The use of grey-based Taguchi methods to determine Process Parameter of linear motion guide with Multiple Performance Characteristics

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Abstract

By the grey-based Taguchi methods, this study attempts to analyze the process parameters pertinent to the multiple performance characteristics of linear motion guides and obtain the multiple performance characteristics of the noise level, push force value and horizontal combination precision of the linear motion guide with multiple qualities. Optimal process parameters are determined by using the parameter design proposed by the Taguchi method. Experimental results have shown that optimal linear motion guide process parameters can be determined effectively so as to improve multiple qualities through this new approach.

Keywords: Linear motion guide，Taguchi method，Grey relational analysis，Noise level

1. Introduction

Any automatic equipment related to linear motion needs the important linear motion guide part. Due to diversified application of the linear motion guide, it is necessary to develop linear motion guides of new capacities. The development is direct toward the high-speed, low-noise level, high precision, energy conservation. In recent years, environmental protection has become a key issue. The impact of factory noise on the health of operators is expansively studied [1-2]. It is very important for the proper selection of linear motion guide process parameters to improve noise level, push force value and precision. The Taguchi method [3-8] is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality.

The grey system theory proposed by Deng [9] is useful for dealing with poor, incomplete, and uncertain information. The grey system theory can solve complicated inter-relationships among multiple performance characteristics effectively [10-11]. Optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. Basically, classical process parameter design [12] is complex and not easy to use. The Taguchi method uses an orthogonal arrays design to study the entire process parameter space with a small number of experiments only.

The optimal level of the process parameters is the level with the highest grey relational grade in optimization. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design. The use of the grey-based Taguchi method [6-11] to optimize the processing of type-25 linear motion guides and multiple qualities is studied in this paper.

2. Research procedures

In recent years, due to rapid development of automated machinery and NC tooling machines toward the direction of high precision, high speed and energy conservation, conventional sliding-guided motion have become inadequate for work requirements, and they are gradually replaced by roller-guided linear motion guides. In response to this trend, we conduct the research on type-25 linear motion guides. The experiment process of this section consists of the following steps: preparation of linear motion guides, design and manufacturing of the test machine, testing of the experiment parameters of linear motion guides.

2.1. Selection of linear motion guide process parameter

This study employs Type-25 linear motion guides produced by ABBA Linear Technology Company. The width of the rail is 23mm, and the length 3m. The structure of linear motion guides is illustrated in Fig.1. The materials are shown in Table 1. Linear motion guides with or without the flange are illustrated in Fig. 2. For this experiment we design and produce a testing machine, which is shown in Fig. 3. The carriage of this testing machine is for fastening three block sets of the same model. CNC Controller HUST3 is employed to control the server motor. This control device can be used to set up the travel and the speed, which through a timing belt causes the carriage to make left-right movement at the speed of 1.2m/s. A load cell rated load is set at 420kg, or about 20% of the basic static load rating of the linear motion guide. The load only affects the linear motion guide in the middle. The purpose of the linear motion guides on either side is to guide the left-right movement. This experiment tests the noise level, push force value and horizontal combination precision of these linear motion guides with major process parameters including with/without ball cage, with/without flange, preload level, ball level and lubricant level. The preload is an internal load exerted on rolling element in the block, for the purposes of increasing the block rigidity and reducing clearances. Preloading creates an effect that is similar to a spring-like effect (Table2). The initial process parameters of the linear motion guide include: without ball cage and with flange, preload level 105kg, lubricant viscosity level 295 and ball level 0.5um. In order to determine the optimal parameters this experiment is completed through the setup of with ball cage and with flange (A1B1); with ball cage and without flange (A1B2); without ball cage and with flange (A2B1); preload levels Z0(0kg), Z2(105kg) and Z3(147kg); lubricant viscosity levels No.0(295), No.1(340) and No.2(385); ball levels G3(0.13um), G5(0.25um), G10(0.5um) (Table3). The following is an explanation of the codes used in this study pertinent to the linear motion guide.

