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Robustness Evaluation of a Miniaturized Machine Tool

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ABSTRACT
This paper applies the method of robust design to machine tool design. The new design focuses on miniaturization that provides significant for energy and space saving. Our approach combines an analytical procedure representing the machining motions of a machine tool (form-shaping theory) with procedures for robust design. The effort identifies the design parameters of a machine tool that significantly influence the machining tolerance and leads to a general design guidelines for robust miniaturization. Further, this research applies the Taguchi method to the form-shaping function of a prototype miniature lathe. The analysis addresses five machine tool dimensions as control factors, while treating local errors in the machine structure as noise factors. The robustness study seeks to identify the importance of each factor in improving performance of the machine tool. The result shows that the thickness of the feed drive unit affects the performance most significantly. Among the local errors, straightness error of the same feed drive unit has a critical importance.

1. INTRODUCTION
Machine tools must be capable of machining products in a variety of different shapes and to the required tolerance. To this end, machine tool designers have adopted highly rigid and precise structural components. However, there has not been sufficient discussion of such basic concepts as a basis for choosing a particular structure or dimensions when designing a machine tool. Because machine tool design is rather experience basis, a fundamental design change is often difficult. For instance, the machine tools used to produce watches and other precise miniature products is excessively large compared with the target components. The machine tool community has not addressed the question of whether such size is necessary for machining to the required tolerance. 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 , a "micro-factory" (Kawahara et al, 1997), demonstrated a prototype ultra-miniature machine tool (Kitahara, 1996) that serves as the basic unit of such a factory. However, the design of the micro-lathe did not involve an in-depth evaluation of the required size and structure. Machine tool designers will need a general guideline to appropriately reduce the size of machine tools. This study combines an analytical procedure representing the machining motions with a procedure for robust design. The effort identifies critical design parameters that have significant influence on the machining tolerance. There exist an analytical procedure known as form-shaping theory (Reshtov and

Portman, 1988) and studies on design evaluation of machine tools using the theory or other numerical representation (Slocum, 1992; Mou, 1997). The robust design tool called the "Taguchi method" is well-known (Taguchi, 1994; Feng and Kusiak, 1997). This paper applies this method to analyze the effect that the design parameters of aforementioned micro-lathe have on its machining performance, and proposed a procedure for design evaluation. These results lead to the combination of design parameters that optimize the performance of existing micro-lathe. The paper also relates these results to guidelines for the future systematic miniaturization of machine tools in accordance with the product size and required machining tolerance.

NOMENCLATURE

k = number of components
i = component number index
S_i = local coordinate system assigned for component i
A = homogeneous transformation matrix
j_i = the kind of transformation between S_i and S_{i+i}
l_i = motion amount for the transformation between S_i and S_{i+i}
$A(i)(j_i)(l_i)$ = matrix indicates a transformation between S_i and S_{i+i} which has kind j_i and motion amount l_i
$\vec{r}_0$ = form shaping function
$\vec{r}t$ = tool shape vector
$\vec{r}_{e0}$ = form shaping function including errors
A_{ei}= the transformation errors between S_i and S_{i+1}
$\Delta \vec{r}_0$ = form shaping error function
ls = thickness of the work holder
ly = shaft - Z feed unit distance
ld = shaft - motor distance
lz = thickness of the feed units
lt = length of the cutting tool
R = radius of the workpiece
h = height of the workpiece
v = rotational speed of the shaft
α_i = angular error about x axis in the transformation between S_i and S_{i+i}
β_i = angular error about y axis
γ_i = angular error about z axis
δ_{xi} = parallel translation error to x axis in the transformation between S_i and S_{i+i}
δ_{yi} = parallel translation error to y
δ_{zi} = parallel translation error to z
Δx = deviation from the target to x direction
Δy = deviation from the target to y direction
Δz = deviation from the target to z direction
n = number of run
f_{em} = average value of the objective function
f_{ei}= value of the objective function
V = variance
Sn = Signal-to-noise ratio

2. REPRESENTATION OF FORM-SHAPING MOTIONS

2.1 Form-shaping function

The machine tool structure is considered as a chain of directly linked rigid components extending from the workpiece through the cutting tool, from component 0 to k, as illustrated in Fig. 1. An orthogonal coordinate system S_i is defined to element i (i=0 to k). The transformation from S_i to S_{i+1} represents a coordinate transformation between components.

