CASE 52

Functionality Evaluation of Spindles

Abstract: In the development of spindles for machining, many quality characteristics, such as temperature rise of bearings, vibration noise, or deformation, have traditionally been studied, spending a long time for evaluation. Recently, the evaluation of machining by electricity was developed, which makes the job easier. This study was conducted from the energy transformation viewpoint, aiming for the stability of machining and reducing development cycle time.

1. Introduction

Although in most studies of machine tools, we evaluate performance by conducting actual machining, essentially it is important to change the design of machine tools. However, since this type of study can be implemented only by machine manufacturers, we tentatively conduct research on a main spindle as one of the principal elements in a machine tool. Figure 1 depicts a main spindle in a machining center. A tool is to be attached at the main spindle end and a motor is connected to its other end. The main spindle is required of stable performance for various tools and cutting methods under the condition ranging from low to high numbers of revolutions.

In general, manufacturers and users stress quality of a product for evaluating performance. In the traditional study of high-speed machining, temperature rise at bearings is the most focused on, and quality characteristics such as vibration, noise, and deformation are measured separately, thereby leading to an enormous amount of labor hours and cost. But to secure its stability in the development phase and shorten the development cycle from the standpoint of energy conversion, we studied the evaluation method grounded on functionality as well as quality characteristics.

2. Generic Function and Measurement Characteristic

A good main spindle is regarded as what can maintain a smooth revolution for instructed numbers of revolutions ranging from low to high speed and generate less heat and energy loss caused by vibration and noise. Setting a square root of spinning time to a signal and a square root of cumulative electric power to output (Figure 2), we considered the generic function, $\sqrt{y} = \beta\sqrt{T}$. On the other hand, since the main spindle is driven by the motor, we defined as the on-state the revolution when the main spindle is connected to the motor and as the off-state the revolution made only by the motor, and set the difference between the on- and off-states to the SN ratio. Figure 3 summarizes the transition of the measurements, and Figure 4 magnifies a part of them. Details are as follows:

- *Characteristics:* cumulative electric power when the main spindle is spinning, $\sqrt{y}$.
- *Signal factor:* revolution time, $\sqrt{T}$.
- *Noise factor:* since the number of revolutions changes all the time, we select the revolution-increasing phase (N_1) and decreasing phase (N_2). In addition, we chose the minimum

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

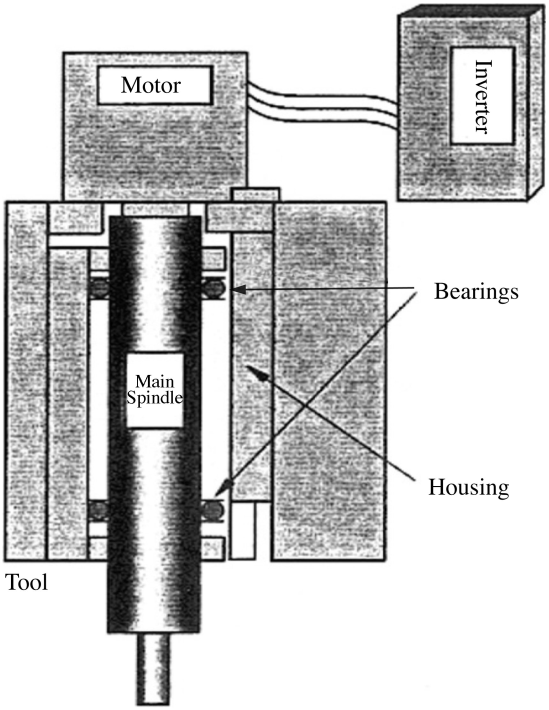

Figure 1
Main spindle in machining center

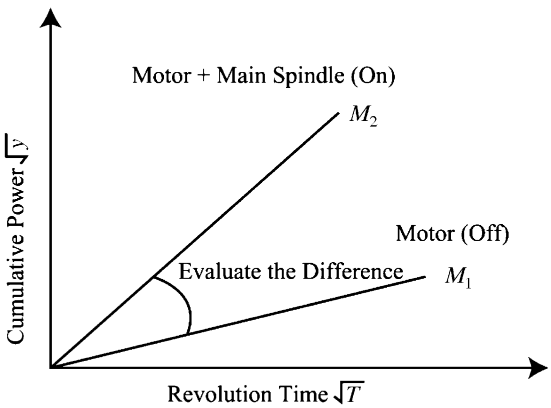

Figure 2
Generic function

value of electric power (N'_1) and maximum value (N'_{2r}) at each number of revolutions.