BRH 25 - A - L3000 - N - Z2

(1) (2) (3) (4) (5) (6)

(1) BCH and BRH stand for linear motion guides with and without the ball cage respectively.

(2) Number 25 means the rail width is 23mm.

(3) A and B stand with-flange type and without-flange type respectively.

(4) The length of the rail. For example, L3000 means the rail length is 3000mm.

(5) Precision levels, generally divided into 5 levels: N (Normal), H (High), P (Precision), SP (Super- Precision) and UP (Ultra- Precision).

(6) Preload grades, generally divided into 5 levels as shown in the table 2.

2.2. Linear motion guide performance evaluation

The linear motion guide performance is evaluated by the following measurement. The noise level is first measured. The SE322 noise gauge is situated in the middle 20cm from the testing machine at the height of 1m. Data measured are transmitted via RS232 to a notebook computer (as shown in Fig.3). Due to the fact that the environmental noise level is less than the measured noise level by over 10dB, the measured data are employed without adjustment. A noise level is measured each time after the linear motion guide set moves for 50km. The total movement distance is 500km, so 10 measured data are obtained for each linear motion guide set. The second involves measurement of the push force value and horizontal combination precision. The block set in the middle under the pressure of the load cell is removed in conjunction with 600mm rails cut from the same 3000mm rail and situated on the designated test platform. The push force value is measured by pushing the block set steadily from the one end to the other via a push-force gauge (as shown in Fig.4). Then a dial test indicator is used to measure the absolute value of the height difference of the block between point A and point B (as shown in Fig.5). These two numbers are measured each time after the linear motion guide set moves for 50km. The total movement distance is 500km, so 10 measurements are obtained for each linear motion guide set.

In essence, when it comes to horizontal combination precision, push force value and noise level, the value is the smaller the better in quality testing of linear motion guides.

3. Determination linear motion

guide process parameters

In this section, the use of the grey-based Taguchi method to determine the linear motion guide process parameters is reported. Optimal linear motion guide process parameters with considerations of the multiple performance characteristics are obtained and verified.

3.1. Orthogonal array experiment

An L9 orthogonal array with 4 columns and 9 rows is used. This array has eight degrees of freedom and it can handle three-level process parameters. Nine experiments are required to study the entire linear motion guide parameter space when the L_9 orthogonal array is used. The experiment layout for the linear motion guide process parameters using the L_9 orthogonal array is shown in Table 4.

3.2. S/N ratio for the multiple performance characteristics

Noise level, push force value and horizontal combination precision are the lower-the-better performance characteristics, the loss function can be expressed as

$$L_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}^{2} \qquad (1)$$

where L_{ij} is the loss function of the ith performance characteristic in the jth experiment, y_{ijk} the experimental value of the ith performance characteristic in the jth experiment at the kth trial, and n the number of trials. The loss function is further transformed into an S/N ratio to determine the deviation of the performance characteristic from the desired value. The S/N ratio η_{ij} for the ith performance characteristic in the jth experiment can be expressed as

$$\eta_{ij} = -10\log(L_{ij}) \qquad (2)$$

In the next section, the grey relational analysis is used to analyze the complicated inter-relationships among the S/N ratios shown in Tables 5-7.

3.3. Grey relational analysis for the S/N ratio

The grey relational generating [9], a linear normalization of the S/N ratio, is performed in the range between zero and unity. The normalized S/N ratio x_{ij} for the ith performance characteristic in the jth experiment can be expressed as

$$x_{ij} = \frac{\eta_{ij} - \min_j \eta_{ij}}{\max_j \eta_{ij} - \min_j \eta_{ij}} \qquad (3)$$

Table 8 shows the normalized S/N ratio for noise level, push force value and horizontal combination precision. Basically, the larger normalized S/N ratio corresponds to the better performance and the best-normalized S/N ratio is equal to unity. The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized S/N ratio. The grey relational coefficient ξ_{ij} for the ith performance characteristic in the jth experiment can be expressed as

$$\xi_{ij} = \frac{\min_i \min_j \left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|}{\left|x_i^0 - x_{ij}\right| + \zeta \max_i \max_j \left|x_i^0 - x_{ij}\right|} \qquad (4)$$

where x_i^0 is the ideal normalized S/N ratio for the ith performance characteristic and ζ distinguishing coefficient which is defined in the range $0 \le \zeta \le 1$.

