Development of a Design Tool for Machine Tools Combining Conceptual Design Support and Detail Design Method

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1 Backgrounds

Machine tool design has been a rather 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 tools design should have efficiencies. For that purpose, a design tool which can review machine tools design in its early stage whether the design is appropriate or not, will be helpful. The design tool does not need to be too accurate in predicting machine tool performance. But it should review machine tool design without prototyping or precise modeling. In order to support machine tool design, the author proposed a design tool [1]-[3] combines the form-shaping theory [4] of machine tools and the Taguchi method [5]. Originally, the form-shaping theory assumes that the structural components of the machine tool are rigid objects. However, deformation of the machine tool structures such as deformation caused by static force or heat affect the machine tool performance significantly. The proposed design tool offers a simplified method to consider those deformations of machine tool structure, combining with component errors which are also critical for machine tool performances. By this extension, the design tool can clarify which error factors of machine tools have considerable effect on the performance. By doing this, it can support systematic design of machine tools.

2 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 S_i corresponding to element i (i = 0 to k) is defined. The translation from S_i to S_{i+1} is represented by a coordinate transformation. Form-shaping theory represents these respective coordinate transformations by homogeneous transformation matrices [7]; A_i. In an ordinary machine tool, A_i is represented by a parallel translation along the *x, y* or *z* axes or rotation around the axes. Each of these six coordinate transformations is assigned a distinguishing number, with movement parallel to the *x*-axis being 1, and so on. When the homogeneous transformation matrices A_i are represented by the transformations j_i, (= 1 to 6), and the amount of each motion is represented by l_i, we define $A(i)(j_i)(l_i)$ as the expression of the matrices. Vector $\vec{r}_0$ represents the relative displacement between the product and the tool, and the tool shape vector $\vec{r}_t$ is also defined. The relation between $\vec{r}_0$ and $\vec{r}_t$ is as given by equation (1), and $\vec{r}_0$ is the definition of the form-shaping function that expresses the cutting motions of the machine tool. The theory that expresses cutting motions mathematically is called form-shaping theory. 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 may for convenience's sake be treated as errors in transformations between elements. I defined another homogeneous transformation matrix $A_{\varepsilon i}$ (eq. (2))to generally represent transformation error between elements. By inserting the error component matrix $A_{\varepsilon i}$ between $A(i)(j_i)(l_i)$ and $A(i+1)(j_{i+1})(l_{i+1})$ into equation (1), the form-shaping function including errors, $\vec{r}_{\varepsilon 0}$ is written as equation (3). The form-shaping error function $\Delta \vec{r}_0$, 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). The form-shaping error function $\Delta \vec{r}_0$ is a 4 dimensional vector which has error lengths in the *x, y, z* directions for the first three elements. The last element of $\Delta \vec{r}_0$ is 0, because $\Delta \vec{r}_0$ is defined as the difference between $\vec{r}_0$ and $\vec{r}_{\varepsilon 0}$.

$$\begin{aligned}\vec{r}_0 &= A(0)(j_0)(l_0)\cdot\cdot A(i)(j_i)(l_i)\\ &\quad A(i+1)(j_{i+1})(l_{i+1})\cdot\cdot A(k-1)(i_{k-1})(l_{k-1})\vec{r}_t\end{aligned} \tag{1}$$

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

$$\begin{aligned} \vec{r}_{\varepsilon 0} = A(0)(j_0)(l_0)A_{\varepsilon 0} \cdot\cdot A(i)(j_i)(l_i)A_{\varepsilon i} \\ A(i+1)(j_{i+1})(l_{i+1})A_{\varepsilon i+1} \cdot\cdot \\ A(k-1)(j_{k-1})(l_{k-1})A_{\varepsilon k-1} \cdot \vec{r}_t \end{aligned} \quad (3)$$

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

To achieve a machining tolerance that is stable under a variety of machining conditions, a method is needed to obtain a design that is robust with respect to unknown local errors. The Taguchi method is widely used in the field of quality engineering, and provides an environment for robust design. 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 by applying the method to the form-shaping error function. The Taguchi method allows us to calculate combinations of values of control factors to optimize an evaluation function, when given noise factors fluctuate within given ranges. In this study, the primary objective is to determine the effect on machining performance of structural design, when some local errors exist in the various components of the machine tool. Therefore, it is appropriate to use the design parameters and product dimensions as control factors and the local errors as noise factors. We define Δx, Δy, Δz as the magnitudes of the errors in each direction. In other words, Δx, Δy, Δz are the first 3 elements of the form-shaping error function defined by equation (4) Then $(\Delta x^2+\Delta y^2+\Delta z^2)^{1/2}$ is used as the evaluation function and the quantity that indicates machine performance. As the Taguchi method presents, orthogonal arrays are applied to the defined control and noise factors. When the value of the evaluation function at *i*th trial is expressed as equation (5) and the number of trials is "*n*", the average of the function is given by equation (6). And with *V* being the variance of the function, the SN ratio, which indicates the robustness of machine performance to the noise factors, is expressed by equation (7).

