviation of component i between two next local coordinate systems by $\delta_{xi}$ and $\gamma_{xi}$, overall transformation between the first and the last local coordinate system of the component i can be written by equation (5) within the X-Y plane. Other deformations of the structure such as thermal deformation and deformation caused by vibration were assumed simply and considered in the calculation.

$$A_{xi} = \begin{bmatrix}
1 & -\gamma_i & \beta_i & \delta_{xi} \\
\gamma_i & 1 & -\alpha_i & \delta_{yi} \\
-\beta_i & \alpha_i & 1 & \delta_{zi} \\
0 & 0 & 0 & 1
\end{bmatrix}$$  \hspace{1cm} (4)

$$A_{xi} = \begin{bmatrix}
1 & -(\gamma_i + \cdots + \gamma_{in}) & 0 & \delta_{x1} + \cdots + \delta_{xn} \\
\gamma_i + \cdots + \gamma_{in} & 1 & 0 & \delta_{y1} + \cdots + \delta_{yn} \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}$$  \hspace{1cm} (5)

3. DESIGN EVALUATION BASED ON THE METHOD

Fig. 2 is an example of a 3DOF milling machine having a column, spindle head, tool and actuator to each axial direction. Table 2 shows the defined design parameters which should be clarified their effect on the machine performance. 15 error factors were also defined to clarify the effect on the machine performance. Among the error factors, some are caused by structural deformations, some are caused by component errors and the others are combinations of both errors. Using the design parameters and error factors, it is possible to calculate the form-shaping function shown in equation (1) and the form-shaping function including component errors and structural deformation shown in equation (2). And calculating the difference of the two functions by equation (3), the form-shaping error function can be calculated. The Taguchi method [10], [11] is widely used in the field of quality engineering. This study uses the Taguchi method to evaluate the dimensional effect imposed on machining errors by the machine structure, when local errors are unknown. Analysis was performed applying the method to the calculated form-shaping error function. The form-shaping theory defines that the length of the form-shaping error function is the shift of the cutting point of the machine tools from the target point. So

<table>
<thead>
<tr>
<th>Component</th>
<th>Y1</th>
<th>\ldots</th>
<th>Yn-1</th>
<th>Yn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate system: S1</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>Component: i-1</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>Component: i</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>Coordinate system: Si+1</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
<tr>
<td>Coordinate system: Si+2</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
</tr>
</tbody>
</table>

Fig.1 Sub-components and the local coordinate systems
that, using the Taguchi method, calculating how the parameters in Table 2 affect the output of the form-shaping error function shows how the design parameters affect the overall machine performance. And the information gives significant suggestions to the design of the machine tool. Fig. 3 shows the effects of the design parameters shown in Table 2 have on the performance of the 3 DOF milling machine shown in Fig. 2.

![Fig. 2 Schematic view of a 3 DOF milling machine](image)

<table>
<thead>
<tr>
<th>Table 2 Design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design parameters</td>
</tr>
<tr>
<td>Workpiece size</td>
</tr>
<tr>
<td>Bearing diameter</td>
</tr>
<tr>
<td>Tool length</td>
</tr>
<tr>
<td>Rotational speed</td>
</tr>
<tr>
<td>Spindle - column distance</td>
</tr>
<tr>
<td>Thickness of the linear slides</td>
</tr>
</tbody>
</table>

Fig. 3 Effect of design parameters to machine performance

4. APPLICATION TO A DIFFERENT DESIGN CONCEPT
   At this section the paper takes a gantry type milling machine as an example and compares to the single column machine. Fig.4 shows the schematic view of the machine. The design parameters defined in the machine are also shown in the table 3. Values of the design parameters were set as the machine has the same working area as the single column type. And the ranges of the error factors were determined by assuming that the machine components have the same tolerance as those of the single column type machine.

![Fig.4 Schematic view of the gantry type milling machine](image)

<table>
<thead>
<tr>
<th>Table 3 Defined design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design parameters</td>
</tr>
<tr>
<td>Product size</td>
</tr>
<tr>
<td>Bearing diameter</td>
</tr>
<tr>
<td>Cross bar length / 2</td>
</tr>
<tr>
<td>Length of the spindle head</td>
</tr>
<tr>
<td>Spindle - cross bar distance</td>
</tr>
<tr>
<td>Thickness of the slides</td>
</tr>
</tbody>
</table>
Fig. 5 shows the result of the calculation expressing how design parameters affect overall machine performance. The result shows that although the error amount itself is almost the same, no design parameter is so critical as “Ld” of the single column type. Fig. 5 indicates that “Ws”, “Lw” and “Ld” are the relatively critical design parameters. Though, all the design parameters are not so critical as “Ld” of the single column type milling machine shown in Fig. 5. It means that the gantry type milling machine is more robust than the single column type against the change of the design parameters.

![Fig. 5 Effect of design parameters on machine performance](image)

In creating a new design concept, there are many possible structures that have different design parameters and error factors. The issue is how a designer can choose an appropriate design for the target products. The Taguchi method does not refer to conceptual design. Some researchers have created another design method for conceptual stages. Since the examples in the paper had different structures and different design parameters, direct comparison wasn’t possible. However, by introducing the assumption that the two machine have the same working area and the two machines uses the same machine components, it was possible to compare the characteristics of the design concepts. By assuming these, the calculation results based on the Taguchi method can show the priority of the designs. By this extension, a machine tool designer can determine the best design concepts for machine tools from several candidates. The accuracy of predicting the positioning error was not enough for assuring the performances of the machines for machine tool users, but was accurate enough in reviewing the designs.

5. CONCLUSIONS

By introducing some simple assumptions to the proposed design evaluation method, it was able to consider not only component errors but also deformations of the structure. Although the component errors were still critical to the overall machine performance, structural deformations had significant effects, too.

Using the extended design evaluation method, two different design concepts of milling machines were compared. As the result, single column type milling machine was sensitive to the variation of “column-spindle distance”. On the other hand, gantry type milling machine was relatively robust against the change of the design parameters such as cross bar length, cross bar-spindle distance”, and so on. Further more, by the extension, it was shown that the design evaluation method was usable for a machine tool designer to determine the best design concepts from several candidates.

References