A weighting method is then used to integrate the grey relational coefficients of each experiment into the grey relational grade. The overall evaluation of the multiple performance characteristics is based on the grey relational grade, i.e.

$$\gamma_j = \frac{1}{m}\sum_{i=1}^{m} w_i \xi_{ij} \qquad (5)$$

Assume that: $w_1 = w_2 = w_3 = 1$

where γ_j is the grey relational grade for the jth experiment, the weighting factor for the ith performance characteristic, and m the number of performance characteristics. Table 9 shows the grey relational grade for each experiment using the L_9 orthogonal array. A higher grey relational grade indicates that the corresponding S/N ratio is closer to the ideally normalized S/N ratio. It has been shown that experiment 5 has the best multiple performance characteristics among the nine experiments because it has the highest grey relational grade as shown in Table 9. In other words, optimization of the complicated multiple performance characteristics can be converted into the optimization of a single grey relational grade.

The effect of each linear motion guide process parameter on the grey relational grade at different levels can be independent because the experimental design is orthogonal. The grey relational grade for each level of the linear motion guide process parameters is summarized and shown in Table 10. In addition, the total mean of the grey relational grade for the 9*10 experiments is also calculated to be 0.5363. Fig. 6 shows the grey relational grade graph, where the dashed line in this figure is the value of the total mean of the grey relational grade. Basically, the larger the grey relational grade, the better are the multiple performance characteristics. However, the relative importance among the linear motion guide process parameters for the multiple performance characteristics still needs to be known, so that the optimal combinations of the linear motion guide process parameter levels can be determined.

3.4. Analysis of variance

The purpose of the ANOVA is to investigate which linear motion guide process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the grey relational grades, which is measured by the sum of the squared deviations from the total mean of the grey relational grade, into contributions by each linear motion guide process parameter and the error. The percentage contribution by each of the process parameter in the total sum of the squared deviations can be used to evaluate the importance of the process parameter change on the performance characteristic. In addition, the F-test named after Fisher [12] can also be used to determine which linear motion guide process parameters have a significant effect on the performance characteristic. Usually, the change of the linear motion guide process parameter has a significant effect on the performance characteristic when the F value is large.

Results of ANOVA (Table 11) indicate that noise level, push force value and horizontal combination precision are the significant linear motion guide process parameters for affecting the multiple performance characteristics. Furthermore, the ball cage, as well as flange, is the most significant process parameter due to its highest percentage contribution among the process parameters. Based on the above discussion, the optimal linear motion guide process parameters are with ball cage but no flange at level 2, preload level at level 2, and ball level at level 1. The effect of the lubricant is negligible. Therefore, experiment 5 shown in Table 4 fits the optimal process conditions.

3.5. Confirmation tests

The final step is to predict and verify the improvement of the performance characteristic using the optimal level of the linear motion guide process parameters. The estimated S/N ratio using the optimal level of the process parameters can be calculated from Table 10, considering only the process parameters that significantly affect the multiple performance characteristics. Table 12 shows the comparison of experimental results using the initial and optimal linear motion guide process parameters. It will be noted that the linear motion guide performance has been greatly improved through this study. As shown in Table 12, the noise level is decreased from 76.82 to 67.40 dB, the push force is changed from 1217 to 1130g, and horizontal combination precision is reduced from 3.8 to 3.4um.

4. Conclusion

This study engages in testing of the noise level, propulsion and horizontal combination precision through type-25 linear motion guide in conjunction with the designed testing device. The following conclusions are presented:

(1) One can obtain multiple performance characteristics of the lowest noise level, push force value and horizontal combination precision from process parameters, and the greatest grey relation value (0.8444).