$$f_{ei} = (\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2} \quad (5)$$

$$f_{em} = \sum_{i=1}^{n} f_{ei} / n \quad (6)$$

$$Sn = -10\log(V + f_{em}) \quad (7)$$

3 Consideration of structural deformations

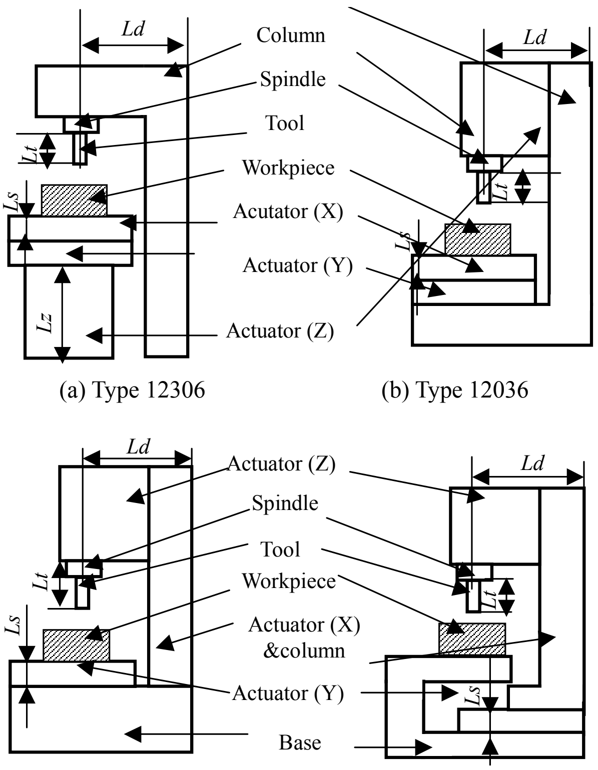
Although the original form-shaping theory does not handle structural deformations, those have significant effects on machine tool performance. Therefore, most CAE tools try to calculate the deformations. However, CAE tools are not very efficient in handling component errors such as straightness errors 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 cuttin heat.
b) Thermal deformation of a spindle caused by heat generation at the motor/bearing.
c) Thermal deformation caused by external heat sources

To take these error factors into account, a relatively simple machine tool structure was assumed and deformation of each component caused by abovementioned error sources was calculated. Not only the 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.

4 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. The performance 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 means of this extension, a machine tool designer can determine the best design concepts for machine tools from several listed designs. Tracking the components from the workpiece to the cutting tool, it is possible to categorize machine tool structures by the number of components that appear before the machine tool base. It is common to represent translational 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 translational motions and one spindle rotation can be categorized into 4 major structural types, by the distribution of DOF. Those 4 are shown in Fig. 1. (a) –(d). Type 12036 is frequently seen in small/medium size drilling machines. Type 20136 is called a column-traverse type machine and is often used for relatively large products such as automobile parts, because it does not require extra space for table movement. Type 01236 is sometimes seen in a manufacturing system called "transfer line," while type 12306 is rarely seen in actual machine tools. 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.



(a) Type 12306 (b) Type 12036

(c) Type 20136 (d) Type 01236

Fig.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	α_1
	β_1
	γ_1
Axial error of the horizontal guide ways	δ_{x1}
Straightness error of the horizontal guide ways (H)	δ_{y1}
Straightness error of horizontal guide ways (V)	δ_{z1}
Rotational errors of the vertical guide way	α_3
	β_3
	γ_3
Straightness error of the vertical guide way (H)	δ_{x3}
Straightness error of the vertical guide way (V)	δ_{y3}
Axial error of the vertical guide way	δ_{z3}
Rotational errors of the spindle	α_4
Eccentricity of the spindle	δ_{x4}
Expansion of the spindle	δ_{z4}

These factors were defined in four machine tool types to clarify the effect of machine tool structure on machine performance. The six control factors, *Ws, Db, N, Lt, Ld* and *Ls* from Table 1 were considered to be independent control factors. At the same time, *Ld* was selected to represent the overall size of the machine tool. An L25 array was used for the control factors, and an L16 array for 15 noise factors shown in Table 2. Each form-shaping error function ($\Delta\vec{r}_0$ for the design shown in Fig. 1) can be expressed using the parameters defined in Tables 1 and 2. Equations (8) – (11) are the form shaping error functions of milling machines corresponding to the design candidates shown in Fig. 1(a) - (d). A designer needs to compare these four equations to evaluate the performance difference of the designs with the same control and noise factors.

