

# DEVELOPMENT OF A DESIGN TOOL SUPPORTING CONCEPTUAL DESIGN OF MACHINE TOOLS

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## INTRODUCTION

Since processes of machine tool design are rather experience basis, design procedures from conceptual design through detailed design often take long time. At the same time, the variety of target products of machine tools is growing larger and larger. Conceptual design is said to be very important to create appropriate designs and to shorten the time-to-market of products. The series of the research [1]-[3] including this paper has been trying to develop a new design tool to support decision making at the conceptual design of machine tools. The design tool which has been proposed by the author combines the form-shaping theory [4] of and the Taguchi method [5]. It was effective in selecting generic size and structure of machine tools, or determining critical design parameters and error factors for its performance. However, since the original form-shaping theory assumes that the structural components of the machine tool are rigid, it couldn't consider deformation of the machine tool structures such as deformations caused by machine weight or thermal deformations. As the result, the values of the error factors used in the calculation were not very accurate and the accuracy of the prediction wasn't enough. This paper combines the proposed design tool with FEM analysis to determine the amount of error factors. The FEM tool is used to calculate structural deformations of machine tool structures. The proposed design tool offers a simplified method to consider not only component errors but also structural deformations, combining proposed design tool with FEM analysis. By this extension, the tool can support systematic design of machine tools.

## DESIGN EVALUATION METHOD

A machine tool structure can be thought of as a chain of directly linked rigid components extending from the product through the cutting tool. An orthogonal coordinate system corresponding to each element is defined. The transformation between two local coordinate systems is represented by a coordinate

transformation. Form-shaping theory represents these respective coordinate transformations by homogeneous transformation matrices (HTM) [6]. In an ordinary machine tool, HTM is represented by a parallel transition along the X, Y or Z axes or rotation around the axes. Each of these six coordinate transformations is assigned a distinguishing number, such as transformation along the X-axis being 1, and so on. By writing the HTM of  $i$ th element as  $A_i$ , vector represents the relative displacement between the product and the cutting tool, is given by equation (1). The equation is the definition of the form-shaping function that expresses the cutting motions of the machine tool. Actual machine tools have imperfect alignment, and experience thermal deformation, wear, and many other sources of error. In order to describe actual cutting motions, one must take these errors into account. Such errors can for convenience's sake be treated as errors in transformations between elements. Another homogeneous transformation matrices  $A_{\varepsilon_i}$  to generally represent transformation error between elements are defined. (Equation 2) By inserting the error component matrix  $A_{\varepsilon_i}$  between  $A_i$  and  $A_{i+1}$  in equation (1), the form-shaping function including errors, is written as equation (3). The form-shaping error function expressing the error as a quantitative deviation from the target value, is defined as the difference between the form-shaping function with and without errors, as equation (4). By analyzing the equation, it is possible to evaluate how each design parameter and error factor affects the overall performance.

$$\vec{r}_0 = A_1 A_2 \cdots A_i A_{i+1} \cdots A_n \times \vec{r}_t \quad (1)$$

$$A_{\varepsilon_i} = \begin{bmatrix} 1 & -\gamma_i & \beta_i & \delta_{xi} \\ \gamma_i & 1 & -\alpha_i & \delta_{yi} \\ -\beta_i & \alpha_i & 1 & \delta_{zi} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\vec{r}_{\varepsilon 0} = A_1 A_{\varepsilon 1} A_2 \cdots A_i A_{\varepsilon i} A_{i+1} \cdots A_n \times \vec{r}_i \quad (3)$$

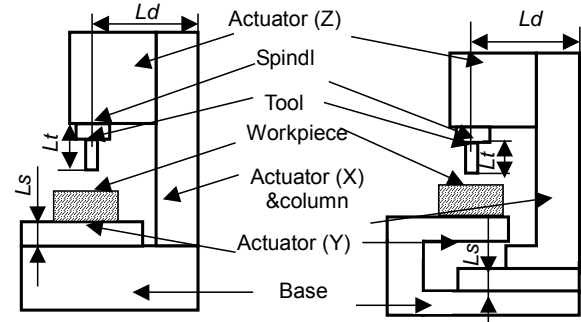
$$\Delta \vec{r}_0 = \vec{r}_{\varepsilon 0} - \vec{r}_0 \quad (4)$$

$\vec{r}_0$ : from-shaping function,  $\vec{r}_i$ : tool shape vector,

$\vec{r}_{\varepsilon 0}$ : form-shaping function with errors,  $\Delta \vec{r}_0$ : from-shaping error function

### LISTING OF DESIGN OPTIONS

In creating a new design concept, there are many possible structures that have different sequences of motion axes. The issue is how to apply the proposed design evaluation method to create a design concept for a machine tool. Performances of several designs can be compared by introducing some assumptions into the Taguchi method. By assuming that every design concept has the same control factors, noise factors and their ranges of variation, the results calculated by the Taguchi method are expected to show the rank order of the designs directly. By the calculation result, a machine tool designer can determine the best design concepts for machine tools from several listed designs. It is common to represent transitional motions along the X, Y and Z axes as 1, 2 and 3, and rotational motions around the X, Y and Z axes as 4, 5 and 6. Using this convention, milling machines that have three transitional motions and one spindle rotation can be categorized into 4 major structural types. Those 4 are shown in Fig.1 (a)–(d). A significant question is which of the four commonest types has the best theoretical performance. To isolate the effect of machine tool structure, common design parameters and noise factors were defined. Tables 1 and 2 show the defined noise and control factors.



