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Controller gain tuning of a simultaneous multi-axis PID control system using the Taguchi method

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Abstract

This paper presents a gain-tuning scheme for multi-axis PID control systems using the Taguchi method. A parallel-mechanism machine tool has been selected as an experimental set-up. This machine has eight servodrivers and each servodriver has four controller gains, resulting in a total of 32 controller gains to be tuned. Through a series of 'Design of Experiments' suggested by the Taguchi method, an optimal and robust set of PID controller gains has been obtained. The index of aggregate position and velocity errors has been reduced to 61.4%, regardless of feedrate variation, after the experimental gain tuning.

Keywords: Taguchi method; Design of experiment; Gain tuning; PID controller

1. Introduction

Automatic controllers are used in many manufacturing processes. These are generally of the PID type because they are standard industrial components. Moreover, owing to modeling uncertainties, a more sophisticated control scheme is not necessarily more efficient than a well-tuned PID controller. Alongside the advantages, however, the problem of tuning PID controllers has remained an active research area.

Since the early work of Ziegler and Nichols (1942), many techniques have been proposed for the manual or automatic tuning of PID controllers. The so-called Ziegler–Nichols method consists of two tuning rules. In the first method, the choice of controller parameters is based on obtaining a 25% maximum overshoot. In the second method, the criteria for adjusting the parameters are based on evaluating the system at the limit of stability. Thanks to its simplicity, the empirical Ziegler–Nichols tuning rules are still among the most popular schemes. Their relevance, however, is only guaranteed to a limited range of applications and the second method only applies if the output exhibits sustained oscillations.

Astrom and his associates (Astrom & Hagglund, 1984; Astrom, Hang, Persson & Ho, 1992) applied the relay feedback technique to the auto-tuning of PID controllers. In this method, relay feedback contributes to robustness, and auto-tuning of the PID controller helps to save time. However, due to the adoption of an approximation to the describing function, this method is not accurate enough for many kinds of processes, such as long-dead-time processes. It is also difficult to apply it to multi-input-multi-output (MIMO) systems, because the relay feedback technique tunes gains separately.

The majority of the regulators used in industry are tuned using frequency response methods, because the modeling errors and the application specifications can be expressed directly in the frequency domain. However, it is not convenient to obtain mathematical models of plant. Additionally, like the auto-tuning technique, frequency response methods are difficult to apply to the MIMO system.

Ferrell and Reddivari (1995) believed that PID controllers are poorly tuned because traditional methods of controller design and tuning to achieve minimum variance require the engineer to create a closed-form mathematical model of the system and controller dynamics. The result is frequently degradation in product quality and productivity. They proposed a technique using the Taguchi method (Taguchi, 1993; Peace, 1993; Fowlkes & Creveling, 1995), which is very convenient

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when mathematical models of plants are not available. They tuned 11 controller gains for adjusting the flows of steam and water in a chemical process, using a fractional factorial experiment with an orthogonal array. Only 16 experiments were required to tune the controller gains using the fractional factorial experiment while 2^{11} (2048) experiments would be required in a full factorial experiment. Furthermore, these experiments did not require additional devices because controller gains were tuned by only measuring the exit moisture and temperature of the product. Noise factors, however, were not considered in this technique, and controller gains obtained by these experiments were not necessarily optimal because only two levels of controller gains were adopted in the experiments.

Commonly, with changes in system dynamics and variations in operating points, PID controllers should be retuned regularly. It is very important that the controller gains obtained are robust even though system dynamics change and operating points vary. This paper proposes a technique using the Taguchi method, which tunes controller gains optimally and robustly in real process control systems. In this study, three levels of controller gain are adopted for the purpose of obtaining optimal controller gains. This technique can easily adapt single-input–single-output systems as well as multi-input–multi-output systems without mathematical models of plants.

The Eclipse, a parallel-mechanism machine tool, is selected as an experimental set-up, and is shown in Fig. 1. This machine has eight servodrivers and each servodriver has four controller gains. Therefore, a total of 32 controller gains must be tuned. In order to evaluate the technique using the Taguchi method, a comparison of control outputs by manual tuning (which Samsung Electronics Co. recommends as the tuning method) and by the Taguchi method is made. The experimentation consists of two 'Design of Experiments.' In the 'Design of Experiment I,' the eight servomotors are divided into three groups, each of which has an identical model. Then, one servomotor is selected from each group, and the four controller gains of each servomotor are tuned while the fixed rod is disconnected from the main spindle plate of the Eclipse. There are four stages in the 'Design of Experiment I' for tuning controller gains robustly and optimally. The need for four stages will be explained later in this paper. In the 'Design of Experiment II,' based on the controller gains obtained from the 'Design of Experiment I,' a total of 32 controller gains of eight servomotors are fine-tuned for the representative machining path of the Eclipse and for various feedrates. There are two stages in the 'Design of Experiment II.'

