CONCEPTUAL DESIGN SUPPORT AND PROTOTYPING OF A MINIATURE MACHINE TOOL

Nozomu MISHIMA
Fine Manufacturing System Group
Institute of Mechanical Systems Engineering
National Institute of Advanced Industrial Science and Technology
1-2 Namiki, Tsukuba, Ibaraki, Japan

1. INTRODUCTION

In the former researches [1, 2], the author proposed a new design tool for machine tools combining the form-shaping theory [3, 4] of machine tools with the Taguchi method [5]. The proposed design tool was first applied to miniature machine tools for the "Microfactory" [6] and proved the effectiveness in determining critical design parameters on machine performance. It was also possible to compare several design concepts of miniature machine tools and identify which of the designs had better performance than the other. Since the miniature machine tool designs are not fully supported by existing design experience like conventional machine tools, guidelines for miniature machine tool designs are strongly demanded. Because a machine tool design is a time-consuming process, a design tool that enables the designer to evaluate the machine performance without prototyping must be useful in accelerating the design procedure.

2. CONCEPTUAL DESIGN OF A MINIATURE MILL

2.1 Categorization of design concepts

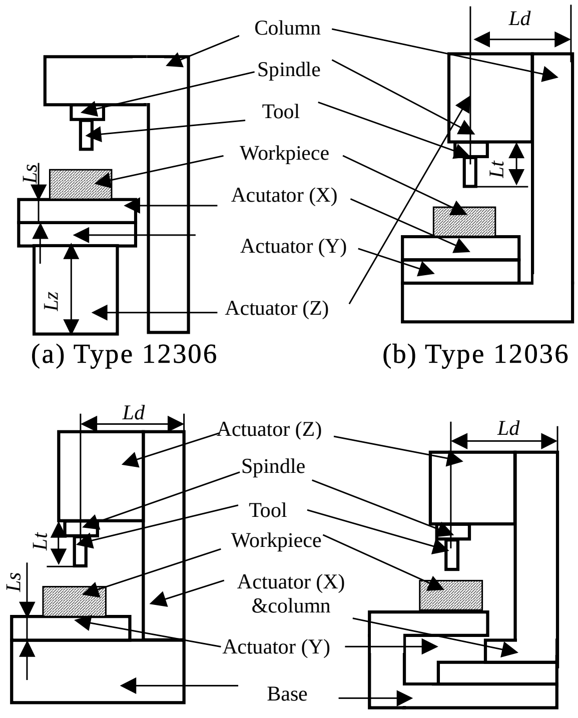
A machine tool structure can be considered as a chain of rigid components that move against the next components. Tracking the components from the workpiece to the cutting tool, it is possible to categorize machine tool structures by the number of the components that appear before the static part. By expressing 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, major structure types of milling machines that have three transitional motions and one spindle rotation are categorized as Table 1. Among all the structure types, vertical types were thought to be appropriate for the microfactory, since drilling capability was rather important for the target product. By assuming two horizontal axes have the same characteristics, the candidates were cut down to half. Because two types switching *X*-axis and *Y*-axis, such as 12306 and 21306 would have the same performance. In addition, space effective design required that the last transitional motion before the main spindle should be the motion along *Z*-axis. Determining that "3" comes after 1 and 2, the candidates were reduced to 4 types emphasized in the table.

Table 1 Combinations of axes for a mill

Number of components before the base	Vertical type	Horizontal type
3	**12306**, 13206, 21306, 23106, 31206, 32106	12305, 13205, 21305, 23105, 31205, 32105
2	**12036**, 21036, 13026, 31026, 23016, 32016	12035, 21035, 13025, 31025, 23015, 32015
1	10236, 10326, **20136**, 20316, 30126, 30216	10235, 10325, 20135, 20315, 30125, 30215
0	**01236**, 01326, 02136, 02316, 03126, 03216	01235, 01325, 02135, 02315, 03125, 03215

2.2 Design candidates for a miniature mill

As considered in the former section, 4 major structure types were selected as candidates. Fig. 1 shows the outline of the 4 design types. 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. A significant question is which of the four typical types has the best theoretical performance. To calculate machine tool behaviors under various conditions, some control factors representing workpiece dimensions and machine tool sizes were defined. Tables 2 shows the defined control factors. And 15 noise factors to express error sources in machine tools were also defined.