For the number of revolutions (k indicates 1000 revolutions), three values, 8k, 12k, and 16k per minute, were allocated to the outer array as the second signal. As control factors, we selected eight factors, such as type of bearing, part dimension, part shape, or cooling method, and assigned them to an L_{18} as the inner array.

3. Experimental Procedure and Calculation of the SN Ratio

Only for the main spindle shown in Figure 1, we prepared the experimental device. Using this, we measured momentary voltage by an electric power meter connected to the secondary terminal of the inverter control board to drive the motor. Two measurements were taken, one for revolution only by the motor, denoted by M_1^*, and the other for revolution by both motor and spindle, denoted by M_2^*. Table 1 shows the results of experiment 1. All data in Table 1 are expressed in the unit of a square root of cumulative electric power. The reason that we take a square root of time and cumulative electric power is that the original data is energy. That is, we followed the principle of quality engineering that squared data should become energy so that we can obtain energy through decomposition of variations. Based on these, by regarding the SN ratio, η^*, and sensitivity, S^*, of the effect difference between M_1^* obtained only by the motor only (off-state) and M_2^* by both the motor and main spindle (on-state) as the effective portion of the energy of the main spindle's revolution, we proceeded with calculations as follows.

Total variation:

$$S_T = 0.410^2 + 0.578^2 + \cdots + 2.945^2$$
$$= 257.62 \qquad (f = 120) \qquad (1)$$

Effective divider:

$$r = 5.477^2 + 7.746^2 + \cdots + 12.247^2 = 450.00 \qquad (2)$$

Linear equations:

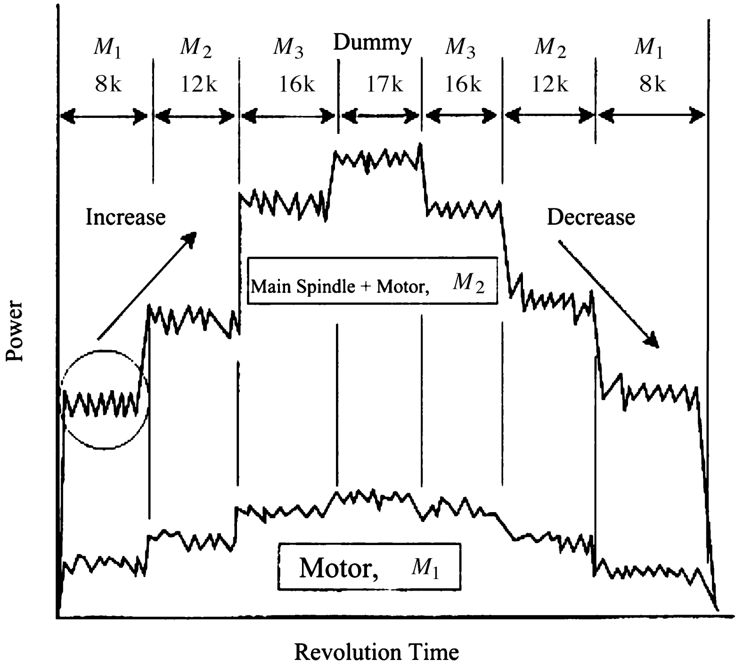

Figure 3
Transition of electric power at on- and off-states when main spindle is spinning

