

A Study on Evaluation of Conceptual Designs of Machine tools

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1. Introduction

In terms of energy efficiency, a large machine represents considerable waste. Miniaturization of machine tools to size compatible to the target products without compromising machining tolerance lead to enormous savings in energy, space, and resources. Recent years have seen the proposal of a factory comprised of such miniaturized machine tools. “Microfactory” [1] demonstrated a prototype ultra-miniature manufacturing system. However, the design of those miniature machine tools did not involve an in-depth evaluation of the required size and structure. Because machine tool design is rather experience basis, a fundamental design change is often difficult. Machine tool designers will need a general guideline to appropriately reduce the size of machine tools or determine the structure. In the former research [2], the author proposed and have examined a new design tool for machine tools combining the form-shaping theory [3] of machine tools; an analytical procedure representing the machining motions, with the Taguchi method [4]; 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 for the aforementioned microfactory, and predicted that the design with distributed degrees of freedom (DOF) had better machining tolerances than the other. Although, in the former study, the design tool can evaluate and compare existing designs, was not helpful enough to create a new design concept. As the next step, the design tool is required to show general design guidelines and aid conceptual design stage of a machine tool. The design tool will be helpful to shorten the time-to-market of machine tools and create a new design strategy to meet various design requirements.

2. Basics of the proposed design tool, and former applications

2.1 Form-shaping theory

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 can be treated as errors in transformations between elements. The form-shaping error function, indicating 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 product dimensions, the form-shaping theory can calculate the form-shaping error function of the machine tool.

2.2 Application of a robust design tool

The next step is to evaluate the calculated function by using a robust design method. When all variables of the form-shaping error function are known, the value of the error function can be easily calculated. However, when only the overall machining tolerance is specified, the inverse problem cannot be solved. Hence, the equation indicates the degree of machining error anticipated, given known local errors, but one cannot readily use it to estimate in advance the machining errors or assembly errors of component elements at the time of design. On the other hand, in order to obtain machining tolerance that is stable under a variety of machining conditions, a method is needed for obtaining a design that is robust with respect to unknown local errors. The Taguchi method is widely used in the fields of experimental design and quality engineering, and provides an environment for robust design. The design evaluation procedure uses the Taguchi method to evaluate the dimensional effect imposed on machining errors by the design parameters of the machine tool, when local errors are unknown. Simulations were performed applying the method to the form-shaping error function.

2.3 Examples of former applications

Microfactory is a name of a super miniature manufacturing system consists of miniature machine tools and manipulators, which has benefits to reduce energy consumption and space occupied by the machines. The first microfactory was prototyped by author's research group in 1999. The system shown in fig.1 contains three machine tools including the micro-lathe [5] and the micro mill. In trying to find a general design guideline for miniature machine tools, the micro-lathe and the micro mill of the microfactory have been analyzed as examples. [6] As the result, the design tool concluded that among five defined design parameters of the micro-lathe, some had larger effects on its performance and some didn't. The tool also clarified which of the two design candidates of the micro mill had better theoretical performance than the other.

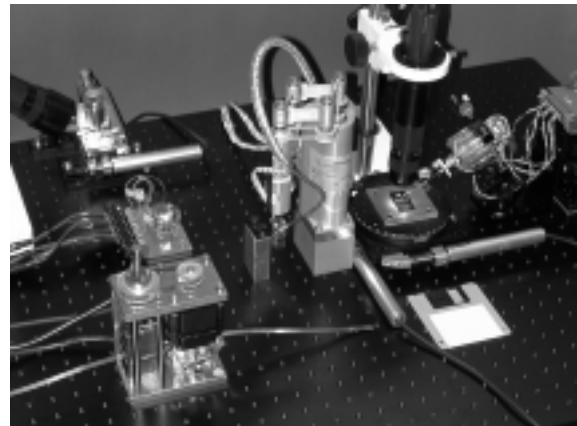


Fig. 1 Overview of the microfactory

3. Evaluation of a new machine tool design

3.1 Listing of possible design configurations

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 created another design method for conceptual stages. [7] Though, one can compare performance of several designs by the Taguchi method with some assumptions. In creating a new design concept, there are many possible structures that have different sequences of motion axes. The 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. To express configurations of machine tools clearly, we often use "1" for transitional motion along X axis, "2" for motion along Y and "3" for Z. Under this expression rule rotational motion around X, Y and Z axes are written as "4", "5" and "6", respectively. Using this expression, structure of machine tools can be expressed by those numbers from 1 to 6 focusing on the sequence of the motion axes. Expressing a static component of a machine tool by "0", the structure of the micro-lathe used in the microfactory can be written as 6013. 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. 2. 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.