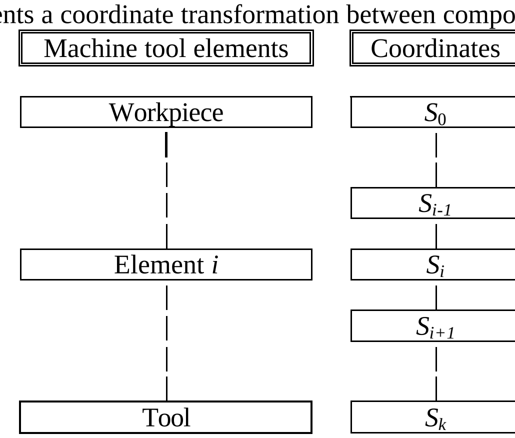

Fig.1 Corresponding elements and local coordinates

We represent these respective coordinate transformations by homogeneous transformation matrices (Paul, 1981) A_i. In the case of 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 x, y, or z axes, or combination of these. 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_i, (=1 to 6), and the amounts of motion (distance if a parallel transformation, a rotation angle if rotational motion) are represented by l_I we define $A(i)(j_i)(l_i)$ as the expressions of the matrices. Vector $\vec{r}_0$ represents the relative displacement between workpiece and tool, and in the coordinate system given for the tool, the tool shape vector by $\vec{r}t$ is 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.

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

2.2 Form-shaping error functions

In actual machine tools there are assembly tolerances, thermal deformation, wear, deformation caused by external forces, and many other sources of error. In order to describe actual form-shaping motions, one must consider these errors. Such errors may appear as transformations within an element, as in deformation of a component, or they may appear as a transformation between elements, as imperfect straightness error of guide ways. However, errors may for convenience's sake be treated as either kind of transformation. In this study, we treat such errors in transformations between elements. We define another homogeneous transformation matrix $A_{\varepsilon i}$ to generally represent transformation error between elements S_i and S_{i+1}. By inserting the error component matrix $A_{\varepsilon i}$ between $A(i)(j_i)(l_i)$ and $A(i+1)(j_{i+1})(l_{i+1})$ in eq. (1), the form-shaping function including errors, $\vec{r}_{e0}$ is written as follows.

$$\vec{r}_{e0} = A(0)(j_0)(l_0)A_{e0}\cdot\cdot A(i)(j_i)(l_i)A_{ei}A(i+1)(j_{i+1})(l_{i+1}) \cdot\cdot A(k-1)(j_{k-1})(l_{k-1})A_{ek-1}\cdot\vec{r}_t \quad (2)$$

The form-shaping error function $\Delta\vec{r}_0$, expressing the shift from target values of the form-shaping motion of the machine tool, is defined as the difference between the form-shaping function not containing errors that containing the errors.

$$\Delta\vec{r}_0 = \vec{r}_{e0} - \vec{r}_0 \quad (3)$$

3. APPLICATION TO MINIATURIZED MACHINE TOOL

The previous section explained the general procedure for deriving the form-shaping function of a machine tool. In order to derive a strategy for miniaturized design of machine tools, which is the objective of this study, we analyze an existing micro-lathe, and attempt to evaluate the robustness of its design. By this means we can identify those design parameters and local error sources of the machine tool that have a major influence on the machining performance of machine tools with the same axial configuration as the micro-lathe.

3.1 Form-shaping function of the micro-lathe

Fig.2 shows the construction of the micro-lathe studied in this paper. In response to requests to reduce the overall machine dimensions as much as possible, in this machine tool the spindle unit moves with respect to the fixed tool to perform cutting and feed motions.