(2) The optimal multiple performance characteristics with ball cage, no flange, preload level at Z3(147kg), and ball precision level at G3(0.13um) is achieved.

(3) Through variable analysis, the presence of the ball cage and flange has significant impact on the multiple performance characteristics while ball levels have secondary significant impact.

(4) Experiment outcomes indicate based on the optimal parameter combination level of the multiple performance characteristics, the experiment observation values of the noise level, propulsion and horizontal combination precision have been enhanced. The grey relation is improved by 0.46. The grey relation value of the optimal parameter level fits the predicted value of the optimal parameter level very well. That serves as the proof of the projection power of this experiment.

The optimization of the complicated multiple performance characteristics can be greatly simplified through this approach. It is shown that the performance characteristics of the linear motion guide process such as the noise level, push force value, and horizontal combination precision are improved together by using the method proposed. It is shown that the use of the Taguchi method with the grey relational analysis can greatly simplify the optimization procedure for determining the optimal process parameters with the multiple performance characteristics in the linear motion guide process.

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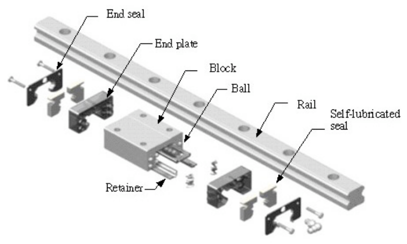


Fig. 1 Structure of regular linear motion guide, illustrated

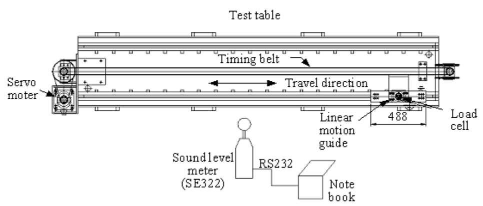
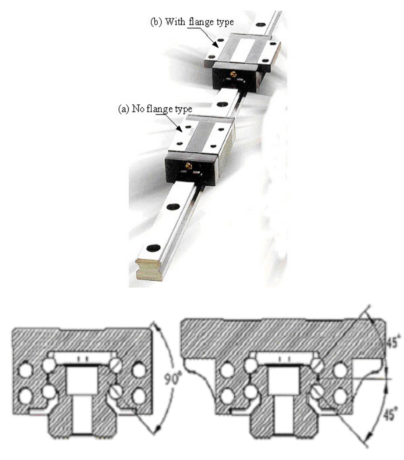


Fig. 3 Layout of test machine & noise gauge



(a) (b)

Fig. 2 (a) Type-25 linear motion guide without flange, and (b) with flange

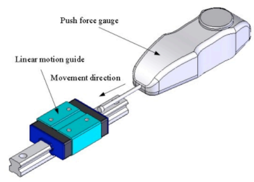


Fig.4. Testing of push force value

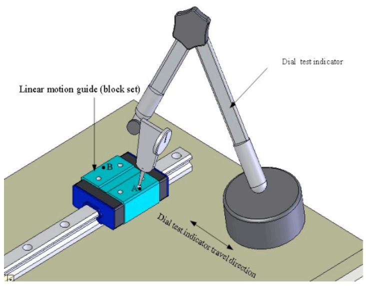


Fig.5. Testing of horizontal combination precision

Table 2 Preload grade

Grade	Symbol	Preload force
Clearance	ZF	0
No Preload	Z0	0
Light Preload	Z1	0.02C
Middle Preload	Z2	0.05C
Heavy Preload	Z3	0.07C

C: Basic dynamic load rating

Table 3 Linear motion guide process parameters and their levels

Symbol	Process parameter	Level 1	Level 2	Level 3
AB	Ball cage、Flange	A1B1 (with ball cage、with flange)	A1B2 (with ball cage、without flange)	A2B1 (without ball cage、with flange)
C	Preload type (kg)	Z0(0)	Z2(105)	Z3(147)
D	Lubricant type (viscosity)	No.0(295)	No.1(340)	No.2(385)
E	Ball grade (precision)	G3(0.13um)	G5(0.25um)	G10(0.5um)