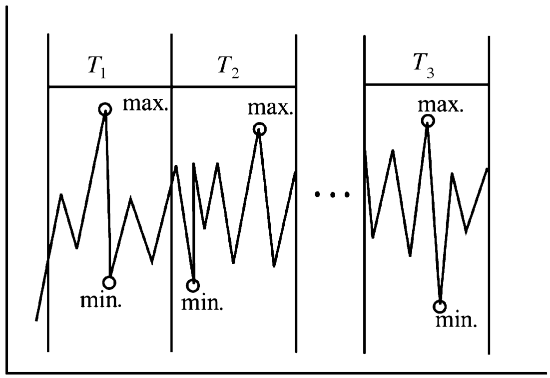

Figure 4
Data selection of minimum and maximum electric power values when main spindle is spinning

$$
\begin{aligned}
L_1 &= (0.410)(5.477) + \cdots + (0.913)(12.247) \\
&= 32.566 \\
&\ \vdots \\
L_{24} &= 107.842
\end{aligned} \tag{3}
$$

Variation of proportional term:

$$
S_\beta = \frac{(L_1 + L_2 + \cdots + L_{24})^2}{24r} = 219.13 \qquad (f = 1) \tag{4}
$$

Variation of differences of proportional terms regarding number of revolutions:

$$
\begin{aligned}
S_{M\beta} &= \frac{(L_1 + L_2 + L_3 + L_4 + L_{13} + L_{14} + L_{15} + L_{16})^2 + (L_5 + \cdots + L_{20})^2 + (L_9 + \cdots + L_{24})^2}{8r} \\
&\quad - S_\beta = 12.00990 \qquad (f = 2)
\end{aligned} \tag{5}
$$

Variation of differences of proportional terms regarding motor only and motor and main spindle:

Table 1
Square root data of cumulative electric power

	Time: Revolutions:	T_1 5.477	T_2 7.746	T_3 9.487	T_4 10.954	T_5 12.247	Linear Equation	
M_1^* (motor only)	8k increase max.	0.410	0.578	0.708	0.816	0.913	33.566	L_1
	min.	0.394	0.556	0.681	0.786	0.879	32.305	L_2
	8k decrease max.	0.403	0.575	0.707	0.818	0.915	33.546	L_3
	min.	0.396	0.560	0.686	0.791	0.883	32.488	L_4
	12k increase max.	0.529	0.748	0.917	1.058	1.177	43.399	L_5
	min.	0.515	0.728	0.893	1.023	1.138	42.080	L_6
	12k decrease max.	0.529	0.749	0.917	1.058	1.181	43.452	L_7
	min.	0.515	0.726	0.891	1.028	1.147	42.206	L_8
	16k increase max.	0.670	0.948	1.160	1.338	1.496	54.991	L_9
	min.	0.644	0.915	1.119	1.291	1.443	53.051	L_{10}
	16k decrease max.	0.674	0.951	1.167	1.349	1.511	55.409	L_{11}
	min.	0.650	0.923	1.136	1.313	1.471	53.883	L_{12}
M_2^* (motor and main spindle)	8k increase max.	0.904	1.216	1.461	1.673	1.855	69.279	L_{13}
	min.	0.733	1.057	1.303	1.506	1.683	61.680	L_{14}
	8k decrease max.	0.642	0.914	1.121	1.297	1.453	53.230	L_{15}
	min.	0.629	0.887	1.087	1.256	1.402	51.557	L_{16}
	12k increase max.	1.351	1.866	2.132	2.344	2.535	98.801	L_{17}
	min.	1.211	1.588	1.852	2.077	2.280	87.186	L_{18}
	12k decrease max.	0.937	1.325	1.623	1.876	2.094	76.994	L_{19}
	min.	0.911	1.292	1.581	1.826	2.038	74.964	L_{20}
	16k increase max.	1.407	1.981	2.422	2.794	3.119	114.838	L_{21}
	min.	1.330	1.896	2.331	2.690	3.009	110.398	L_{22}
	16k decrease max.	1.345	1.907	2.343	2.711	3.035	111.231	L_{23}
	min.	1.304	1.847	2.269	2.629	2.945	107.842	L_{24}

$$S_{M^*\beta} = \frac{(L_1 + L_2 + L_3 + \cdots + L_{12})^2 + (L_{13} + L_{14} + \cdots + L_{24})^2}{12r} - S_\beta = 22.92859 \qquad (f = 1) \tag{6}$$