This paper is organized as follows: The Taguchi method is introduced briefly in Section 2, and the structure and the distinctive characteristics of the Eclipse is discussed in Section 3. The designs and results of the

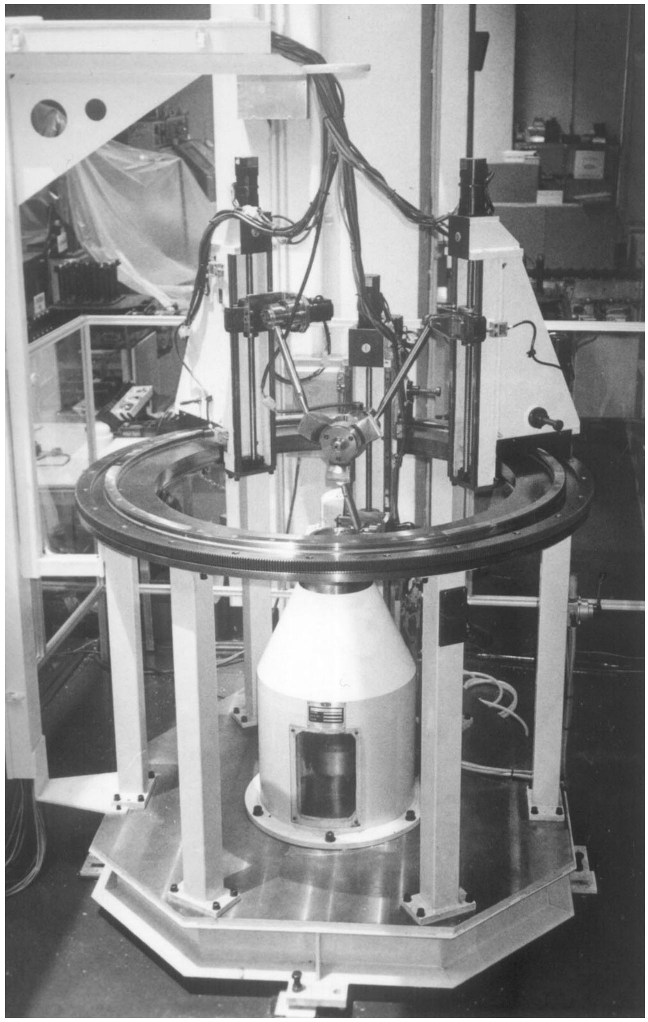

Fig. 1. Photo of the parallel-mechanism machine tool: *Eclipse*.

'Design of Experiments I and II' are discussed in Sections 4 and 5, respectively. Section 6 concludes the paper.

2. Taguchi method

As shown in Fig. 2a, the Taguchi method, based on the fractional factorial experiment, divides the independent variables into controllable factors and noise factors. Controllable factors are those that can be maintained to a desired value, while noise factors are those that may not be controlled. According to the Taguchi method, a robust design is one that maintains high performance while remaining insensitive to changes in noise factors. As can be seen in Fig. 2b, this means that a robust tuning technique using the Taguchi method would enable regulators not only to reduce control errors but also to decrease variations in those values while remaining insensitive to changes in system dynamics and variations in operating points. In this paper, experiments to tune a

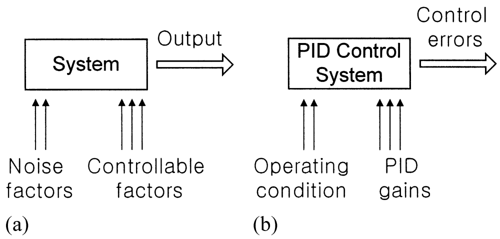

Fig. 2. Definition of a system in the Taguchi method and a PID control system. (a) A system, (b) a PID control system.

total of 32 position controller gains of eight servomotors are presented. The 'Design of Experiment' using the Taguchi method is briefly outlined below:

(1) *Identifying the objectives*: In the first step of the Taguchi method, identifying a specific objective is important. In the authors' experiments, the phenomenon of increasing position and velocity errors with increases in feedrate was detected. Therefore, the objective is a robust tuning of controller gains for minimizing position and velocity errors regardless of feedrate variation.

(2) *Determining the quality characteristic*: The Taguchi method classifies quality characteristics into one of three types: *nominal-the-best*, *smaller-the-better* and *larger-the-better*. In this paper, the smaller the sum of position and velocity errors, the better the performance. Therefore, the quality characteristic in this case is the sum of position and velocity errors, and it is a *smaller-the-better* problem.

(3) *Selecting the controllable factors and noise factors*: The selection of factors to be tested for their influence on the quality characteristic is one of the most important procedures. Careless selection of controllable factors and noise factors can lead to false conclusions and can require experiments to be repeated. After selecting factors, their desired number of levels is determined. In this paper, controller gains are used as the controllable factors and feedrate is used as the noise factor. The number of levels for controller gains is three and for feedrate is also three. The next step is to assign a physical value to each level of controllable factors and noise factors. In this paper, for example, the feedrate has three levels: *Level* 1, *Level* 2, and *Level* 3. Actually a physical value of 1350 pulse/50 ms is assigned to *Level* 1 of the feedrate. In a similar way, physical values of 4000 and 6800 pulse/50 ms are assigned to *Levels* 2 and 3 of the feedrate, respectively.