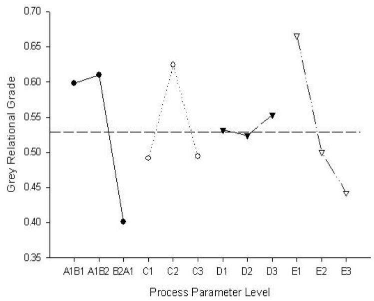


Fig. 6 Grey relational grade graph

Table 1 Materials

	Linear motion guide test specimen		
	Rail and block	Ball cage	Ball
Material	SNCM 21	NYLON21	SUJ 2

Table 4 Experimental layout using an $L_9(3^4)$ orthogonal array

Experiment number	Process parameter level			
	AB Ball cage and Flange type	C Preload type	D Lubricant type	E Ball grade
1.BCH25-A-L3000-N-Z0	1	1	1	1
2.BCH25-A-L3000-N-Z2	1	2	2	2
3.BCH25-A-L3000-N-Z3	1	3	3	3
4. BCH25-B-L3000-N-Z3	2	1	2	3
5. BCH25-B-L3000-N-Z0	2	2	3	1
6. BCH25-B-L3000-N-Z2	2	3	1	2
7. BRH25-B-L3000-N-Z0	3	1	3	2
8. BRH25-B-L3000-N-Z2	3	2	1	3
9. BRH25-B-L3000-N-Z3	3	3	2	1

Table 8 Data preprocessing of the S/N ratios

Experiment number	Noise level	Push force value	Horizontal combination precision
Ideal sequence	1	1	1
1	0.5147	0.51	1
2	0.6574	0.6290	0.6163
3	0.4912	0.4383	0.5167
4	0.4936	0.4258	0.4534
5	1	1	0.5331
6	0.6645	0.3816	0.5169
7	0.3444	0.3358	0.3333
8	0.3479	0.3333	0.4885
9	0.3333	0.5487	0.5705

Table 5 Experiment results for noise level and its S/N ratio

Movement distance(km)	50	100	150	200	250	300	350	400	450	500		
No	Y_1 (dB)	Y_2 (dB)	Y_3 (dB)	Y_4 (dB)	Y_5 (dB)	Y_6 (dB)	Y_7 (dB)	Y_8 (dB)	Y_9 (dB)	Y_{10} (dB)	Average	S/N Ratio(db)
1	68.2	69.2	73.5	73.5	73.5	73	72.7	72.5	72.1	71.6	71.98	-37.1442
2	69.5	69.2	69.2	69.2	70.3	70.5	70	70	70.5	70.5	69.89	-36.8883
3	72.7	73	73.2	72.6	72.6	72.6	72	72	72	71.8	72.45	-37.2008
4	73	73	73.2	72.5	72.6	72.3	72	72	71.7	71.7	72.4	-37.1948
5	67.2	67.3	67	66.9	67.2	66	67.5	67.8	68	69	67.39	-36.5719
6	69	69.2	69.2	69.2	69.6	70.3	70.3	70.3	70.5	70.5	69.81	-36.8784
7	77	77.8	77.5	77.5	77.5	76.5	76.5	76.5	76.5	76.5	76.98	-37.7276
8	78	77.5	77.5	77.6	77.2	76	76	76	76.1	76.3	76.82	-37.7095
9	78.2	78.2	78	78	78	78	77.5	77.1	76	76	77.5	-37.786