(c) Type 20136

(d) Type 01236

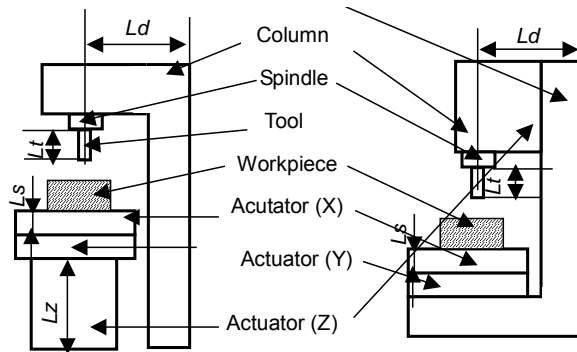
FIGURE 1 Design options of milling machines

TABLE 1 Control factors

Factor name	Variable
Workpiece size	$Ws$
Bearing diameter	$Db$
Rotational speed	$N$
Tool length	$Lt$
Spindle - column distance	$Ld$
Thickness of the linear actuators	$Ls$

TABLE 2 Noise factors

Name of the factor	Variable
Rotational errors of the horizontal guide ways	$\alpha_1, \beta_1, \gamma_1$
Axial error of the horizontal guide ways	$\delta_{\alpha 1}$
Straightness error of horizontal guide ways (H)	$\delta_{\beta 1}$
Straightness error of horizontal guide ways (V)	$\delta_{\gamma 1}$
Rotational errors of the vertical guide way	$\alpha_3, \beta_3, \gamma_3$
Straightness error of the vertical guide way (H)	$\delta_{\alpha 3}$
Straightness error of the vertical guide way (V)	$\delta_{\beta 3}$
Axial error of the vertical guide way	$\delta_{\gamma 3}$
Rotational errors of the spindle	$\alpha_4$
Eccentricity of the spindle	$\delta_{\alpha 4}$
Expansion of the spindle	$\delta_{\beta 4}$



(a) Type 12306

(b) Type 12036

These factors were defined in four machine tool types to clarify the effect of machine tool structure. The six control factors,  $Ws$ ,  $Db$ ,  $N$ ,  $Lt$ ,  $Ld$  and  $Ls$  from Table 1 were considered to be independent control factors. Each form-shaping error function (for the design shown in Fig.1) can be expressed using the parameters defined in Tables 1 and 2. A designer needs to compare four form-shaping error function to evaluate the performance difference of the designs with the same control and noise factors.

### CONSIDERATION OF STRUCTURAL DEFORMATIONS

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 calculation of structural deformation based on FEM. Considered structural deformations are categorized and shown below.

- (1) Deformation caused by static force.
  - a) Deformation caused by machine weight
  - b) Deformation caused by cutting force
- (2) Thermal deformation.
  - a) Thermal deformation of a tool caused by cutting heat.
  - b) Thermal deformation of a spindle caused by heat generation at the motor/bearing.

Not only the above-mentioned structural deformation, but also component errors such as eccentricity of bearings or straightness errors of slides should be considered. Component errors are also important for overall machine performance. As it was mentioned, to calculate component errors would not be easy. So, the paper assumed component errors by using guaranteed value in component catalogs. Sum total of the calculated structural deformation and component errors are equivalent to the geometric errors of the machine tool element that can be written generally by equation (2) in the previous section.

### COMBINING WITH FEM

To combine the proposed design evaluation method to an existing FEM based analysis, it is necessary to calculate the deformation of each structural component by FEM. Deviation between the local coordinate system assigned to one end of the component, and the one assigned to the other end, can be expressed by equation (2) in the former section. The result of the calculation by FEM expresses each element of the homogeneous transformation matrix

shown in the equation. For example, expansion of the component to Z axis is equal to  $\delta z$  shown in the matrix, and bending around the X axis is  $\alpha$ , as well. The next figure shows deformation of a column of a milling machine. Of course, since the purpose of the design tool is to support conceptual design of a machine tool, the detailed structures of the components have not been determined yet, in this stage. However, it is possible to roughly estimate the deformation by deciding dimensions and the material. More detailed inner structures such as ribs, wall thickness, etc. can be determined by referring examples of existing machine tool structures in the database. The result shown in Fig.2 was used to calculate the overall positioning error between the cutting tool and the workpiece, which was defined by equation (4).