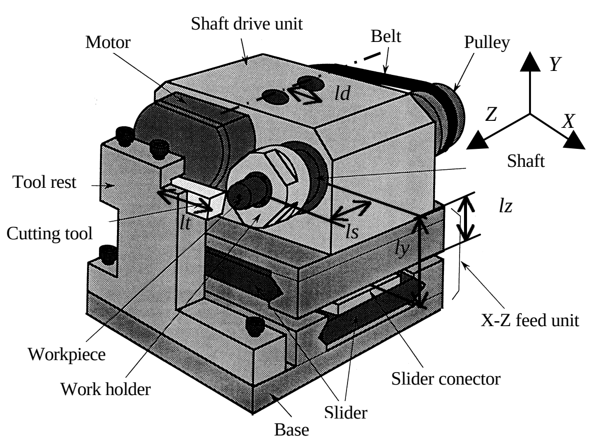

Fig.2 Schematic view of the micro-lathe

The machine is extremely small, with the height, length and width dimensions each around 1 inch or so. The machine is capable to machine small workpiece made from brass or plastic and the machining tolerance is better than an ordinal lathe. As shown in the figure, we define five different design parameters for this machine tool (Table 1). In addition, although not design parameters, the table defines the height h and the radius R of the cylindrical workpiece as variables necessary for analysis. Using these design parameters, Fig. 3 shows the elements of the micro-lathe of Fig. 2, the corresponding local coordinate systems, and the homogeneous transformation matrices used to transform between each local coordinate system.

Table 1 Design parameters of the micro-lathe

Name of the parameters	Variable
Work holder thickness	*ls*
Shaft - Z feed unit distance	*ly*
Shaft - motor distance	*ld*
Feed unit thickness	*lz*
Cutting tool length	*lt*

Elements	Coordinates	HTM
Workpiece	S_0	
		$A(0)(3)(0)$
Shaft	S_1	
		$A(1)(3)(-ls)$
Z feed unit	S_2	
		$A(2)(2)(-ly)$ $A(2)(1)(ld)$
X feed unit	S_3	
		$A(3)(2)(-lz)$
Base	S_4	
		$A(4)(1)(R+lt-ld)$ $A(4)(3)(lz+ly)$
Tool	S_5	

Fig.3 Corresponding elements, coordinatesand HTM for the micro-lathe

As explained in the preceding section, the form-shaping function of the machine tool is defined by linear super-positioning of the transformation matrices between local coordinates of the machine tool, and then taking the tool shape vector. We express a multi-directional transformation as a combination of homogeneous transformation matrices. Thus, the form-shaping function $\vec{r}_0$ of the micro-lathe may be expressed as follows:

$$\vec{r}_0 = A(0)(3)(0)A(1)(3)(-ls)A(2)(2)(ly)A(2)(1)(ld) A(3)(3)(h+ls)A(3)(2)(-lz) A(4)(1)(r+lt-ld)A(4)(3)(lz+ly)\vec{r}_t \quad (4)$$

3.2 Form-shaping function including errors

There are six elements of the machine tool, including the workpiece, as shown in Fig. 3. In other words, there exist five transformations between elements. We define, for each of these transformations, three parallel-translation errors along the three orthogonal axes and three rotation errors about the three axes. These transformation errors provide expressions of errors in the machine tool arising from thermal deformation, wear, motion error, tolerances in machined parts, and other causes. To distinguish these errors from the overall machining error, we shall refer to them as local errors. We let the rotation errors about the *x, y, z* axes in the transformation between element *i* and *i*+1 be respectively α_i, β_i, γ_i, and the parallel translation errors be δ_{xi}, δ_{yi}, δ_{zi}. Table 2 below lists the defined local errors. The form-shaping function of the micro-lathe including errors, $\vec{r}_{e0}$ may be expressed as eq. (5).

Table 2 Defined local errors

HTM	Error parameters	
	Rotational errors	Transitional errors
A_{e0}	a_0, b_0, g_0	d_{x0}, d_{y0}, d_{z0}
A_{e1}	a_1, b, g_1	d_{x1}, d_{y1}, d_{z1}
A_{e2}	a_2, b_2, g_2	d_{x2}, d_{y2}, d_{z2}
A_{e3}	a_3, b_3, g_3	d_{x3}, d_{y3}, d_{z3}
A_{e4}	a_4, b_4, g_4	d_{x4}, d_{y4}, d_{z4}

$$\begin{aligned}\vec{r}_{e0} &= A(0)(3)(0)A_{e0}A(1)(3)(-ls)A_{e1}A(2)(2)(-ly)\\ &A(2)(1)(ld)A_{e2}A(3)(3)(h+ls)A(3)(2)(-lz)A_{e3}\\ &A(4)(1)(R+lt-ld)A(4)(3)(lz+ly)A_{e4}\cdot\vec{r}_t\end{aligned} \qquad (5)$$

3.3 Form-shaping error function

To simplify, we introduce the following assumptions regarding the local errors defined in the preceding subsection.