$$\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta z\\ 0\end{bmatrix}=\begin{bmatrix}\delta_{x1}+\delta_{y1}+\delta_{x3}+\delta_{x4}-\beta_4\cdot Lt+\beta_3(Lz+2Ls)\\ +\alpha_1(2Ls+h)+\beta_1(Ls+h)-\gamma_1\cdot d\\ \delta_{x1}+\delta_{y1}+\delta_{y3}+\delta_{x4}-\alpha_3\cdot(Lz+2Ls)\\ -\beta_1\cdot(2Ls+h)-\alpha_1\cdot(Ls+h)\\ 2\delta_{z1}+\delta_{z3}-\delta_{z4}+\alpha_1\cdot d\\ 0\end{bmatrix} \quad (8)$$

$$\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta z\\ 0\end{bmatrix}=\begin{bmatrix}\delta_{x1}+\delta_{y1}+\delta_{x3}+\delta_{x4}-(\beta_3+\beta_4)\cdot Lt\\ +\alpha_1(2Ls+h)+\beta_1(Ls+h)-\gamma_1\cdot d\\ \delta_{x1}+\delta_{y1}+\delta_{y3}+\delta_{x4}-(\alpha_3+\alpha_4)\cdot Lt\\ -\beta_1\cdot(2Ls+h)-\alpha_1\cdot(Ls+h)\\ 2\delta_{z1}+\delta_{z3}-\delta_{z4}+\alpha_3\cdot Ld+\alpha_1\cdot d\\ 0\end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ 0 \end{bmatrix} = \begin{bmatrix} \delta_{x1} + \delta_{y1} + \delta_{x3} + \delta_{x4} - (\beta_3 + \beta_4) \cdot Lt \\ + (\alpha_1 + \beta_1)(Ls + h) - (\gamma_1 + \gamma_3) \cdot Ld \\ \delta_{x1} + \delta_{y1} + \delta_{y3} + \delta_{x4} - (\alpha_3 + \alpha_4) \cdot Lt \\ - (\alpha_1 + \beta_1)(Ls + h) + \gamma_1 \cdot w \\ 2\delta_{z1} + \delta_{z3} - \delta_{z4} + (\alpha_1 + \alpha_3) Ld - \alpha_1 \cdot w \\ 0 \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ 0 \end{bmatrix} = \begin{bmatrix} \delta_{x1} + \delta_{y1} + \delta_{x3} + \delta_{x4} - (\beta_3 + \beta_4) \cdot Lt + \alpha_1 (2Ls + h) \\ + \beta_1 (Ls + h) - (\gamma_1 + \gamma_3) \cdot Ld - 2\gamma_1 \cdot d \\ \delta_{x1} + \delta_{y1} + \delta_{y3} + \delta_{x4} + (\alpha_3 + \alpha_4) \cdot Lt \\ - \beta_1 (2Ls + h) - \alpha_1 (Ls + h) + \gamma_1 \cdot w \\ 2\delta_{z1} + \delta_{z3} - \delta_{z4} + (\alpha_1 + \alpha_3) Ld - \beta_1 \cdot w \\ 0 \end{bmatrix} \quad (11)$$

5 Design review of machine tools

The same ranges of noise factors and design parameters were estimated roughly, and substituted into the four form-shaping error functions shown in the previous section. In the calculation, the scale effects of the noise factors were also considered. For example, the "expansion of the spindle" is likely to be smaller, when the machine tool size is small. Fig. 2 shows comparisons of the theoretical performance. According to the figure, when the design parameters vary within the 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, "*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 and01236. 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.3 shows the more detailed analysis of the effect of machine tool size which is represented by "*Ld*". The horizontal axis of the figure shows that the "*Ld*" divided by that of the standard machine tools. The sizes of the machine tools were assumed to be changed proportionally.

