

# DEVELOPMENT OF A DESIGN TOOL FOR CONCEPTUAL DESIGN STAGES OF MACHINE TOOLS

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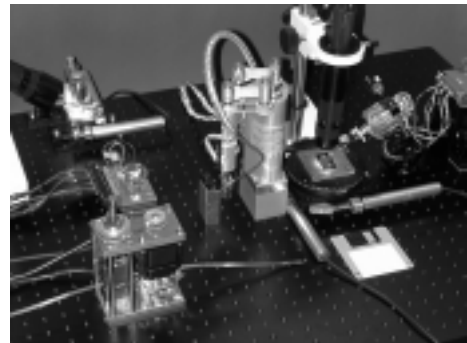
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## 1. Introduction

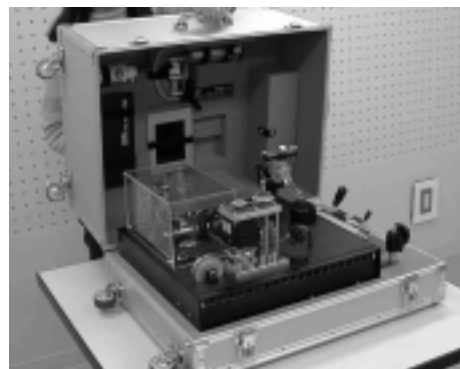
In the former research [1], the author proposed and have examined a new design tool for machine tools combining the form-shaping theory of machine tools; an analytical procedure representing the machining motions, with the Taguchi method [2]; a well-known robust tool to optimize processes or design parameters. Using the design tool, machine tool designers can evaluate how design parameters, local error factors and structures affect the machine performances without prototyping. The design tool was applied to the two designs of miniature mills which were used in the “microfactory” [3], and predicted that the design with distributed degrees of freedom (DOF) had better machining tolerances than the other. This paper first describes about measurement of positioning errors between the product and the cutting tool of each micro mill. Comparison of the measured and the calculated errors shows that the positioning errors of machine tools are roughly predictable by the proposed design tool. Secondly, the paper focuses on a conceptual design creating process of a lathe. In creating a design concept, there are many possible structures that have different sequences of motion axes. After considering every possible structure, the design tool compares three major structures of a lathe. Assuming that all designs use same machine components and being same sizes, the comparison based on the design tool leads us to conclude that one design has better theoretical performance than the other two. Throughout the measurement of the micro mills and the design trial of the lathes, the proposed design tool is proved to be a useful method to create conceptual designs of miniature machines.

## 2. Microfactory and miniature machine tools

Microfactory is a name of an ultra miniature manufacturing system consists of miniature machine tools and manipulators and benefits to reduce energy consumption and space occupied by the machines. The first microfactory was prototyped by author’s research group in 1999 as fig. 1. The system contains three machine tools including the micro-lathe [4] and the micro mill. The total area of the factory was approximately 50cm x 70cm. The factory was able to produce miniature mechanical parts by machining and assembled them into a miniature pivot ball bearing that was 0.9mm in diameter and 3mm in length. Through the test production, the microfactory indicated its capability as a rather practical miniature manufacturing system. Consecutively in 2000, the group prototyped the portable microfactory shown in fig.2 to demonstrate the concept of future manufacturing systems which enable “on-site” or “on-demand” manufacturing. However, especially for these miniature



**Fig. 1 Desktop microfactory**



**Fig. 2 Portable microfactory**

machine tools for the microfactory, designers may not have enough design experience and conceptual design procedure of machine tools has not been well examined. So, a design tool to evaluate the performances of machine tools and tell which size and structure is appropriate for the target product must be helpful for designers. Having this purpose, the author proposed a design tool that can predict machine tool performances without prototyping in the former research and applied to miniature machines shown in fig. 3 and 4.