(a) Type 12306 (b) Type 12036

(c) Type 20136 (d) Type 01236

Fig.1 Four major types of mills

Table 2 Control factors and its ranges

Factor name	Variable	Ranges
Workpiece width	*w*	1, 2, 3, 4mm
Workpiece depth	*d*	1, 2, 3, 4mm
Workpiece height	*h*	0.5, 1, 1.5, 2mm
Tool length	*Lt*	5, 10, 15, 20cm
Spindle - column distance	*Ld*	5.75, 12.5, 25, 50cm
Height of the vertical actuator	*Lz*	2.5, 5, 10, 20cm
Thickness of the linear actuators	*Ls*	1.25, 2.5, 5, 10cm

2.3 Comparison of the machine performance

The form-shaping theory can analyze form-shaping capabilities of machine tools when the defined control factors vary within the defined ranges and the noise factors affect the performance. By assuming the same control factors and the noise factors to four types, performance of each type can be compared directly. In the calculation, size effects of the noise factors were considered. Figure 2 shows the comparison of the theoretical performances. According to the figure, lines to express the positioning error of type 12036 are always the lowest, and those of type 12306 are the largest. Among the 5 control factors, "spindle-column distance: *Ld*" 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 design with 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.

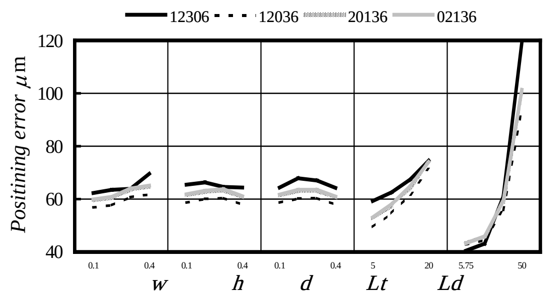


Fig. 2 Comparison of the performance

2.4 Determination of the machine size

The next step was to determine the suitable size for the miniaturization. Basically, positioning error of the machine decreases when the machine tool size represented by "*Ld*" decreases. However, the optimum size was decided according to the detailed calculation shown in Fig. 3. The vertical axis of the figure shows the mean positioning error and the horizontal axis shows the normalized machine tool size. In this calculation, "*Ld*; column-spindle distance" of the normal machine tool was set to 50cm. So, when the index is 1.0, *Ld* is 50cm. The figure tells that suitable size targeting machining up to 4mm is about 0.075 to 0.125. It means that column-spindle distance of the suitable miniature mill is about 4 to 6 cm.

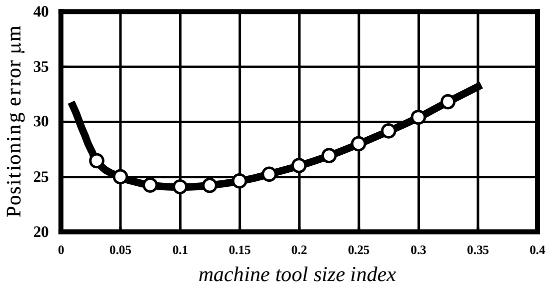


Fig.3 Optimum size for a miniature mill

3. PROTOTYPING OF A MINIATURE MILL

3.1 Comparison of two designs

As it was calculated in the former section, type 12036 was predicted to have the best performance among the 4 major types, and the suitable size represented by “column-spindle distance” is 4 to 6 cm. Actual miniature mill was designed, based on these results. To confirm that the predicted results are reliable, a contrast model for measurement was also prototyped. Fig. 6 is the sketch of the selected design, and Fig. 7 shows that of the other model which was predicted to have worse performance. Both machines have 57.5mm column-spindle distance, according to the optimum size decided by Fig.3.

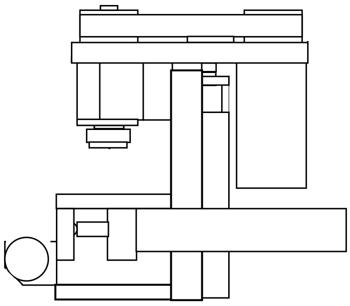


Fig.4 Miniature mill design (type 12036)

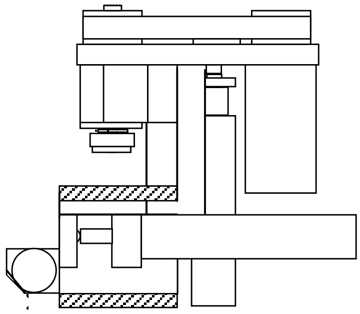


Fig.5 Miniature mill design (type 01236)

Fig. 6 shows the actual miniature mill designed in Fig. 4. The machine size being approximately 12x12x10cm, it can perform drilling up to 2mm in depth, and surface milling up to 4x4mm in area. For the transitional motions and the rotational motion, DC servo motors were used.