(1) In this study we do not include the workpiece and spindle mounting errors, α_0, β_0, γ_0, δ_{x0}, δ_{y0}, δ_{z0}.

(2) The errors of the main shaft may both be rotationally symmetrical, so we set $\delta_{y1}=\delta_{x1}$ and $\beta_1=\alpha_1$.

(3) The rotational error of the spindle about its own axis has no practical meaning, so that γ_1 is omitted.

(4) The same feed units are used for driving in both the X and Z directions, so we set $\beta_3=\beta_2$, $\gamma_3=\alpha_2$, $\alpha_3=\gamma_2$, $\delta_{x3}=\delta_{z2}$, $\delta_{z3}=\delta_{x2}$, and $\delta_{y3}=\delta_{y2}$.

(5) In mounting the tool on the tool rest, we consider only the rotational errors α_4, β_4, γ_4, and do not consider the parallel-translation errors δ_{x4}, δ_{y4}, δ_{z4}.

Using these assumptions, the number of independent local errors decreased to 12. Further, in the case of this micro-lathe equation (7) gives the tool-shape vector.

$$\vec{r}_t = \{-lt \quad 0 \quad 0 \quad 1\}^T \qquad (6)$$

From eqs. (3), (5) and (6), the form-shaping error function for the micro-lathe analyzed in this study can be written as in eq. (7). Each element of the vector indicates error amount to *x*, *y* and *z* direction.

$$\Delta\vec{r}_0 = \begin{bmatrix} d_{x1}+d_{x2}+d_{z2}-a_2(lz+ly) \\ +(a_1+b_2)(h+ls)-g_2 ly \\ d_{x1}+2d_{y2}+(a_2+g_2)(R-ld) \\ -(a_1+a_2)(h+ls)-g_4 lt \\ d_{x2}+d_{z1}+d_{z2}-a_1 R-2b_2(R-ld) \\ +g_2(lz+ly)+a_2 ly+b_4 lt \\ 0 \end{bmatrix} \qquad (7)$$

4. APPLICATION OF THE TAGUCHI METHOD

In eq. (7) of the previous section, when all variables are known the form-shaping error function $\Delta\vec{r}_0$ can be calculated; but when only the overall machining tolerance is specified, the inverse problem of eq. (7) cannot be solved. Hence, this 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 which 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. This study 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.

4.1 Control factors and noise factors

The Taguchi method allows us to calculate combinations of values of control factors to optimize an evaluation function, given noise factors fluctuating within given ranges. In this study, the primary objective is to determine the effect on machining performance of design parameters, when some local errors exist in the various components of the machine tool. Therefore, it is appropriate to take the design parameters to be control factors and the local errors to be noise factors. Here the dimensions *R*, *h* of the workpiece shape are given as fixed values and act as constraining conditions. Conversely, by setting the local errors to be the control factors, one can identify those parts that require special care in order to improve the machining precision of a miniaturized machine tool.

4.2 Objective function

Since, this study focuses on the error amount (distance) at a point, among those points on the workpiece, at a target distance *R* from the shaft center and height *h* from the work holder surface. We define Δx, Δy, Δz to be the error amounts in each axis direction when the tool and the workpiece are displaced relative to each other with this point as the target. Then, we take the absolute length of these errors, $(\Delta x^2+\Delta y^2+\Delta z^2)^{1/2}$, to be the evaluation function.