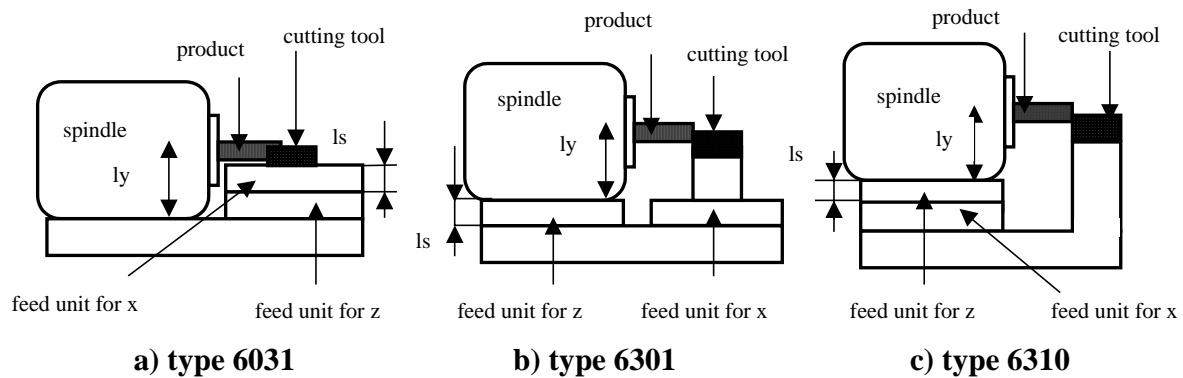


Fig. 2 Three different configurations of lathes

3.2 Comparison of design candidates of a lathe

Using the proposed design evaluation method, it was possible to predict the mean positioning error of each configuration. Table 1 and 2 are the defined error factors and the design parameters for the calculation. To isolate the effect of configurations only, these parameters have to be defined commonly to the three configurations. The nominal value of the design parameters came from the specification of sliders, the spindle and so on, that are used in the miniature-lathe model for measurement. Error factors in table 2 are from the catalog data of those sliders and the spindle. Just the axial expansion of the spindle is from measured data. Fig. 3 is the theoretical performance comparison, based on the calculation. The figure shows how the positioning error of the machines changes when the design parameters are changed along the value shown in table 1. The error

Table 1 Design parameters

Name of the factors	Ranges
Radius of the work-piece	0.1~0.4mm
Height of the work-piece	0.1~0.4mm
Height of the spindle center	15~60mm
Feed unit thickness	7.5~30mm
Cutting tool length	20mm

Table 2 Error factors

Parameter	Ranges
Angular inclination of the spindle axis	± 0.005 deg.
Radial eccentricity of the spindle	± 3 μ m
Axial expansion of the spindle	0~3 μ m
Pitching angular error of the sliders	$\pm 10''$
Towing angular error of the Z sliders	$\pm 10''$
Rolling angular error of the Z sliders	$\pm 5''$
Straightness error of the sliders (horizontal)	± 2 μ m
Straightness error of the sliders (vertical)	± 2 μ m
Scale error of the sliders	± 2 μ m

factors vary within the ranges defined in table 2. The vertical axis of the view graph indicates the mean positioning error, and the horizontal axis shows how each parameter affects the overall positioning error. A steep line tells that the corresponding parameter strongly affects the performance and a shallow line does not. Three series of lines in the figure corresponds to the performance of the three configurations, respectively. Comparing the results, the figure clarifies that type 6031 evidently has the smallest positioning error, and type 6301 has the next best performance.