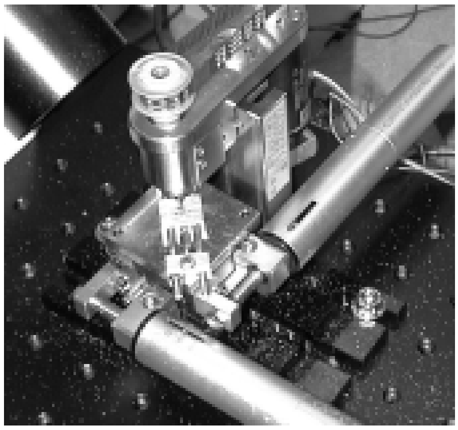


Fig. 6 Prototyped miniature mill (type 12036)

3.2 Measurement of actual errors

The figure showed in the former section tells that the distributed DOF type has a higher performance than the concentrated DOF type. However, to prove the effectiveness of the proposed design tool, it is necessary to compare the measured value and the calculated value. Fig.7 and 8 shows the result of the comparison of calculated and measured positioning errors of the two machines. Straight lines indicate calculated errors. Horizontal lines show *Y* value of the error vectors, while the vertical lines show *X* value. Calculated values of the figures indicate that the area surrounded by the vertical line, the horizontal line, *X*-axis and *Y*-axis is the predicted area where the measurement data expected to exist.

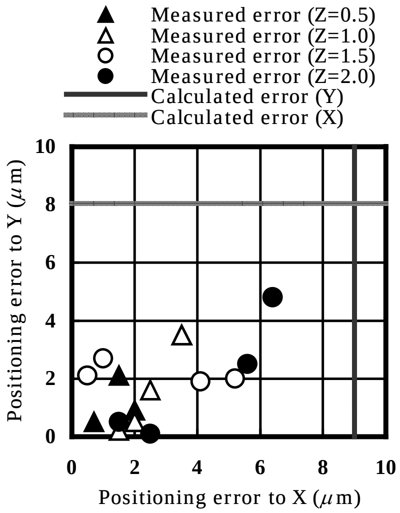


Fig.7Comparison of measured and calculated errors for type 12036 machine

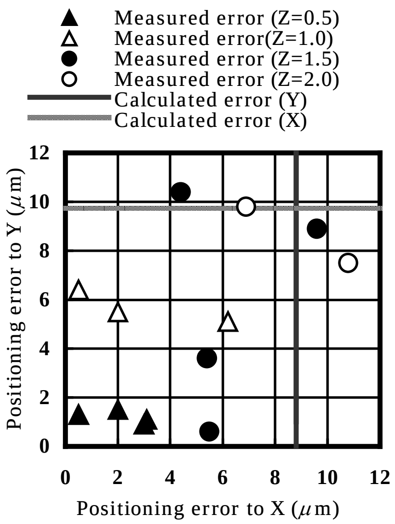


Fig.8 Comparison of measured and calculated errors for type 02136 machine

4. DISCUSSION

The results shown in Fig.7 and 8 indicate some measurement data for the type 01236 exceeded the predicted limit. However, most of the measured data exist within the predicted range. Although the accuracy of the calculation is not enough for predicting machining tolerances accurately, it is sufficient for usage in the conceptual design stages. Because the purpose of conceptual design stages of machine tools is to decide basic design concept and determine whether the concept will be sufficient for the objective machining. Comparison of Fig. 7 and 8 basically indicates that the type 12036 has better performance than the other. These results enable us to conclude that the proposed design evaluation tool will be useful to assist conceptual designs of miniature machine tools.

5. CONCLUSIONS

A. Proposed design evaluation tool was effective to identify the proper design from the design candidates of miniature mills.
B. Predicted values of positioning errors were accurate enough for usage in conceptual design stages and the design evaluation results were confirmed by prototyping.
C. Among major structure types of miniature mills, distributed DOF type that has two motion axes before the machine tool base, has the best theoretical performance.
D. To manufacture small mechanical products up to several mm, about 1/10 miniaturization is likely to be appropriate.

References

1. MISHIMA, N. and ISHII K., *Robustness Evaluation of a Miniaturized Machine Tool*, Proc. for ASME Design Engineering Technology Conference, Las Vegas, Sept. 1999, DETC/DAC-8579.
2. MISHIMA, N., *A Study on Evaluation of Conceptual Designs of Machine Tools*, Proc. for ASPE 17th Annual Meeting, St. Louis, Oct. 2002, pp. 210-214.
3. RESHTOV, D.N., and PORTMAN, V.T., *Accuracy of Machine Tools*, ASME Press, New York, 1988.
4. INASAKI, I. et. al., *Form-Shaping Theory of Machine Tools (In Japanese)*, Yoken-do, Tokyo, 1998.
5. TAGUCHI, G. and KONISHI, S., *Quality Engineering Series* Vol.1-4, ASI Press, 1994.
6. MISHIMA, N., ASHIDA, K., TANIKAWA, T., MAEKAWA, H., KANEKO, K. and TANAKA, M., *Microfactory and a design evaluation method for miniature machine tools*, Proc. for ASPE 15th Annual Meeting, Phoenix, Oct. 2000, pp. 567-570.