4.3 Relation between the factors

Prior to setting the range of variation of design parameters and local errors, fixed relations between local errors and design parameters must be introduced. In miniaturization of a machine tool, if we assume that there is no relation between design parameters and local errors and that local errors are always constant, then machining precision should be constant and independent of dimensions. On the other hand, if local errors are proportional to the design parameters, then machining precision should also be nearly proportional to the geometrical dimensions. However, the machining precision of a micro-lathe is known to be superior in absolute terms, but inferior in relative terms to that of an ordinary lathe [2].

This trend is due to the inherent limits on the type and precision of mechanisms used when reducing the size of a machine tool. Consequently, some parts of the machine suffer loss of precision when reduced in size. For instance, when dimensions are reduced to the order of the micro-lathe, considerable care is required in tool mounting due to the short tool length. In addition, the small-diameter bearing adopted due is disadvantageous in terms of precision compared with ordinary bearing.

There are also machine elements that benefit from reduction in size. For instance, miniaturization clearly means a decrease in heat generation in bearings leading to a decrease in thermal displacement of the spindle. In order to express such tradeoffs between miniaturization and the resulting machining tolerance, and to obtain guidelines for use in miniaturized design, we adopt the following assumptions regarding the relation between local errors and design parameters.

(1) The spindle eccentricity δ_{x1} and spindle angular error α_1 are inversely proportional to the spindle offset. (Due to constraints on design, the spindle offset is expected to be proportional to the spindle diameter, so that the smaller the spindle diameter, the more disadvantageous for precision.)

(2) Expansion of the spindle δ_{z1} is due to heat generation, and it is proportional to *ld*.

(3) The rotary errors of the feed-units, α_2, β_2 and γ_2, and the straightness errors of the feed units are inversely proportional to the feed unit thickness *lz*.

(4) The scale error of the feed unit δ_{z2} corresponds to the amount of control overshoot, but depends on the construction of the feed unit and its control algorithm. It is thought to be unaffected by the design parameters; therefore it is assumed to be constant.

(5) The smaller the tool, the more difficult its positioning tends. Hence, we assume that the tool mounting angular errors α_4, β_4, γ_4 are inversely proportional to the tool length *lt*.

4.4 Orthogonal arrays

Based on the assumptions of the preceding section, there are 12 independent local errors. It is unknown how these error factors act on the machining error which is the output of the machine tool; but so long as the error value signs are not reversed, one can expect them to act in monotonic fashion. Hence by performing calculations for three types of error values--positive, negative, and zero--it should be possible to obtain a qualitative grasp of the machining error behavior. A L27 orthogonal array (Falkes and Creveling, 1995) is applicable for systematic inclusion of 12 factors at three levels, by introducing one dummy factor. In addition, there are five design parameters as indicated above, and their effect on machining precision is unknown. We therefore conduct an analysis at the four-variable level, using a L16 orthogonal array [9].

4.5 Ranges of parameter fluctuation

In order to perform calculations based on Taguchi method, the ranges of design parameters and local errors must be specified. We adopt four different factors for the ranges over which design parameters are varied--0.5, 1.0, 1.5, and 2.0 times the design values in current micro-lathe. For local errors, three different factors, -1.0, 0, and 1.0, are multiplied by the normalized local errors measured or estimated in current micro-lathe. However, the error δ_{z1} arising from thermal displacement of the spindle can never be negative, and so values of 0, 0.5, and 1.0 times are used. The design parameters, corresponding variables, and design values for the micro-lathe serving as references for determining ranges appear in Table 4. Table 5 shows the local errors, corresponding variables, and assumed normalized value.

Table 4 Ranges of the design parameters

Name of the factors	Variable	Design value
Work holder thickness	*ls*	8mm
Shaft - X feed unit distance	*ly*	11.5mm
Shaft - motor distance	*ld*	6mm
Feed unit thickness	*lz*	7mm
Cutting tool length	*lt*	5mm

Table 5 Ranges of the local errors

Name of the factors	Variable	Normalized value
Spindle inclination	α_1	±0.003°
Angular error of the sliders	α_2, β_2, γ_2	±0.002°
Angular error of the tool	α_4, β_4, γ_4	±0.005°
Spindle eccentricity	δ_{x1}	±2μm
Spindle expansion	δ_{z1}	1μm
Scale error	δ_{z2}	±1μm
Straightness error	δ_{x2}, δ_{y2}	±1μm