(4) *Selecting an orthogonal array*: The full factorial experiment requires the testing of all combinations of the factor levels under study. For example, a study involving 13 factors at three levels each would require $3^{13} = 1{,}594{,}323$ experiments. Orthogonal arrays produce smaller, less costly experiments. Using an $L_{27}(3^{13})$ orthogonal array, for example, a study involving 13 factors at three levels can be conducted with only 27 experiments. Besides being efficient, the procedures for using orthogonal arrays are straightforward and easy to use. In this paper, an $L_9(3^4)$ orthogonal array is selected.

(5) *Conducting the experiment and analysis*: Conducting the experiment includes the execution of the experiment as developed in the planning and design phases. The analysis phase of experimentation relates to calculations for converting raw data into the representative signal-to-noise ratio (S/N ratio, η). As a measurement tool for determining robustness, the S/N ratio is an essential component to optimal parameter design. By including the impact of noise factors on the process or product as the denominator, the S/N ratio can be adopted as the index of the system's ability to perform well regardless of the effects of noise. By successfully applying this concept to experimentation, it is possible to determine the controller gain settings that can produce the minimum velocity and position errors while minimizing the effect of the feedrate variation. Analysis also includes determination of the most important controllable factors, which can maximize the S/N ratio, and selecting the optimal levels for those factors. In this paper, determination of the most important controller gains and selection of the optimal levels are analyzed.

3. The parallel-mechanism machine tool 'Eclipse'

In order to evaluate the tuning technique using the Taguchi method, the Eclipse, a parallel-mechanism machine tool (Kim, Park, Kim & Park, 1997; Ryu et al., 1998), was used. As shown in Fig. 3, the Eclipse consists of three PRS serial subchains that move independently on a fixed circular guide, where P, R and S denote prismatic, revolute, and spherical joints, respectively. The mechanism has six kinematic degrees of freedom, and eight actuated joints. Servomotors M_1, M_2 and M_3 drive each vertical column independently on the fixed circular guide. Each column has a carriage, which moves up and down on the column slideway. Servomotors M_4, M_5 and M_6, which are installed in each column, drive the carriage. Servomotor M_7 drives a revolute joint on the carriage of the downward vertical column. Servomotor M_8 drives a revolute joint on the carriage of the upward vertical column. Servomotors M_7 and M_8 are necessary to avoid the kinematic singularity problem (Kim et al., 1997; Ryu et al., 1998).

Fig. 4 shows the 90° tilting capability of the Eclipse. The home position of the Eclipse is shown in Fig. 4(a). The spindle platform maintains the vertical posture. As the three vertical columns move along the circular guide to the side-by-side position shown in Fig. 4(b), the spindle platform goes into the horizontal posture with its tilting angle reaching 90°. The 90° tilting capability is one of the unique features of the Eclipse.

The Eclipse consists of a total of eight servo systems, and each servo system consists of a servomotor and

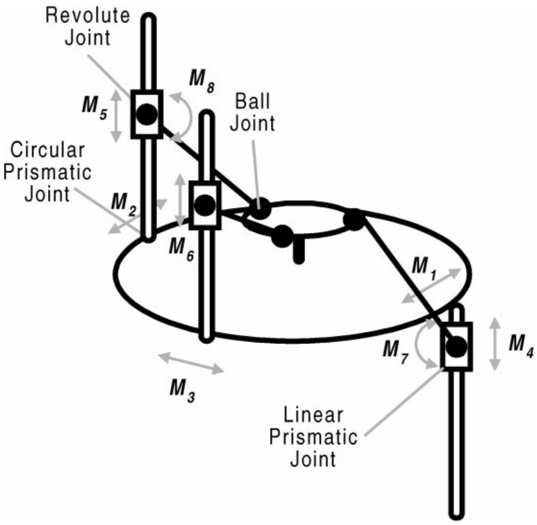

Fig. 3. Schematic diagram of the Eclipse mechanism.

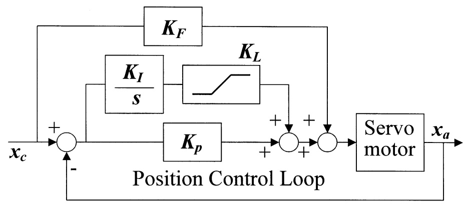

Fig. 5. Position controller structure of the Eclipse servo system.

Table 1
Initial values of controller gains determined by the *Samsung method*

Group	Servomotors	K_P	K_I	K_L	K_F
I	M_1, M_2, M_3	50	3	1000	100
II	M_4, M_5, M_6	80	4	800	100
III	M_7, M_8	60	2	1000	3

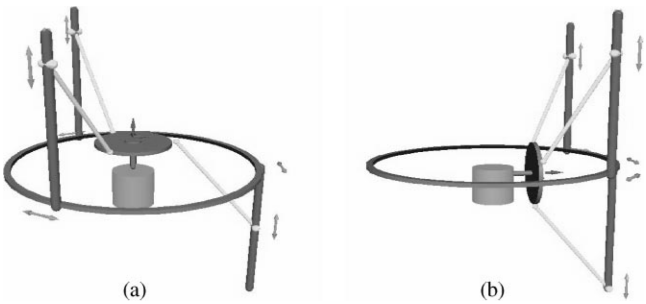

Fig. 4. Unique feature of the Eclipse mechanism: 90° tilting capability. (a) Vertical posture, (b) horizontal posture.

a servodriver. The position control algorithm is executed in the DSP board. At each sampling time, through the inverse kinematics of the Eclipse, eight electronic motion controllers drive eight servomotors, respectively, to achieve the required path of the tool-tip.