Table 6 Experiment results for push force value and its S/N ratio

Movement distance(km)	50	100	150	200	250	300	350	400	450	500		
No	Y_1 (g)	Y_2 (g)	Y_3 (g)	Y_4 (g)	Y_5 (g)	Y_6 (g)	Y_7 (g)	Y_8 (g)	Y_9 (g)	Y_{10} (g)	Average	S/N ratio(db)
1	1350	1330	1280	1250	1200	1150	1150	1050	1000	950	1171	-61.3711
2	1400	1350	1250	1200	1100	1100	1000	1050	1050	1050	1155	-61.2516
3	1450	1400	1350	1250	1150	1150	1100	1000	1000	1000	1185	-61.4744
4	1400	1350	1300	1250	1280	1150	1100	1100	1000	950	1188	-61.4963
5	1350	1300	1250	1200	1200	1100	1000	1000	950	950	1130	-61.0616
6	1400	1300	1300	1200	1200	1150	1150	1100	1100	1100	1200	-61.5836
7	1450	1400	1380	1350	1250	1180	1050	1050	1050	1000	1216	-61.6987
8	1400	1350	1320	1300	1280	1200	1170	1100	1050	1000	1217	-61.7058
9	1500	1400	1300	1200	1150	1050	1050	1000	1000	1000	1165	-61.3265

Table 7 Experiment results for horizontal combination precision and its S/N ratio

Movement distance(km)	50	100	150	200	250	300	350	400	450	500	Average	S/N ratio(db)
No	Y_1 (um)	Y_2 (um)	Y_3 (um)	Y_4 (um)	Y_5 (um)	Y_6 (um)	Y_7 (um)	Y_8 (um)	Y_9 (um)	Y_{10} (um)		
1	3	2	2	3	3	2	2	2	2	2	2.3	-7.2346
2	4	3	2	3	2	3	3	4	3	4	3.1	-9.8272
3	5	4	3	3	2	3	4	4	4	4	3.6	-11.1261
4	5	4	4	4	5	5	4	3	3	4	4.1	-12.2557
5	4	5	4	3	3	3	3	3	4	3	3.5	-10.8814
6	4	4	5	4	3	3	4	3	3	3	3.6	-11.1261
7	7	5	6	5	5	6	6	7	6	7	6	-15.5630
8	4	3	5	5	5	4	3	3	3	3	3.8	-11.5957
9	4	4	4	3	3	3	2	3	4	3	3.3	-10.3703

Table 9 Grey relational grade and its order

Experiment number	Grey relational grade	Order
1	0.6749	2
2	0.6342	3
3	0.4821	6
4	0.4576	7
5	0.8444	1
6	0.5210	4
7	0.3378	9
8	0.3899	8
9	0.4842	5

Table 10 Response table for the grey relational grade

Symbol	Process parameter	Grey relational grade			
		Level 1	Level 2	Level 3	Maximum-minimum
AB	Ball cage、Flange type	0.5971	0.6077	0.404	0.2037
C	Preload type	0.4901	0.6228	0.4958	0.1327
D	Lubricant type	0.5286	0.5253	0.5548	0.0295
E	Ball grade	0.6678	0.4977	0.4432	0.2246
Total mean value of the grey relational grade=0.5363					

Table 11 Analysis of variance (ANOVA)

Variation source	Degree of freedom	Sum of squares	Variance ratio(F)	Mean squares	Contribution
AB, Ball cage、Flange	2	0.0789	50.52	0.0394	39.33%
C, Preload	2	0.0338	21.64	0.0167	16.39%
D, Lubricant	2	(0.0016)	-	-	
E, Ball	2	0.0824	52.75	0.0412	41.1%
Residual	2	(0.0016)		-	3.18%
Total	8	0.1966		0.0973	100%

Table 12 Results of linear motion guide performance using the initial and optimal process parameters

	Initial process parameters	Optimal process parameters	
		Prediction	Experiment (Average)
Level	$A_2B_1C_2D_1E_3$	$A_1B_2C_2D_3E_1$	$A_1B_2C_2D_3E_1$
Noise level (dB) (Average)	76.82		67.4
Push force value (g) (Average)	1217		1130
Horizontal combination precision (um) (Average)	3.8		3.4
Grey relational grade	0.391	0.826	0.85
Improvement of the grey relational grade=0.46			