5 RESULTS

5.1 Optimization of design parameters

Based on orthogonal arrays as stipulated in Taguchi method, values for the parameters of the preceding subsection were substituted into eq. (8), and computer simulations executed in place of experiments. A single set of calculations involves 16 combinations of the five design parameters, each combined with 27 combinations of local errors. By this means, the effects on machining error and S/N ratio of each design parameter for local errors varying over the ranges shown in Table 4 are clarified. In other words, those design parameters can be identified which must be emphasized to enhance the machine robustness when local errors exist. Eq. (8) calculates the mean of the machining. Moreover, this problem is a "the-smaller-the-better", and the S/N ratio is as given by eq. (9). The S/N ratio is widely used as an index of robustness.

$$f_e m = \sum_{i=1}^{n} f_e i / n \qquad (8)$$

$$Sn = -10 \log \left[V + f_e m^2 \right] \qquad (9)$$

Here n is the number of simulation trials (n=16), f_{em} is the mean value of the objective function, V is the variance, and Sn is the S/N ratio. The above calculations were executed, and the mean value and dispersion of the objective function were analyzed. In the “analysis of mean,” the mean value of the objective function obtained from eq. (8) above, was plotted along the vertical axis, and the types and values of design parameters along the horizontal axis. In “analysis of variation” the vertical axis plotted values obtained from eq. (9). These results appear in Figs. 4 and 5. The results of the “analysis of mean” indicate effects of the design parameters on the machining tolerance, and the “analysis of variation” shows the degree of robustness. In the figures, where the slope of each segment for a design parameter is steep, that parameter has a large influence on the machining tolerance or S/N ratio.

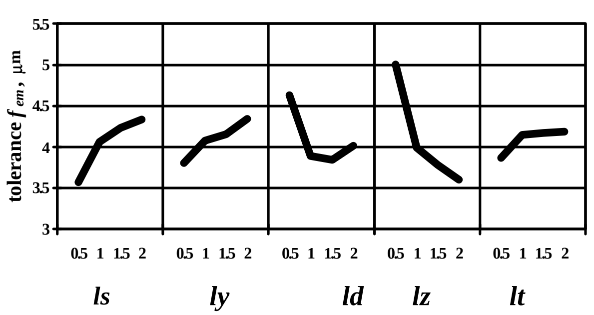

Fig. 4 Effect of design parameters on the machine performance: Analysis of Mean

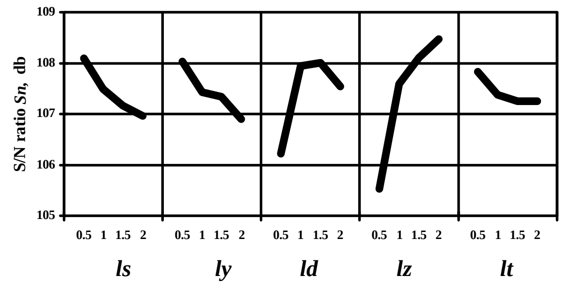

Fig. 5 Effect of design parameters on the machine performance: Analysis of Variation

5.2 Estimation of influence of local errors

By employing local errors as control factors in this method, it is possible to identify those errors which must be tightly controlled in fabricating a miniature machine tool. The objective of this method is to optimize control factors with respect to noise factors that can assume random values within a given range; hence, design parameters are not suitable for use as noise factors. As the latter values, therefore, we assume the fixed values used in current micro-lathe. The analysis adopts three parameters--the workpiece height h, radius R, and spindle rotation rate v-- as noise factors that vary with the shape of the workpiece and the operating conditions of the machine. Hence, this problem is equivalent to identifying the local errors that have the greatest effect on machining tolerance, for unspecified workpiece shape and spindle rotation speed. Here, a L16 five-parameter four-level orthogonal array is again applicable for the noise factors, with two parameters as dummy parameters. Ranges are 0.5, 1.0, 1.5 and 2.0 times normalized values, shown in Table 6.