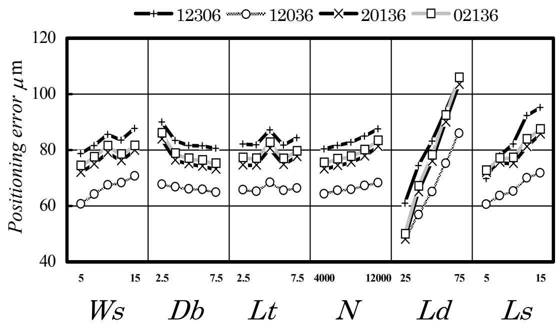


Fig. 2 Performance comparisons

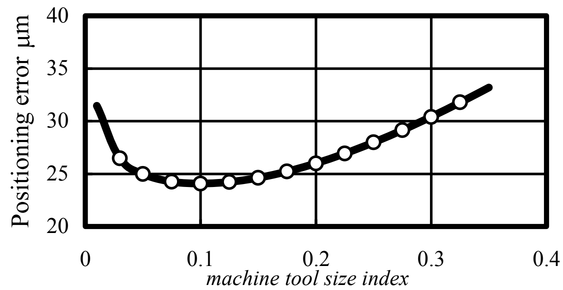


Fig.3 Effect machine tools size

According to fig.3, it can be said that, considering only the theoretical positioning errors, a machine tool that is 1/10 of the standard machine tool has the smallest error. Although there are many other design constraints and requirements for machine tools, a miniature machine tool having 1/10 size of the standard machine tool has a better theoretical performance. Especially, for micro mechanical fabrication which is getting practical and important in recent micro device productions, miniature machine tools are possible options for design. Actually some miniature machine tools have been developed and showed practical capability for machining. [8]-[11]

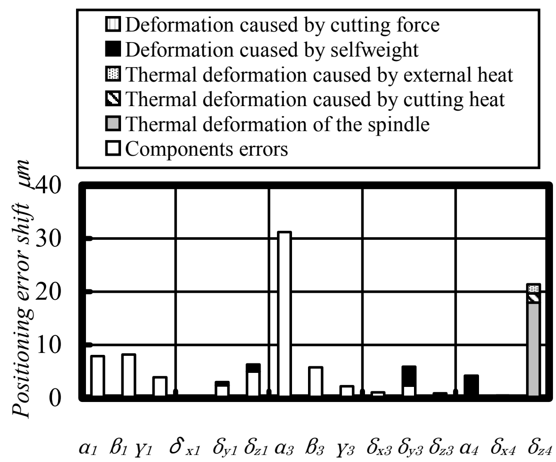


Fig.4 Contributions of error sources (standard)

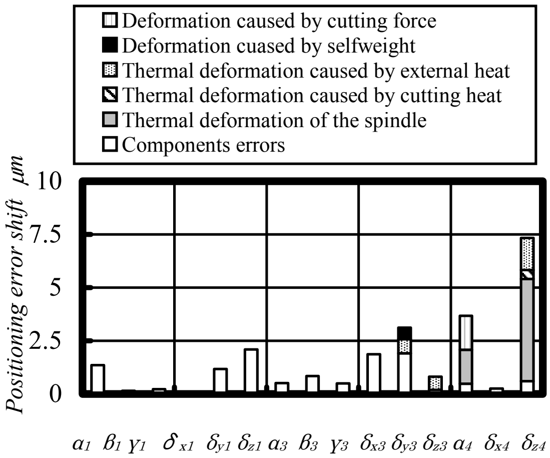


Fig.5 Contributions of error sources (miniature)

Fig.2 suggests which design parameter and fig. 4 and 5 indicate which error factors have large influence on the overall error amount. To calculate the error contributions shown in fig.4 and 5, noise factros defined in the table 2 were changed accordingly to the assigned range of each factors. The each bar shows the difference of the overall error amount when the corresponding noise factors take the lowes and highest value. The information suggests us to determine which design parameters should be designed carefully to obtain higher machining tolerance. And it also clarifies which machine components should have tight tolerance to improve the machine performance. From fig.2, following design suggestions about design parameters can be derived.

1) The most critical design parameters was the distance of the spindle from the slide.
2) The thickness of the slides and the product size had the next largest influence.
3) The diameter of the spindle and the rotational speed has relatively smaller impacts.
4) The length of the tool has no evident influence on the machine performance.

From fig.4 and 5, design review concerning error factors is possible. By comparing two figures, it is also possible to obtain design guidelines corresponding to the sizes of machine tools, such as, "when a machine tool designer designs a miniature machine tool, it these components and these error sources should be improved", etc. Following descriptions are some of the results of the design review.

1) Rotational errors of the vertical guide way have the largest influence on the performance of the standard machine tool.
2) Rotational errors of the horizontal guide ways have relatively large impacts.
3) Thermal expansion of the spindle plays an important role both for the standard machine tool and the miniature machine. It has to be improved to obtain high accuracy.
4) For miniature machine tools, rotaional errors of the vertical guide ways are not very important. Straightness errors of slides are relatively important.
5) External heat sources are more critical for miniature machine tools than for standard machine tools.
6) Structural deformations caused by machine weight are negligible for the miniature machine tool.