4. Experiment I: gain tuning of the representative servomotors

Servomotors are grouped into three groups; three servomotors M_1, M_2 and M_3 for driving three vertical columns, respectively, three servomotors M_4, M_5 and M_6 for moving three carriages, respectively, and two servomotors M_7 and M_8 for rotating two revolute joints, respectively. Servomotors in each group are the same models from Samsung Electronics Co.: CSMG-06 for the group M_1, M_2 and M_3, CSMG-04 for the group M_4, M_5 and M_6 and CSMG-02 for the group M_7 and M_8.

In the 'Design of Experiment I,' controller gains of a representative servomotor per group are tuned while the fixed rod is disconnected from the main spindle plate of the Eclipse. The representative servomotors from each group selected for tuning in the 'Design of Experiment I' are M_2 for the first group, M_5 for the second and M_7 for the third. In this section, a study for tuning servomotor M_5 is presented. However, controller gains of each servomotor, even those in the same group, should be tuned differently. These fine-tunings are discussed in Section 5. As shown in Fig. 5, controller gains consist of four types; proportional gain (K_P), integral gain (K_I), saturation limit (K_L) and feedforward gain (K_F). At the beginning of the experiment, controller gains are tuned using the manual method that Samsung Electronics Co. (1996) suggests (referred to here as *Samsung method*), and the results are shown in Table 1. For the controller gains in Table 1, Fig. 6 represents the position and velocity errors of servomotor M_5 according to the feedrate levels. As an experimental path, servomotor M_5 is programmed to move the carriage a full stroke up and down once on the vertical column. Position and velocity errors vary greatly with respect to low ($f_L = 1350$ pulse/50 ms), middle ($f_M = 4000$ pulse/50 ms) and high feedrate ($f_H = 6800$ pulse/50 ms). This means that the tuning obtained with the *Samsung method* is not robust with respect to feedrate. Therefore, this paper proposes a tuning technique using the Taguchi method, which guarantees robustness in the presence of feedrate variation.

A dimensionless index of aggregate position and velocity errors (y) can be expressed as

$$y = \frac{1}{n}\left(\frac{\sum_{i=1}^{n}|\theta_{a,i} - \theta_{c,i}|}{L} + \frac{\sum_{i=1}^{n}|\dot{\theta}_{a,i} - \dot{\theta}_{c,i}|}{|\dot{\theta}_{\max}|}\right),$$

where θ_a [encoder pulse] is the incremental actual position of each axis, θ_c [encoder pulse] is the incremental command position of each axis, $\dot{\theta}$ [pulse/50 ms] is the velocity of each position, L [encoder pulse] is the total

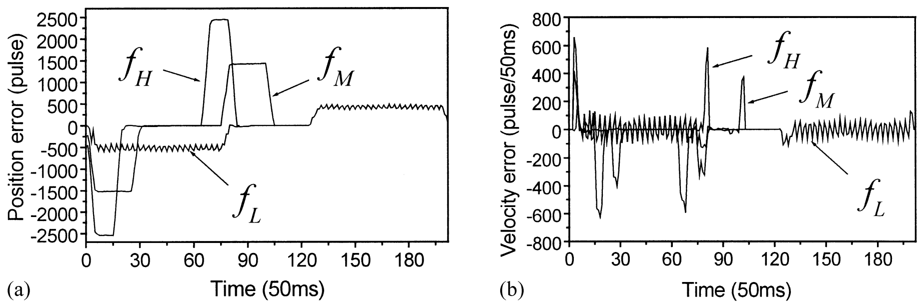

Fig. 6. Position and velocity errors of servomotor M_5 according to levels of feedrate with the initial controller gains selected by *Samsung method* (Table 1). (a) Position error, (b) velocity error.

moving distance and n is total number of data points along the experimental path. Since the data sampling time and the moving distance L are constant for each experimental run, the number of data points n of each run is different according to the feedrate. As the feedrate becomes higher, n becomes smaller. Hence y is a dimensionless index of the average position and velocity errors for one data point.