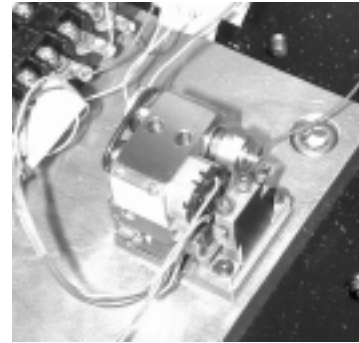
### 3. Design evaluation method

A machine tool structure can be considered as a chain of directly linked rigid components extending from a product through a cutting tool. Defining local coordinate system to each component, transformation between two next coordinates can be represented by a homogeneous transformation matrix. Calculating the transformation consecutively from the product towards the cutting tool, it is possible to express the relative displacement or motion between the product and the tool. The result of the matrices calculation is the definition of the form-shaping function that expresses the cutting motions of machine tools mathematically. However, actual machine tools have many error sources. In order to describe actual cutting motions, one must consider these errors. Such errors may be treated as errors in transformations between elements. And the form-shaping error function, expressing the shift from the target value of the machine tool motion, is defined as the difference between the form-shaping function not containing errors and that containing errors. By defining the design parameters, error factors and dimensions of the product, the form-shaping theory can calculate the form-shaping error function of the machine tool. The next step is to evaluate the calculated function by using a robust design method. The Taguchi method; a well-known robust design tool frequently used to optimize process parameters in manufacturing processes, is applied to the form-shaping error function to clarify how design parameters, machine structures and error factors affect the machining tolerances, which are the critical performance indicators of machine tools.

## 4. Robustness comparison of machine tool structures

### 4.1 Comparison of two design candidates of micro milling machines

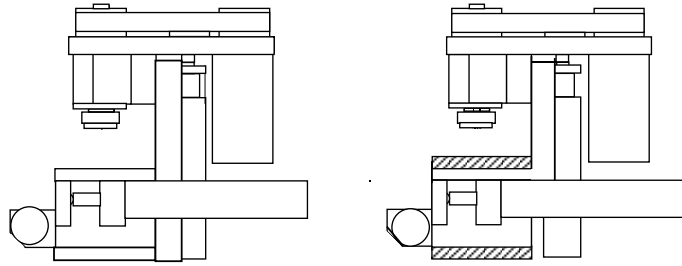
By using the form-shaping theory and the Taguchi method, it was possible to evaluate the effects of design parameters of an existing design. However, the tool did not provide a design suggestion to choose one design from design candidates, or to create an alternative design when the performance of the old design is insufficient. This stage of a design procedure is often called “Conceptual design”. The Taguchi method does not mention about the conceptual design and some researchers [5] tried to create a design method for conceptual stages. Though, one can compare performance of several designs by the Taguchi method with some assumptions. The method was applied to two design candidates of the micro mill used in the microfactory. To obtain a design guideline, I compared two different designs with same parts, same dimensions and different distribution of DOF. Following the machine tool elements from the product towards the cutting tool, one has two axes before the static part, whereas the other has all three axes



**Fig. 3 Micro-lathe**



**Fig. 4 Micro mill**



(a) Type 1 with distributed DOF (b) Type 2 with concentrated DOF

Fig.5 Two designs of the micro milling machines

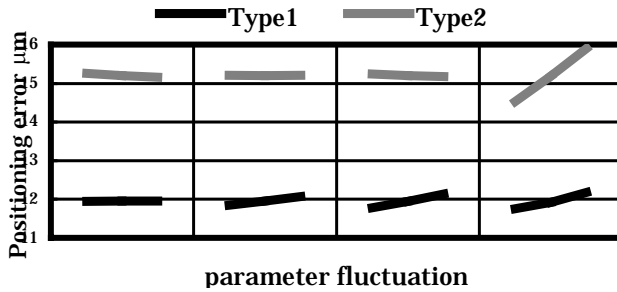


Fig. 6 Machining error comparison

relative positioning errors between the products and the cutting tools for both machines were measured, using laser displacement sensors fixed to the table on which products are usually placed. Fig. 7 shows the comparison between measured and predicted value of errors to y-direction when coordinate value of x are fixed. The figure indicates that there is a difference between predicted and measured value, though, the accuracy of prediction seemed enough for the purpose to aid conceptual design stage. The figure also tells that type 1 had smaller error than the type 2 had, as it was calculated. So, it can be concluded that the prediction based on the design tool matches the results of the measurement. It means that the proposed design tool is helpful to determine which of several designs has better performance in its conceptual design stage.