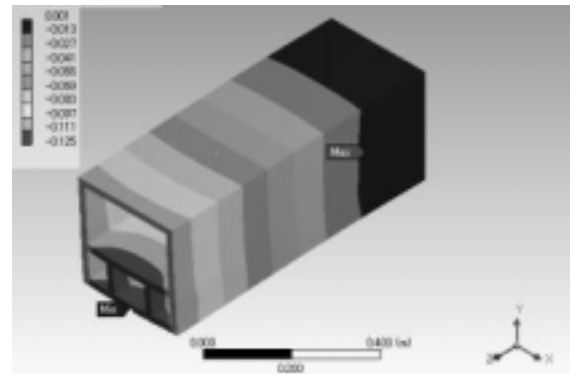
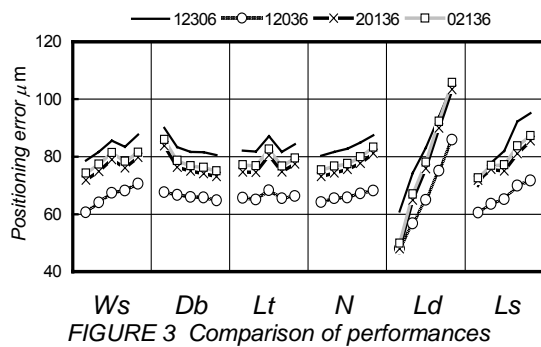


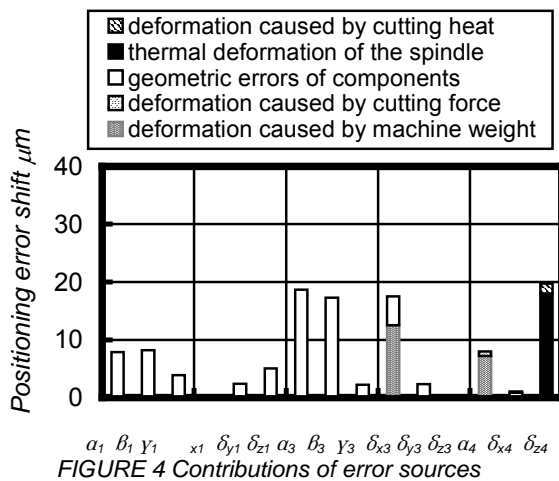
FIGURE 2 Deformation of a typical column of a milling machine

### DESIGN SUGGESTIONS BASED ON THE CALCULATION RESULTS

The same ranges of noise factors and design parameters were estimated roughly, and substituted into the four form-shaping error functions of four machines shown in the previous section. Fig.3 shows comparisons of the theoretical performance. According to the figure, when the design parameters vary within some defined ranges, the lines marking the positioning error of type 12036 are always the lowest, and those of type 12306 are the highest. Among the 6 control factors defined in the Table 1, "Ld," which represents the spindle-column distance, is the most critical parameter affecting machine performance. The figure shows that type 12036 has better theoretical performance than types 12306 and 01236. Based on these results, type 12036 was selected as the "best" design for a milling machine from the 4 options shown in Fig.1.



Next Fig.4 indicate influences of error factors on the overall error amount. To calculate the error contributions shown in the figure, noise factors defined in the Table 2 were changed accordingly to the assigned range of each factor. The each bar shows the difference of the overall error amount when the corresponding noise factors take the lowest and highest value.



The information obtained by Fig.3 and 4 suggest us which design parameters should be designed carefully to obtain higher performance, and also clarify which components should have tighter tolerance to improve the machine performance. From Fig.3, following design suggestions concerning to the design parameters can be derived.

- 1) The most critical design parameters was the distance of the spindle from the vertical column.
- 2) The thickness of the slides ( $L_s$ ) and the product size ( $W_s$ ) had the next largest influence.
- 3) The diameter of the spindle ( $Db$ ) and the rotational speed ( $N$ ) have smaller impacts.
- 4) The length of the tool ( $L_t$ ) has no evident influence on the machine performance.

From Fig.4, some design suggestions about the error factors are also possible.

- 1) Rotational errors of the vertical guide way ( $\alpha_3, \beta_3, \gamma_3$ ) have the largest influence on the performance of the standard machine tool.
- 2) Rotational errors of the horizontal guide ways ( $\alpha_1, \beta_1, \gamma_1$ ) have relatively large impacts.
- 3) Thermal expansion of the spindle ( $\delta_{z4}$ ) plays an important role. It has to be improved to obtain high accuracy.
- 4) Structural deformations caused by machine weight are not the primary error sources, but still have important effects.

### CONCLUSIONS

The proposed design evaluation tool was effective in identifying the critical design parameters and error factors of a machine tool. By combining the tool with FEM analysis which can calculate structural deformation more precisely, it was possible to obtain guidelines for conceptual design of machine tools, without design experience and detailed calculation.

As the results of the design review, spindle-column distance had an important effect. As for error factors, geometric errors of components, especially rotational errors of vertical guides had significant influences on performances. Thermal expansion of the main spindle was also a critical error source. The results help us to determine which errors should be minimized or eliminated, in designing a precise machine tool.

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