

A STUDY ON OPTIMIZATION OF MINIATURE MACHINE TOOL DESIGN

Nozomu Mishima

National Institute of Advanced Industrial Science and Technology
1-2 Namiki, Tsukuba, Ibaraki, 305-8564 JAPAN

Abstract

AIST, Japan proposed and prototyped some new miniature machine tools for micro mechanical fabrication. Although the miniature machine tools had considerable machining capabilities, design optimizations of the machines have not been studied enough. Since the miniature machine tool designs are not fully supported by existing design experience, strategies and guidelines of designs are strongly demanded. In order to support miniature machine tool design, a design tool combines the form-shaping theory of machine tools and the Taguchi method was proposed.

This paper applied the design tool to a new machine tool design procedure of not only miniature machine tools but also wide range of design variations. The tool was effective identifying which of the several designs had the best performance and which of the design parameters had the critical effect on improving the machining accuracy of machine tools. Finally, the paper concludes that the design tool is useful in design optimization of machine tools.

1. Introduction

“Microfactory” is a name of an extremely small manufacturing system that consists of miniature machine tools and manipulators. The concept was proposed by AIST, Japan, in 1989. The first prototype of the microfactory was developed in 1999 by the author’s research group in AIST [1]. It could perform manufacturing processes involving machining and parts assembly in a desktop space. Key components of the microfactory were miniature machine tools such as micro-lathe [2] and micro-mill [3]. However, although each miniature machine tool demonstrated rather good machining capability, there was no assurance that the individual machine designs were optimized. There was no theoretical background for those designs, including an analysis of structures and so on. Since, for miniature machine tools, existing experience with normal machine tool designs may not be applicable and the miniature machines have wider design choices than normal machine tools have, (due to its small size and fewer constraints), there is a strong demand for a design tool to analyze machine performance without the need for prototyping. The proposed design tool [4] is used in this paper for design optimization 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 transformation from S_i to S_{i+1} represents a coordinate transformation between components. Form-shaping theory [5] represents these respective coordinate transformations by homogeneous transformation matrices [6]; A_i . In an ordinary machine tool, A_i is represented by one of either parallel transformation along the x , y or z axes or rotation around the axes. Each of these six coordinate transformations is assigned a number to distinguish them, with parallel movement along the x -axis being 1, and so on. When the homogeneous transformation matrices A_i are represented by the transformations j_b , ($=1$ to 6), and the amounts of motions are represented by l_b , we define $A(i)(j_i)(l_i)$ as the expressions 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 eq. (1), and \vec{r}_0 is the definition of the form-shaping function that expresses the cutting motions of the machine tools. An actual machine tools have alignment errors, thermal deformation, wear and many other sources of errors. Such errors may for convenience's sake be treated as errors in transformations between elements. We define another homogeneous transformation matrix A_{ei} to generally represent transformation error between elements. By inserting the error component matrix A_{ei} between $A(i)(j_i)(l_i)$ and $A(i+1)(j_{i+1})(l_{i+1})$ in equation (1), the form-shaping function including errors, \vec{r}_{e0} is written as equation (2). And the form-shaping error function $\Delta \vec{r}_0$, expressing the error amount from the target value, is defined as the difference between the form-shaping function not containing errors and that containing the errors, as equation (3).

$$\vec{r}_0 = A(0)(j_0)(l_0) \cdots A(i)(j_i)(l_i) A(i+1)(j_{i+1})(l_{i+1}) \cdots A(k-1)(j_{k-1})(l_{k-1}) \vec{r}_t \quad (1)$$

$$\vec{r}_{\varepsilon 0} = A(0)(j_0)(l_0)A_{\varepsilon 0} \cdots A(i)(j_i)(l_i)A_{\varepsilon i}A(i+1)(j_{i+1})(l_{i+1}) \cdots A(k-1)(j_{k-1})(l_{k-1})A_{\varepsilon k-1} \cdot \vec{r}_i \quad (2)$$

$$\Delta \vec{r}_0 = \vec{r}_{\varepsilon 0} - \vec{r}_0 \quad (3)$$

To achieve machining tolerance that is stable under a variety of machining conditions, a method is needed for obtaining a design which is robust with respect to unknown local errors. The Taguchi method [7], [8] 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 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 take the design parameters and product dimensions as control factors and the local errors as noise factors. We defined Δx , Δy , Δz as the error amounts in each direction. Then, $(\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2}$ was set to be the evaluation function. When the value of the evaluation function at the i th trail is expressed as equation (4) and the number of trial is expressed by “n”, the average of the function is shown in equation (5).