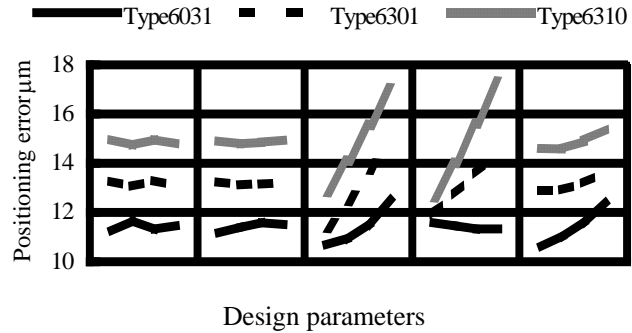


Fig. 3 Machining error comparison

3.3 Measurement of positioning errors

Since, the analytical results shown in fig. 3 depend on some assumptions made in determining the ranges of error factors, it is necessary to measure the positioning error directly and prove that the prediction made by the design tool was reasonable. For the purpose, relative positioning errors between the products and the cutting tools for three configurations were measured, using laser displacement sensors fixed to the table on which products are usually placed. Upper half of fig. 4 shows the comparison between measured and calculated value of errors to z-direction when coordinate value of z are fixed and x are changed. The lower half also indicates when x are fixed and z are changed. In the both figures most of the measured value except a few points of “type 6310” distribute under the lines express the calculated value. It also shows that measured errors of type 6310 are more scattered than that of type 6031 and 6301, as the calculation forecasts. Since, the calculated value means that the positioning error will be smaller than the value, one cannot predict the error itself, though, most of the measured error value exist beneath the calculated lines and the accuracy of the prediction seemed enough for the purpose to aid conceptual design. Since typical design requirement of a machine tool is to assure tolerance, a worst-case-analysis is useful for a designer. The design tool also simulates the performance difference of the structure types, well. The proposed design tool was helpful in determining which of several designs has better performance.

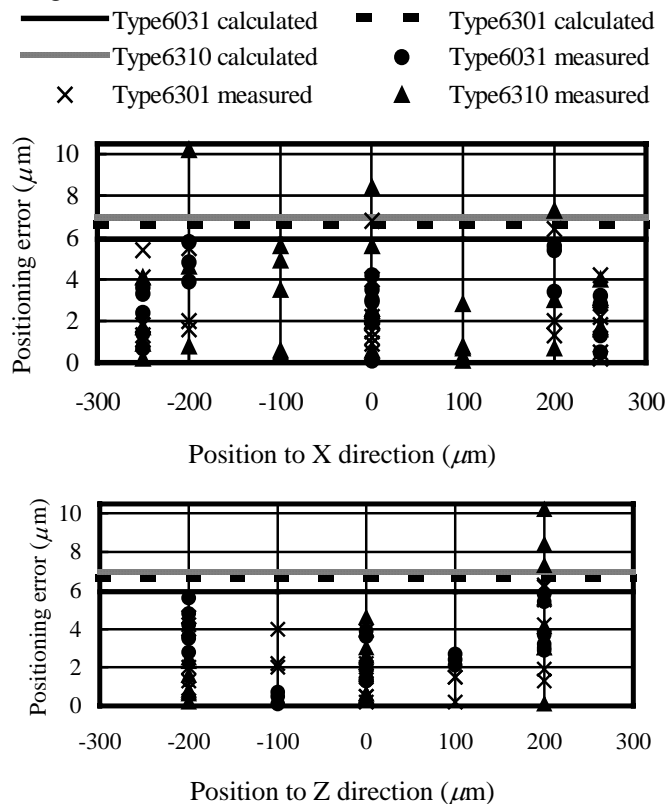


Fig. 4 Calculated and measured errors

4. Conclusions and future work

By applying the proposed design tool to a virtual design procedure of a lathe, following points have been concluded.

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

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

However, to ensure the effectiveness of the design tool, further examination is necessary. Applying the conclusions indicated by the design tool to actual machine tools design will be the future work. Packaging the tool to interactive software will be also useful. The final goal is to supply a design procedure which will be easily operated by a non-experienced machine tool designer.

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