Variation of differences of proportional terms regarding increasing and decreasing phases:

$$S_{N\beta} = \frac{(L_1 + L_2 + L_5 + L_6 + \cdots + L_{21} + L_{22})^2 + (L_3 + L_4 + L_7 + L_8 + \cdots + L_{23} + L_{24})^2}{12r} - S_\beta = 0.38847 \qquad (f = 1) \tag{7}$$

Variation of differences of proportional terms regarding min and max:

$$S_{N'\beta} = \frac{(L_1 + L_3 + L_5 + \cdots + L_{21} + L_{23})^2 + (L_2 + L_4 + L_6 + \cdots + L_{22} + L_{24})^2}{12r} - S_\beta = 0.14159 \qquad (f = 1) \tag{8}$$

Variation of differences of proportional terms regarding rpm and motor/(motor and spindle) combinations:

$$S_{MM^*\beta} = \frac{1}{4r}\begin{bmatrix}(L_1 + L_2 + L_3 + L_4)^2 + (L_5 + L_6 + L_7 + L_8)^2 \\ + (L_9 + \cdots + L_{12})^2 + \cdots + (L_{17} + \cdots + L_{20})^2 \\ + (L_{21} + \cdots + L_{24})^2\end{bmatrix} - S_\beta - S_{M^*\beta} - S_{M\beta} = 2.10615 \qquad (f = 2) \tag{9}$$

Error variation:

$$S_e = S_T - S_\beta - S_{M^*\beta} - S_{M\beta} - S_{N'\beta} - S_{N\beta} - S_{MM^*\beta} = 0.91277 \qquad (f = 112) \tag{10}$$

Error variance:

$$V_e = \frac{S_e}{112} = 0.00815 \tag{11}$$

Total error variance:

Table 2
Control factors and levels

Control Factor	Level 1	Level 2	Level 3
A: bearing type	A_1	A_2	—
B: housing dimension	Small	Mid	Large
C: main spindle dimension	Small	Mid	Large
D: gap seat dimension	Small	Mid	Large
E: gap seat shape	E_1	E_2	E_3
F: tightening dimension	Small	Mid	Large
G: bearing shape	Small	Mid	Large
H: cooling method	H_1	H_2	H_3

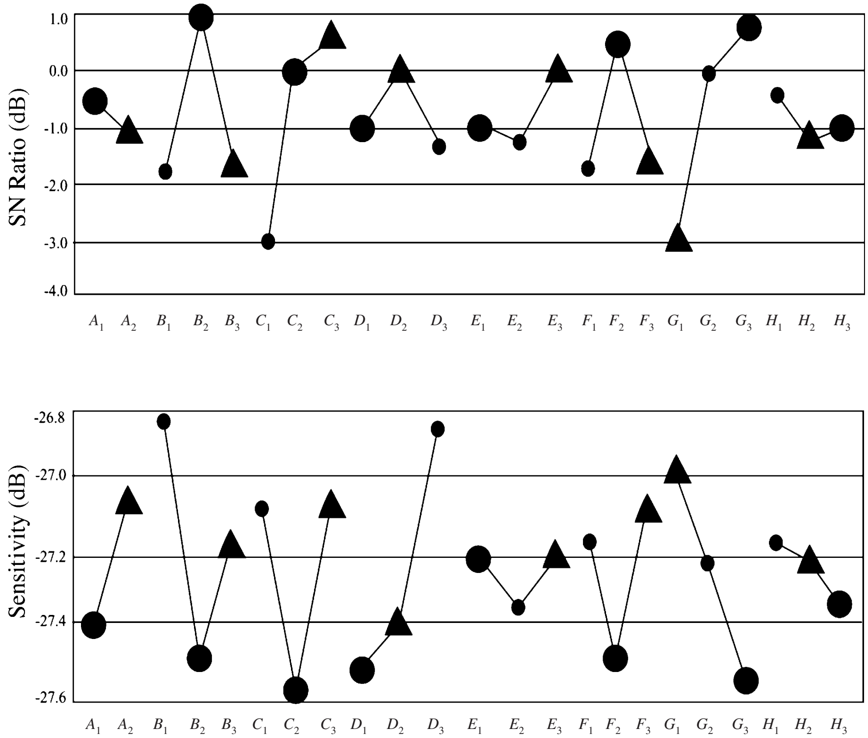

Figure 5
Factor effects plot

Table 3
Confirmatory experimental results (dB)