$$f_{ei} = (\Delta x^2 + \Delta y^2 + \Delta z^2)^{1/2} \quad (4)$$

$$f_{em} = \sum_{i=1}^n f_{ei} / n \quad (5)$$

3. Selection of Design Candidate

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 performances of the designs can be compared by introducing some assumptions to the Taguchi method. By assuming that every design concept has the same control factors, noise factors and its variation ranges, the calculation results based on the Taguchi method are expected to show the priority of the designs directly. By this extension, a machine tool designer can determine the best design concepts for miniature 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 the components that appear before the machine tool base. It is common to express transitional motions along the X , Y and Z -axis as 1,2 and 3, and rotational motions around the X , Y and Z -axis as 4,5 and 6. By using this expression, structure types of milling machines that have three transitional motions and one spindle rotation are categorized to 4 major structures, by the distribution of DOF. Those 4 are shown in Fig. 1. Type 12036 is frequently seen for tabletop drilling machines. Type 20136 is called column-traverse type machine and often used for relatively large product such as automobile parts, because it doesn't require extra space for table movement. Type 01236 is sometimes seen in a manufacturing system called “transfer line”. Whereas type 12306 is rare for actual machine tools. A significant question is which of the four typical types has the best theoretical performance.

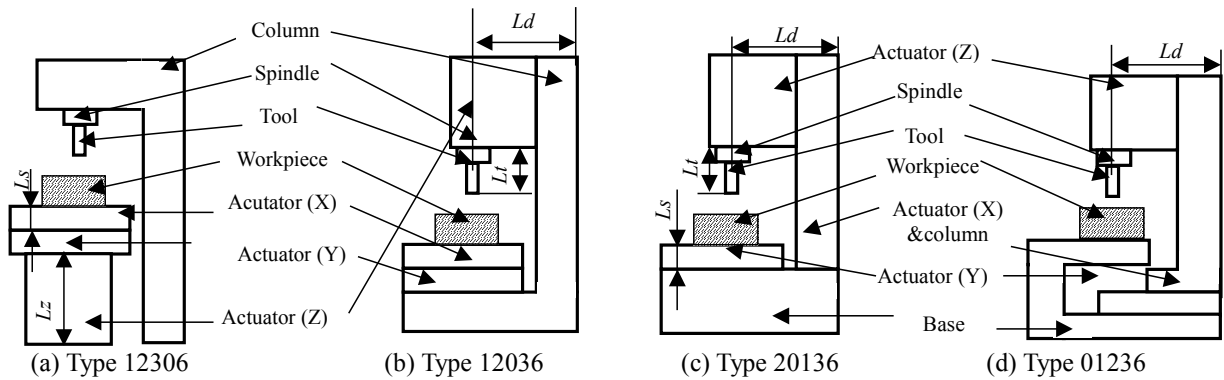


Fig.1 Four major types of mills

To apply the design evaluation method and perform parametric optimization to the structures, 6 design parameters was defined. And 3 of them were shown in the figure. Table 1 is the list of defined design parameters and its deviation ranges. Also, we defined 15 error factors to take the effect of error sources into account. Tables 2 is the list of defined error factors and its deviation ranges obtained from catalog data of machine components and so on.

Table 1 Design parameters and its ranges

Factor name	Variable	Ranges
Workpiece size	Ws	5, 7.5, 10, 12.5, 15cm
Bearing diameter	Db	25, 37.5, 50, 62.5, 75 mm
Tool length	Lt	5, 7.5, 10, 12.5, 15cm
Rotational speed	N	4000, 6000, 8000, 10000, 12000 rpm
Spindle - column distance	Ld	25, 37.5, 50, 62.5, 75cm
Thickness of the linear slides	Ls	5, 7.5, 10, 12.5, 15cm

Table 2 Error factors and its ranges

Name of the factor	Variable	Ranges
Angular error of the linear actuator	α_1	+15''
	β_1	+15''
	γ_1	+15''
Scale error of the linear actuator	δ_{x1}	+2 μ m
Straightness error of the linear actuator (H)	δ_{y1}	+2 μ m
Straightness error of the linear actuator (V)	δ_{z1}	+2 μ m
Angular error of the vertical Actuator	α_3	+15''
	β_3	+15''
	γ_3	+15''
Straightness error of the vertical actuator (H)	δ_{x3}	+2 μ m
Straightness error of the vertical actuator (V)	δ_{y3}	+2 μ m
Scale error of the vertical actuator	δ_{z3}	+2 μ m
Angular error of the spindle	α_4	+30''
Eccentricity of the spindle	δ_{x4}	+5 μ m
Expansion of the spindle	δ_{z4}	0~20 μ m

Six control factors shown in Table 1 were set to be independent control factors and L25 array was used for the control factors. L16 array was used for 15 error factors shown in Table 2. Four different form-shaping error functions; $\Delta\vec{v}_0$, corresponding to the four designs shown in Fig.1 can be expressed using the parameters defined in table 1 and 2. Equations (6) is an example of a form-shaping error function which corresponds to the structure called "type 12036" in Fig.1. One needs to calculate the value of the equation to evaluate the performance difference of the designs, under the same design parameters and error factors.