As stated before, the controllable factors are the four controller gains K_P, K_I, K_L and K_F of servomotor M_5, and the noise factor is feedrate f. It is clear that robust controller gains should be different from those in Table 1, because position and velocity errors (Fig. 6) of servomotor M_5 vary greatly according to feedrate. As in the Taguchi method, the number of levels of controllable factors and the values for them are determined. Since the objective in this case is to find optimal and robust controller gains, the number of levels should be at least three. The next step is to assign a physical value to each level of controllable factors and noise factors. Table 2 shows the physical values that are assigned to each level of controller gains (for servomotor M_5) and feedrate. They are determined on the basis of Table 1. The physical value of each level in Table 2 is determined around the corresponding initial value given in Table 1 (for servomotor M_5). The wider the range between the lowest value and the highest value of the level, the more successful in discovering the real effects of those controller gains on the quality characteristic y. However, there is no general rule. It is heavily dependent on the sound experience and knowledge of the system.

Conducting experiments is based on the orthogonal array $L_9(3^4)$ of the Taguchi method (Peace, 1993), where '3' means three levels, '4' is four controllable factors (K_P, K_I, K_L, K_F), and '9' means nine experimental runs. The number '1', '2' and '3' in Table 3 corresponds to the physical values selected in Table 2. For example, in the case of experiment number 1, $K_P = 1, K_I = 1, K_L = 1$, and $K_F = 1$ means that K_P, K_I, K_L, K_F are set to 40, 1, 500, 100, respectively. After conducting experiments, $y(f_L)$, $y(f_M)$ and $y(f_H)$ are calculated respectively based on the position and velocity errors.

Table 2
Levels of controllable and noise factors at stage 1 in the 'Design of Experiment I' for servomotor M_5

Group	Symbol	Level 1	Level 2	Level 3
Controllable factors (controller gains)	K_p	40	70	100
	K_i	1	3	5
	K_l	500	1000	1500
	K_f	100	200	300
Noise factor (feedrate)	f	1350	4000	6800

As shown in Table 3, experiment number is from 1 to 9 and three experiments according to the feedrate levels were executed for each experiment number. Therefore a total of $9 \times 3 = 27$ experiments were performed. The S/N ratio η in case of smaller-the-better quality characteristic can be written as

$$\eta_i = -10 \log_{10}\left(\frac{1}{3}\sum_{j=1}^{3} y_{ij}^2\right),$$

where y_{ij} for experiment number $i = 1, 2, \ldots, 9$ and levels of noise factor $j = 1, 2, 3$ is the index of aggregate position and velocity errors. After calculating y_{ij}, average S/N ratios for each level of the factor K_P are calculated on the basis of Table 3 as follows:

$$\eta(\text{Level 1of } K_P) = \frac{23.69 + 24.55 + 25.35}{3} = 24.53,$$

$$\eta(\text{Level 2 of } K_P) = \frac{28.94 + 26.48 + 28.26}{3} = 27.89,$$

$$\eta(\text{Level 3 of } K_P) = \frac{29.87 + 30.79 + 28.55}{3} = 29.74.$$

By following the same calculation, the average S/N ratios for each level of the factors K_I, K_L, and K_F can be calculated and are shown in Fig. 7. The strongest factors can be identified graphically. By plotting the average

Table 3
Experimental results based on orthogonal array $L_9(3^4)$ for servomotor M_5 at stage 1 in the 'Design of Experiment I'

	Controller gains				Position and velocity error index (y) at different levels of noise factor			
Experiment number	K_P	K_I	K_L	K_F	f_L	f_M	f_F	S/N ratio η (dB)
1	1	1	1	1	0.052	0.063	0.078	23.69
2	1	2	2	2	0.049	0.057	0.07	24.55
3	1	3	3	3	0.043	0.052	0.065	25.35
4	2	1	2	3	0.038	0.03	0.038	28.94
5	2	2	3	1	0.057	0.036	0.046	26.48
6	2	3	1	2	0.041	0.033	0.041	28.26
7	3	1	3	2	0.041	0.024	0.029	29.87
8	3	2	1	3	0.037	0.022	0.026	30.79
9	3	3	2	1	0.049	0.026	0.033	28.55

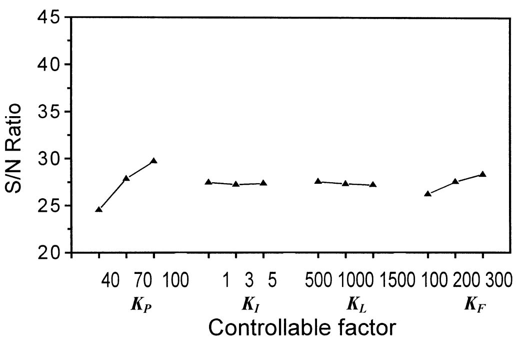

Fig. 7. Response graph obtained at stage 1 in the 'Design of Experiment I' for servomotor M_5.

response value for each factor level, relative comparisons of the slopes between points plotted can be made. The response graphs (Fig. 7) indicate that factors K_P and K_F have strong effects, whereas K_I and K_L have weak effects. In other words, the variations of the K_P and K_F values are more sensitive to the S/N ratio variation than those of K_I and K_L values. As in any signal-to-noise analysis, the greatest S/N ratio is recommended. Based on Table 3, the preferred levels for factors that results in a maximum S/N ratio are those in experiment number 8, that is, K_P at level 3, K_F at level 3, K_I at level 2 and K_L at level 1.