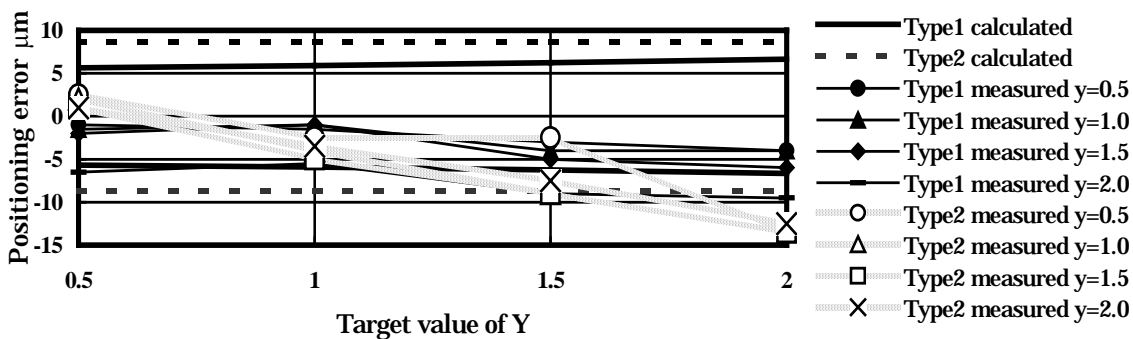


Fig. 7 Comparison of predicted and measured error

### 4.3 Creating a design concept of a miniature lathe

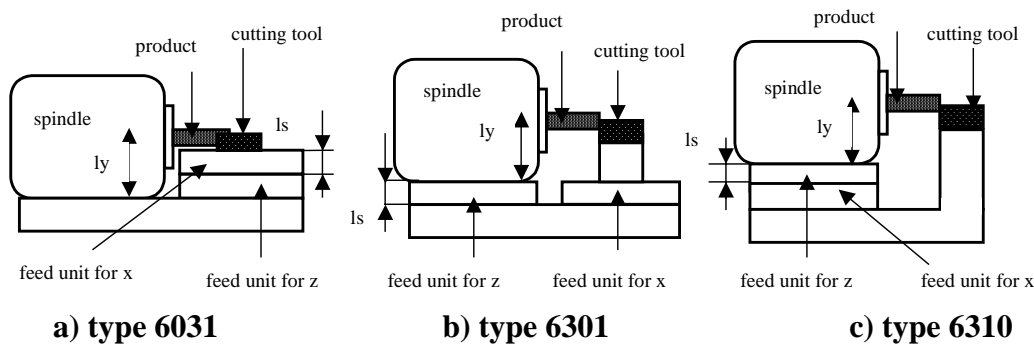
The next issue is to applying the above-mentioned design tool to create a design concept of a machine tool. Assuming to create a new design concept of a miniature lathe, the paper tried to make the use of the design tool to evaluate a few design concepts. Basically, a lathe must have three motion axes. And as the definition of a lathe, following a link of components from a product towards a cutting tool, a main spindle must come first. Expressing transitional motion

concentrated after the static part. Fig. 5 shows the overview of the two designs. Fig. 6 indicates the result of the analysis comparing the predicted tolerance holding capability of two designs, when design parameters varies within certain ranges.

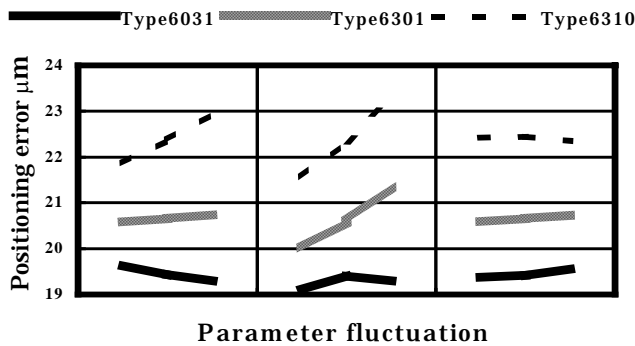
### 4.2 Measurement of positioning errors

Since, the analytical results shown in fig. 6 depend on some assumptions made in determining the ranges of error factor fluctuation, it is necessary to measure the positioning error directly and prove that the prediction made by the design tool was reasonable. For the purpose,

axis along X as 1, along Y as 2 and so on, structure of machine tools can be expressed by those numbers from 1 to 6 focusing on the sequence of the motion axes. A static part being expressed as 0, the micro-lathe shown in fig. 3 can be written as 6310. Using this expression, possible structures of a lathe are categorized into 6 types; those are 6013, 6031, 6301, 6103, 6310 and 6130. Further, assuming the x-axis and the z-axis would have the same characteristics, those 6 will be integrated to 3, shown in fig. 8. Following the machine tool elements from the main spindle towards the cutting tool, the first design has two linear motions after the base. The second one has one linear motion before and the other motion after, whereas the last design has two linear motions and the main spindle concentrated. Using the proposed design evaluation method, it was possible to predict the mean positioning error of each structure. Fig. 9 is the theoretical performance comparison, based on the calculation. The figure shows that type 6031 evidently has the smallest positioning error, and type 6301 has the next best theoretical performance.



**Fig. 8 Three different structures of lathes**



**Fig. 9 Machining error comparison**

## 5. Conclusions and future work

A) Using the proposed design tool, it was able to show that among two designs of micro mills, distributed DOF type has a smaller error.

B) Above-mentioned result was followed by the measurement, and the prediction accuracy was enough for usage in the conceptual design stages.

C) Typical design variations of a lathe are categorized to three types and the type 6031 (or 6013) has the best theoretical performance.

## References

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