$$\Delta\vec{v}_0 = \begin{bmatrix} \delta_{x1} + \delta_{y1} + \delta_{x3} + \delta_{x4} - (\beta_3 + \beta_4) \cdot Lt + \alpha_1 \cdot (2Ls + h) + \beta_1 \cdot (Ls + h) - \gamma_1 d \\ \delta_{x1} + \delta_{y1} + \delta_{y3} + \delta_{x4} + (\alpha_3 + \alpha_4) \cdot Lt - \beta_1 \cdot (2Ls + h) - \alpha_1 \cdot (Ls + h) \\ 2\delta_{z1} + \delta_{z3} - \delta_{z4} + \alpha_3 \cdot Ld + \alpha_1 \cdot d \\ 0 \end{bmatrix} \quad (6)$$

4. Analysis of Design Parameters

Same ranges of the error factors shown in table 2, which are roughly assumed, are substituted to the calculated form-shaping error functions corresponds to 4 major structure types shown in Fig.1. In the calculation, size effects of error factors were also considered. For example, "expansion of the spindle" is likely to be smaller, when the machine tool size is small. On the other hand, straightness error of slides would not be affected by machine size. Considering these size effects, Fig. 2 shows the comparison of the theoretical performances. According to the figure, when the

design parameters vary within the defined ranges, lines to express the positioning error of type 12036 are always the lowest, and those of type 02136 are the largest. Among the 6 design parameters, “spindle-column distance” is the most critical parameter to affect the machine performance. The figure shows that the design with distributed DOF (type 12036) has better theoretical performance than the concentrated DOF (type 12306 or type 01236) has, although the differences between the types are not very large when the machine tool sizes are small. By these results, type 12036 was selected for the design of the miniature mill to be used in the aforementioned microfactory project.

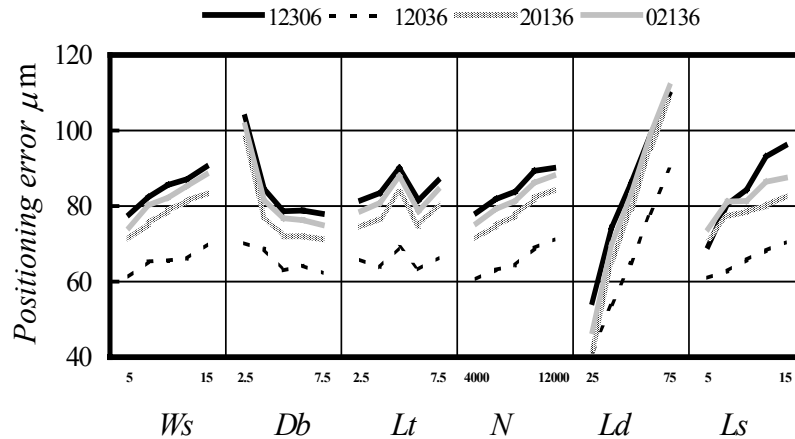


Fig. 2 Comparison of the theoretical performance

From the figure, it is concluded that “type 12036” has the best theoretical performance among four structure types. Among the six design parameters, W_s , N , L_d and L_s have positive impact on machine performance, where as Db has a negative effect. And “ L_d ” which expresses “spindle-column distance” has the most critical influence on machine performances.

5. Conclusions

The proposed design evaluation tool was effective in identifying the proper design from the design candidates for milling machines. “Type 12036” was estimated to have the best theoretical performance.

It was also possible to determine design parameters that had significant influences on machine performance. “ L_d ” which expresses “spindle-column distance” of machine tools had the most critical effect on machine performances. “Thickness of the linear slides; L_s ” and “bearing diameter; Db ” had relatively large influence on machine performances, as well.

References

- [1] Mishima, N., Ashida, K., Tanikawa, T. and Maekawa, H., *Design of a Microfactory*, Proc. of ASME/DETC 2002, Montreal, Sept. 2002.
- [2] Kitahara, T., Ishikawa, Y., Terada, K., Nakajima, N., and Furuta, K., *Development of Micro-lathe*, Journal of Mechanical Engineering Laboratory, Vol. 50, No. 5, p. 117-123 (1996).
- [3] Mishima, N., Ashida, K., Tanikawa, T. and Maekawa, H., *Design of a Microfactory*, Proc. of ASME/DETC 2002, Montreal, Sept. 2002.
- [4] Mishima, N. and Ishii K., *Robustness Evaluation of a Miniaturized Machine Tool*, Proc. of ASME/DETC99, Las Vegas, Sept. 1999.
- [5] Reshtov, D.N. and Portman, V.T., *Accuracy of Machine Tools*, ASME Press, New York, (1988).
- [6] Paul, R.P., *Robot Manipulators*, THE MIT press, Cambridge (1981).
- [7] Taguchi, G. and Konishi, S., *Quality Engineering Series* Vol.1-4, ASI Press. (1994).
- [8] Folkes, W.Y. and Creveling, C.M., *Engineering Methods for Robust Product Design*, Addison Wesley, (1995).