The position and velocity errors of servomotor M_5 with respect to newly selected controller gains are shown in Fig. 8. Compared with Fig. 6, the S/N ratio increased by 2.1 dB and the mean value of aggregate position and velocity errors is reduced by 22.3%. However, the reduction of position and velocity errors is not significant enough to prevent another stage in the 'Design of Experiment I' being tried.

It is observed from Fig. 7 that the preferred levels for K_P and K_F are set at level 3 and the S/N ratio increases continually with each controller gain. This means that values for K_P and K_F that can maximize the S/N ratio may be higher than the preferred levels. Accordingly, based on the preferred levels at stage 1, controller gains should be tuned again, in stage 2.

In stage 2, the experimental procedure is the same as for gain tuning at stage 1 except for the levels of controller gains. After conducting gain tuning at stage 2, if making the S/N ratio greater is feasible, additional gain tuning is performed. By following these methods, gain tuning using the Taguchi method is completed at stage 4 in the 'Design of Experiment I.' Table 4 represents the levels of controller gains selected in stages 1–4. The preferred levels for controller gains at each stage are indicated in bold type in Table 4.

Response graphs at stage 3 in Fig. 9 show that S/N ratios for K_P and K_F do not increase any further and the preferred levels are the second values. This means that their optimal levels exist around the second level at stage 3. Response graphs also indicate that factors K_I and K_L as well as factors K_P and K_F have strong effects. Based on the preferred gains at stage 3, controller gains are finally tuned at stage 4. The position and velocity errors of servomotor M_5 with respect to the settings selected at stage 4 are shown in Fig. 10. Compared with Fig. 8, the S/N ratio has increased by 12.1dB and the mean value of aggregate position and velocity errors is reduced by 79.8%.

5. Experiment II: final fine-tuning of each servomotor

Even though servomotors are included in the same group, their controller gains might be slightly different. Also, controller gains tuned independently while the fixed rod is disconnected in the 'Design of Experiment I' must all be fine-tuned together with the fixed rod connected. Accordingly, in this section, a fine-tuning technique

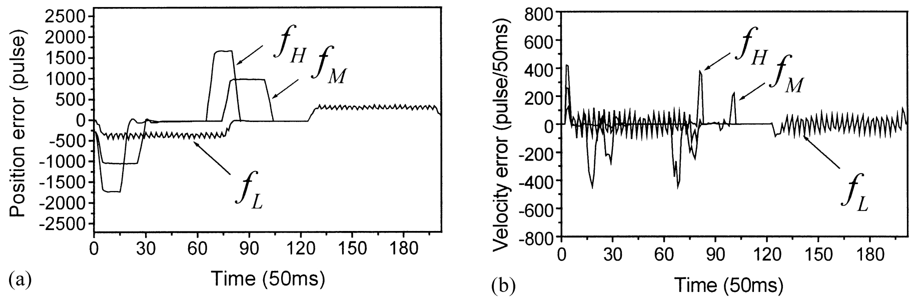

Fig. 8. Position and velocity errors of servomotor M_5 according to levels of feedrate with the controller gains selected at stage 1 in the 'Design of Experiment I'. (a) Position error, (b) velocity error.

Table 4
Levels of controller gains at stages 1–4 in the 'Design of Experiment I' for servomotor M_5

		Controller gains			
Stage	Levels	K_P	K_I	K_L	K_F
Stage 1	Level 1	40	1	500	100
	Level 2	70	3	1000	200
	Level 3	**100**	5	1500	**300**
Stage 2	Level 1	100	1	500	300
	Level 2	130	3	1000	600
	Level 3	**160**	5	1500	**900**
Stage 3	Level 1	160	**1**	**500**	900
	Level 2	**190**	3	1000	**1200**
	Level 3	220	5	1500	1500
Stage 4	Level 1	180	**1**	300	1100
	Level 2	190	2	**500**	1200
	Level 3	**200**	3	700	**1300**
Finally tuned values		**200**	**1**	**500**	**1300**

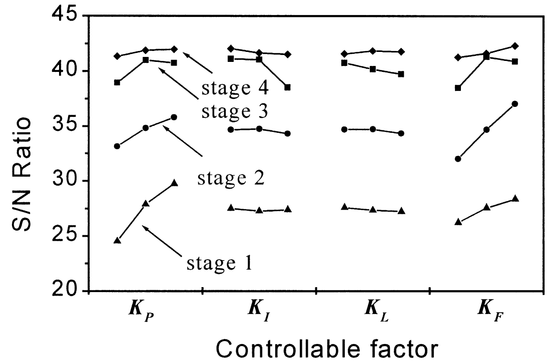

Fig. 9. Response graphs obtained at stages 1–4 in the 'Design of Experiment I' for servomotor M_5.

using the Taguchi method is presented in which a total of 32 controller gains of eight servomotors are fine-tuned for the representative machining path of the Eclipse at various operating velocities.