6 Examination of the method

As calculated in the previous section, type 12036 was predicted to have the best performance among the 4 major types. And a miniature machine tools having 1/10 size of the standard machine is predicted to be the suitable size for micro mechanical fabrication. The best way to examine this result is to make milling machines actually and compare their positioning accuracies. However, producing milling machines of practical size would need too much time and budget, so miniature milling machines were prototyped based on the theoretical results. Fig. 6 show a schematic view of the miniature milling machine designed as an experimental model for the design evaluation tool. The machine has a 57.5 mm column-spindle distance. Positioning errors of the model were measured for comparison with the predicted results. At the same time, the prototyped miniature milling machine was used in the Microfactory project [6] and proved to have practical machining capability. Fig. 7 shows the actual miniature milling machine designed in Fig. 6. The machine size being approximately 12 x 12 x 10 cm, it was able to perform end-milling up to 2 mm in depth, and surface milling of an area up to 4 x 4 mm. DC servo motors were used for the linear and rotational motions. Fig.8 is the results of comparison of the measured errors and calculated errors for the miniature mill shown in fig.6. The figure shows that the measured errors are not very different form the calculated value. The fact leads us to conclude that the proposing design tool have sufficient accuracy for the usage in the conceptual design stage of machine tool.

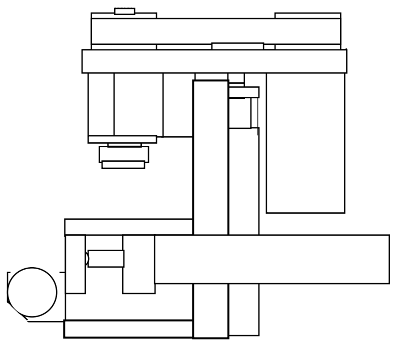


Fig. 6 Miniature mill design (type 12036)

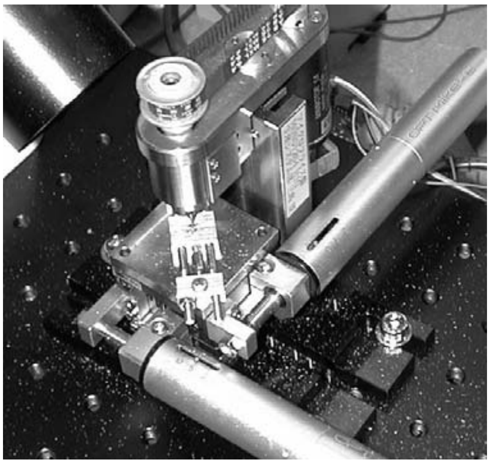


Fig. 7 Prototyped experimental model

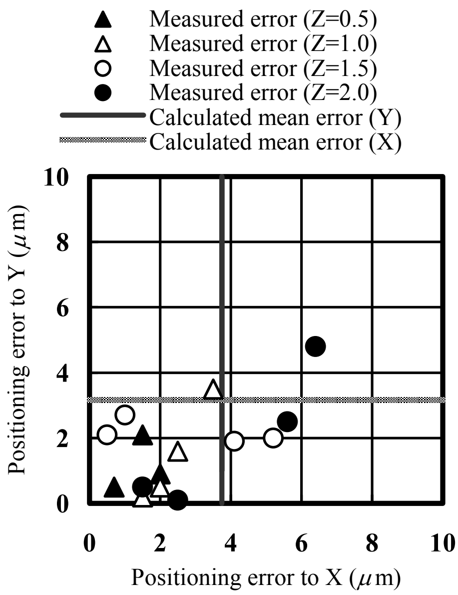


Fig.8 Comparison of measured and calculated errors

7 Conclusions

The proposed design evaluation tool was effective in identifying the critical design parameters and error factors of a machine tool. By combining a method which is suitable for determining which factors are significant for overall machine performance, and a method 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, machine tool size which was represented by spindle-column distance had an important effect on machine performance. Therefore, designing a machine tool in a proper size is a good strategy for obtaining better performances by less cost. As for error sources, geometric errors of components, especially straightness errors of linear slides had significant influences on machine performance. Thermal expansion of the main spindle was also a critical source of error. The results led us to conclude that, in designing a precise miniature machine tool, these errors should be minimized or eliminated.

Calculated and measured errors of a miniature milling machine which was originally developed for the microfactory, were compared to prove the effectiveness of the design tool. The results showed a good match and proved that the design method was effective enough for conceptual design of machine tools.

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