	SN Ratio		Sensitivity	
Condition	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	4.33	1.20	−28.80	−28.25
Current	−2.71	−3.23	−26.55	−27.54
Gain	7.04	4.43	−2.25	−0.71

$$V_N = \frac{S_{N'\beta} + S_{N\beta} + S_e}{114} = 0.012656 \quad (12)$$

SN ratio:

$$\eta^* = 10 \log \frac{(1/24r)(S_{M^*\beta} - V_e)}{V_N} = -7.76 \text{ dB} \quad (13)$$

Sensitivity:

$$S^* = 10 \log \frac{1}{24} (S_{M^*\beta} - V_e) = -26.73 \text{ dB} \quad (14)$$

4. Optimal Condition and Confirmatory Experiment

As control factors, we selected eight factors such as bearing type, part dimension, part shape, and cooling method and assigned them to an L_{18} orthogonal array (Table 2). Based on the results above, we obtained the response graphs shown in Figure 5. Despite many peaks and V-shapes, by focusing on levels that have a higher SN ratio and a lower sensitivity value, we selected each factor level.

Optimal condition: $A_1B_2C_2D_1E_1F_2G_3H_3$

In addition, we chose the comparative conditions by taking into account the workability or compatibility of parts to maximize the gain.

Comparative condition: $A_2B_3C_3D_2E_3F_3G_1H_2$

Table 3 shows the estimations and confirmations. The measurements of the main spindle's temperature as our initial objective are illustrated in Figure 6. As we aimed to do at the beginning, we were able to reduce the temperature at the bearings of the

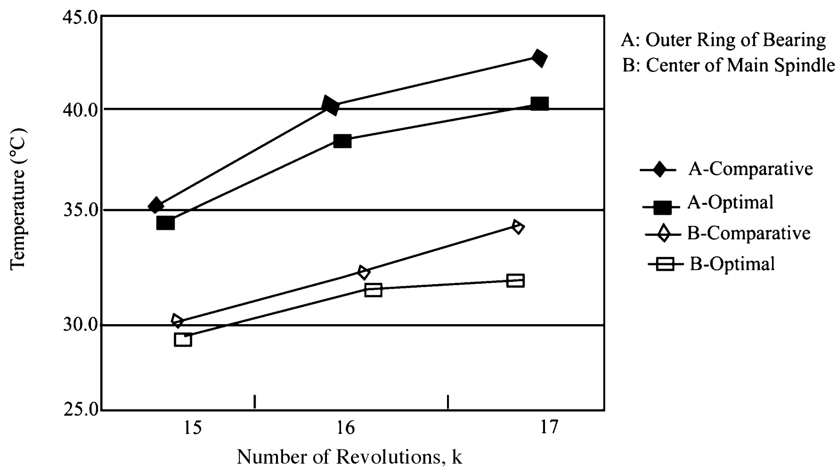

Figure 6
Temperature change of main spindle

main spindle. By measuring the electric power of the motor and evaluating its functionality, we found the optimal condition, which can be confirmed based on the quality characteristics.

Although it has long been believed that we should continue to do experiments on a main spindle until it breaks down, in our study, no breakdown happened. Therefore, we were able to drastically reduce the time necessary for evaluation.

Reference

Machio Tamamura, Makoto Uemura, Katsutoshi Matsuura, and Hiroshi Yano, 2000. Study of evaluation method of spindle. *Proceedings of the 8th Quality Engineering Symposium*, pp. 34–37.

This case study is contributed by Machio Tamamura and Hiroshi Yano.