The quality characteristic belongs to the smaller-the-better problem, which minimizes the sum of position and velocity errors with respect to the machine axes. The controllable factors are the same as those used in the 'Design of Experiment I.' The orthogonal array $L_9(3^4)$ selected in the 'Design of Experiment I' is again selected because gain fine-tuning of eight servomotors is performed with respect to the same servomotors in the 'Design of Experiment I.' Based on the optimal controller gains determined at stage 4 in the 'Design of Experiment I,' levels for controller gains are selected at stage 1 in the 'Design of Experiment II.' In this case the noise factor is the feedrate of the spindle nose; $f_L = 0.6$ m/min, $f_M = 1.2$ m/min and $f_H = 2.4$ m/min. The feedrate of the spindle nose is defined as the tangential velocity of the spindle nose along the moving path. As previously stated, one of the most important features of Eclipse is its 90° tilting capability. Therefore, the experimental path used in the 'Design of Experiment II' is determined as in Fig. 11.

Fig. 12 presents position and velocity errors with respect to optimal gains selected in the 'Design of Experiment I.' The final fine-tuning in the 'Design of Experiment II' is completed in stage 2. Table 5 represents levels of controller gains in the second group selected at each stage in the 'Design of Experiment II.' It is noted that the final controller gains of each servomotor tuned at stage 2 (Table 5) are slightly different even if the three servomotors are identical.

Fig. 13 represents the position and velocity errors of servomotor M_5 with respect to the settings selected finally at stage 2 in the 'Design Experiment II.' Compared with Fig. 12, the S/N ratio has increased by 1.35 dB and the mean value of aggregate position and velocity errors is reduced by 12.2%.

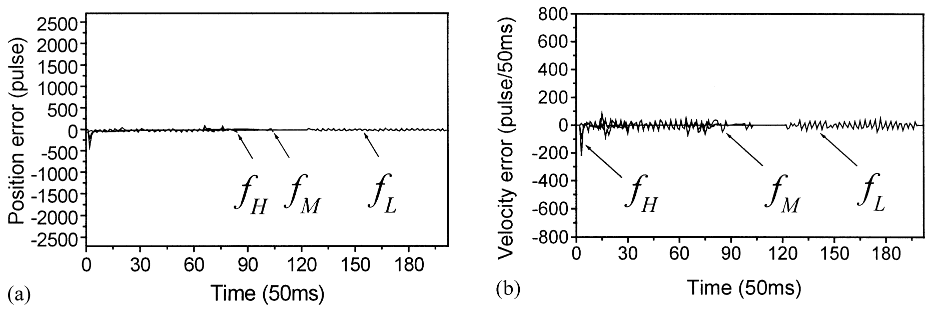

Fig. 10. Position and velocity errors of servomotor M_5 according to levels of feedrate with the controller gains selected at stage 4 in the 'Design of Experiment I'. (a) Position error, (b) velocity error.

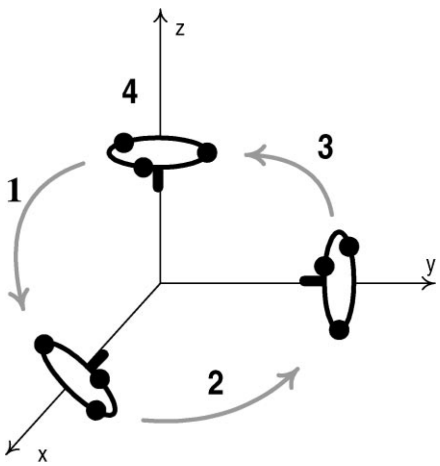

Fig. 11. Experimental path used in the 'Design of Experiment II'.

Fig. 14 represents S/N ratios and mean values of the control errors for each servomotor with manual tuning using the *Samsung method* and final tuning using the Taguchi method. S/N ratios are increased as follows: M_1: 5.8 dB; M_2: 6.1 dB; M_3: 7.3 dB; M_4: 12 dB; M_5: 7.9 dB; M_6: 7.6 dB; M_7: 10.7 dB; M_8: 10.9 dB. Mean values of aggregate position and velocity errors are reduced as follows: M_1: 47.4%; M_2: 49.2%; M_3: 56.5%; M_4: 75.7%; M_5: 59.7%; M_6: 57.6%; M_7: 70.6%; M_8: 71.9%. The average S/N ratio is increased by 8.5 dB and the average mean value of aggregate position and velocity errors is reduced by 61.4%.

6. Conclusions

In this paper, a new gain tuning technique using the Taguchi method is proposed, which can tune controller gains for PID controller systems optimally and robustly. This technique is very convenient when mathematical models of plants are not available and is easily extended to multi-input–multi-output systems from basic single-input–single-output systems. In the authors' experiment, controller gains for the Eclipse machine tool are tuned through a series of 'Design of Experiments.' In the 'Design of Experiment I,' four controller gains for three representative servomotors are tuned independently in four stages. In the 'Design of Experiment II,' 32 controller gains of eight servomotors are simultaneously fine-tuned in two stages. The average index of aggregate position and velocity errors is reduced by 61.4% and the average S/N ratio is increased by 8.5 dB after the final tuning using the Taguchi method.