Table 6 Range of the noise factors

Factors	Variable	Normalized value
Workpiece height	h	5mm
Workpiece diameter	R	1mm
Rotation speed	v	10000rpm

The ranges of fluctuation of local errors are, as in the calculations of the preceding subsection, taken to be -1.0, 0, and 1.0 times the normalized values of Table 5. As correlation between control factors and noise factors, it is assumed that the expansion of the spindle to Z-direction δ_{z1} is proportional to the rotation rate. This assumes that the spindle expansion is proportional to the increase in surface temperature, based on actual measurements of the temperature rise at the surface. As in the previous subsection, eqs. (8) and (9) were used in analyses of mean and variation; the results appear in Figures 6 and 7.

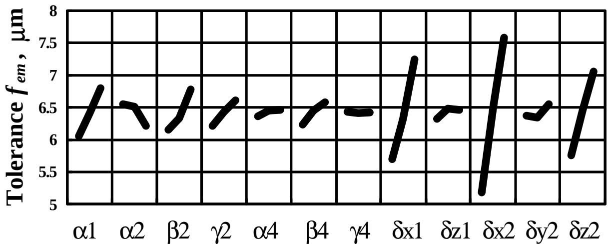

Fig.6 Effect of local errors on the machine performance: Analysis of Mean

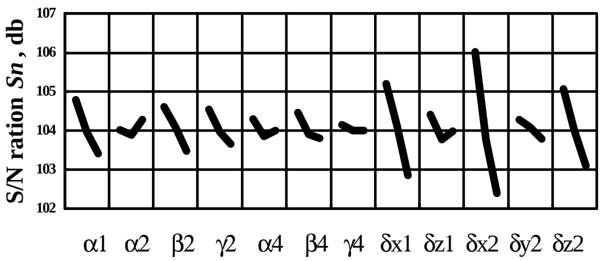

Fig.7 Effect of local errors on the machine performance: Analysis of Variation

5.3 Discussion

The calculation results indicate that among the design parameters for the micro-lathe, the smaller the values of the work holder thickness *ls*, height of the shaft center *ly*, and cutting tool length *lt*, the better. However, of these parameters the tool length has a relatively small effect. In addition, there exists an optimum value for the shaft-motor distance *ld*. The larger the value of the feed unit thickness *lz*, the better, and of the five design parameters, this latter value has the greatest effect.

On the other hand, results for the effect of local errors on machining performance indicate that all local errors have a negative effect on machining performance. In particular, the spindle whirling error δ_{z1}, horizontal-direction error of the feed units δ_{x2}, and scale error of the feed units δ_{z2}, all had a considerable influence on machining tolerance. The range of local errors greatly affects the validity of these. However, these assumptions are based on experience gained to date in machine components. And the results themselves seems to be valid not only for the purpose to establish a method of design evaluation, but also with respect to the results obtained in this study. In particular, the thickness of the feed units among the design parameters and the scale error of the units among the local errors have large effects. This trend is a result of the adoption of inchworm-type feed units using piezoelectric devices with the object of reducing the overall machine size. Studies have been conducted of the control characteristics of the feed units (Okazaki et al, 1998), and it is a fact that these characteristic feed units have major impacts on micro-lathe performance, including difficulty of adjustment and motion accuracy.

On the other hand, according to the calculations of this study the spindle expansion δ_{z1} has little effect. In studies to date, including those on large-size ultra-precise lathes (Mishima et al, 1995), thermal displacement of the spindle has been understood to greatly affect the performance of machine tools. This difference indicates that in the micro-lathe, thermal deformation is no longer a dominant factor. This means that a designer of a micro machine tools doesn't need to care thermal errors so much which have been always annoying in machining.

6. CONCLUSION

The paper presented a robustness evaluation method of machine tool design that combines form-shaping functions and the Taguchi method. In existing micro-lathe, the dimensions and motion characteristics of the feed units have a large influence on machining tolerance. On the other hand, thermal error is no longer a critical factor.

Although this method enables incremental design improvement, it falls short of producing is still fundamental design innovations. To utilize this method more effectively, one needs to apply it at the conceptual design stage and compare the robustness of different design concepts (Ford and Barkan, 1995). Thus, our future work will focus on applying the proposed method to conceptual designs of miniature machine tools.

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