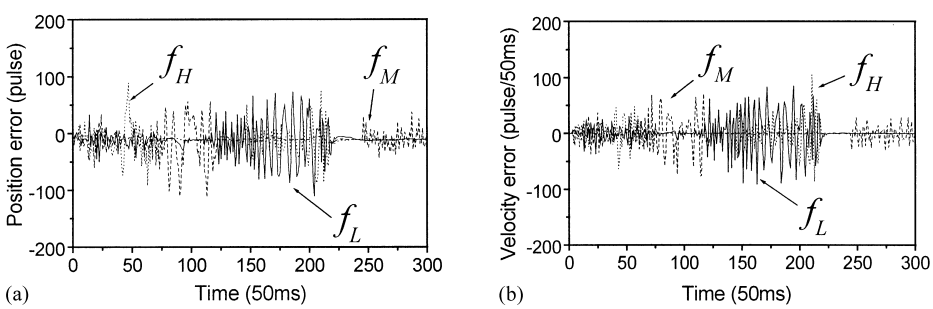

Fig. 12. Position and velocity errors of servomotor M_5 according to levels of feedrate of the spindle nose with the controller gains selected at stage 1 in the 'Design of Experiment II' (Table 5). (a) Position error, (b) velocity error.

Table 5
Levels of controller gains at stages 1 and 2 in the 'Design of Experiment II' for servomotor M_4, M_5 and M_6

Motor number	Controller gains	Initial values	Stage 1 Level 1	Stage 1 Level 2	Stage 1 Level 3	Stage 2 Level 1	Stage 2 Level 2	Stage 2 Level 3
M_4	K_P	200	160	180	**200**	**200**	210	220
	K_I	1	**1**	3	5	**1**	2	3
	K_L	500	**500**	1000	1500	300	**500**	700
	KF	1300	900	**1100**	1300	1000	1100	**1200**
M_5	K_P	200	160	**180**	200	170	**180**	190
	K_I	1	**1**	3	5	1	2	**3**
	K_L	500	**500**	1000	1500	300	500	**700**
	K_F	1300	900	**1100**	1300	1000	1100	**1200**
M_6	K_P	200	160	**180**	200	170	**180**	190
	K_I	1	**1**	3	5	1	**2**	3
	K_L	500	**500**	1000	1500	300	500	**700**
	K_F	1300	900	**1100**	1300	1000	1100	**1200**

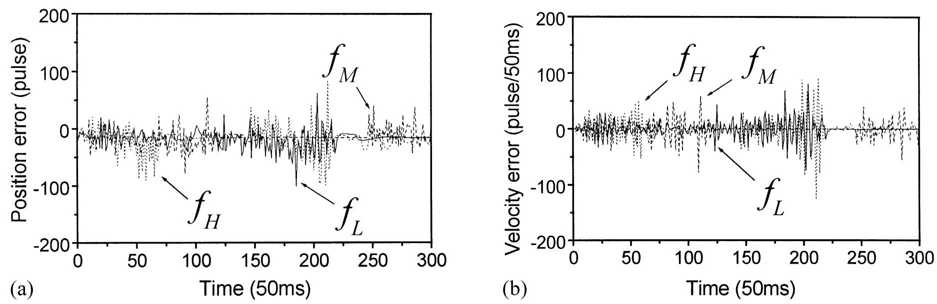

Fig. 13. Position and velocity errors of servomotor M_5 according to levels of feedrate of the spindle nose with the controller gains selected at stage 2 in the 'Design of Experiment II' (Table 5). (a) Position error, (b) velocity error.

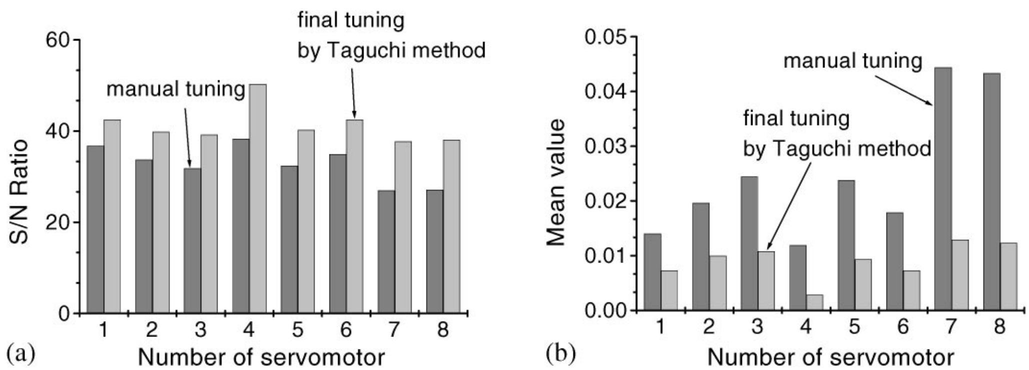

Fig. 14. Final comparison of the controller performance in each servomotor between manual tuning using the *Samsung method* and final tuning using the Taguchi method. (a) Increase of the S/N ratio, (b) reduction of the mean value of control errors.

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