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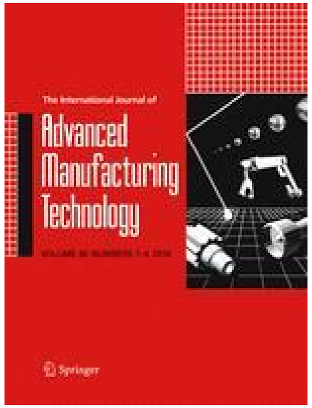

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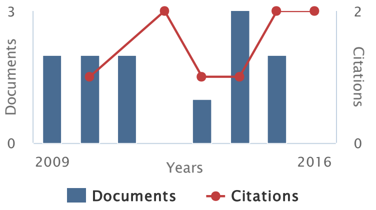

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ORIGINAL ARTICLE

Experimental approached optimisation of a linear motion performance with grey hazy set and Taguchi analysis methods (GHST) for ball-screw table type

Hendro Nurhadi · Yeong-Shin Tarng

Received: 12 March 2008 / Accepted: 24 October 2008 / Published online: 19 November 2008

Abstract In end effect to control a path, tracking, or cutting motion of CNC milling machine or other applications of machine tools, controlling its actuator, specifically a linear table motion, becomes a classical matter to be solved in industries. By applying an optimisation of grey hazy set Taguchi (GHST) analysis methods, it might get a performance improvement of a linear motion of ball-screw table type. In this paper, it is aimed to enhance on multi-performance characteristics, namely, displacement, velocity and torque. An improvement of an average error of position accuracy is from the 0.2100 to 0.0137 mm (S/N ratio from 13.4023 to 37.1935 dB). Average error of position time is significantly improved from 0.1599 to 0.0293 s (S/N ratio from 15.9229 to 29.9305 dB). The average error of torsion standard deviation from 0.0924 Nm is improved to 0.0481 Nm (S/N ratio from 20.5970 to 26.3447 dB). This study indicated that GHST analysis approach might be applied successfully to table motion performance optimisation, which is determined by many parameters at multi-quality performances.

Keywords Grey analysis · Taguchi · Optimisation · Linear motion

1 Introduction

A linear table motion, which is usually used for many industrial applications, is the main object of this paper. In many cases of its applications, problems in positioning and defining a proper velocity are very common to see in fact. Based on those difficulties, a performance optimisation for linear table motion would be performed. This work posits a solution to the problem of optimising a linear table motion where optimisation requirements are conflicted between primary task motions and maintaining a sufficiently accurate position estimate to facilitate primary task motion. The grey hazy set and Taguchi (GHST) method is applied to improve the performances of table motion. A typical ball-screw table, which is often seen in machining industry, is selected as test model. Experiment results show that the GHST method effectively optimise three responses of the table, i.e. displacement, velocity and torque. Therefore, the contribution of this work is of engineering significance.

Hsiao et al. [1] attempted to analyse 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.

Tosun [2] introduced the use of grey relational analysis for optimising the drilling process parameters for the work piece surface roughness and the burr height. Various drilling parameters, such as feed rate, cutting speed, drill and point angles of drill were considered. An orthogonal array was used for the experimental design. Optimal machining parameters were determined by the grey relational grade obtained from the grey relational analysis for multi-performance characteristics (the surface roughness and the burr height).

Kang et al. [7] make a comparison between the grey systems theory and stochastic analysis and fizzy mathematics. As a new research with strong capabilities to transect

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across and to permeate into various traditional scientific fields and disciplines, the grey systems theory has made astonishing progress in the world of learning and its wide range employment in such scientific areas as industry, agriculture, economics, energy, transportation, geography, geology, meteorology, hydraulic power, ecology, environment studies, medicine, education, military science, finance and life sciences. Lastly, the further study advices for grey systems theory are put forward.

Zhang et al. [8] introduced grey system theory into sliding mode control of high order nonlinear system and developed a novel grey fuzzy sliding mode controller. In this controller design, grey prediction model combined with fuzzy reasoning is proposed to obtain sliding mode control strategy. The controller can drive the state from an arbitrary initial point of state to the origin along a sliding mode hyper plane quickly and reduce the vibration phenomenon that is caused by switching delay brought by system inertia. Grey system theory is the efficient tool in the analysis and control of nonlinear, uncertain systems.

In this proposed work, visibility and reliability of using hybrid experimental-based grey hazy set (grey theory) with Taguchi method (GHST) are concerned to improved performance of motion for ball-screw linear guideways.

In this paper, previous works will be discussed shortly first, followed by definition of methods used in this research, a discussion of the experimental setup and its results and finally conclusions. The purpose of present work is to introduce the use of created GHST method in optimising a linear table motion on multi-performance characteristics, namely displacement, velocity and torque. Thus, by properly adjusting the control factors, we can improve performance effectively and may produce high motion quality.

2 Grey hazy set and Taguchi

Natural phenomena have given us numerous difficult problems. To insure continuation of our very existence, it is imperative that we investigate and understand these systems. However, given our present knowledge or scientific information, we have to simplify much of the complex embodiment of these systems. During this process, we have to delete information left and right. After such an endeavor, we have a system that only possesses bone but no flesh and blood. Such a model can only be at best homomorphic to or vaguely resemble the original system. As a result, we can only command partial information or even poor information. Because of the incompleteness of information that can be extracted from the system, the color we can obtain from a system is grey. Therefore, the grey of a system is absolute, and the black and white of a system is relative. Confronting such truths, in 1982, Professor Deng Ju-Long of Huazhong University of Science and Technology, PRC wrote the first landmark article Control Problem of Grey Systems [3] and hence started the theory of grey system.

In grey system theory, we consider such a concept to be narrow. In reality, data is only part of the total information. Information should consist of two types. The first is the qualitative elements, that is, the type that cannot be measured, and it exemplifies the information's qualitative appearance. The second type is the quantitative data elements, exemplifying its measurable property. In real life, we may be faced with a system, knowing only part of its informational qualitative elements and no more. At the same time, we may know only certain variation intervals of its informational quantitative data elements, with their precise numerical values unknown. No doubt, such a system has only provided us with information that is grey. Furthermore, such grey information in the system may be constraining each other, and they may be very interdependent with each other. Therefore, such intrinsic relational behavior may differentiate one grey system from another. Therefore, relations between grey information constitute another central study of grey system theory. Grey systems, in addition, focus keenly on what partial or limited information the system can provide and try to paint its total picture from this. In fact, the theory of grey system bases itself on GHS [5].

Taguchi addresses quality in two main areas: off-line and online quality control (QC). Both of these areas are very cost sensitive in the decisions that are made with respect to the activities in each. Off-line QC refers to the improvement of quality in the product and process development stages. Online QC refers to the monitoring of current manufacturing processes to verify the quality levels produced. The off-line portion of QC is addressed in this research because of the paucity of materials on this phase of Taguchi methods, and the positive impact on cost that is obtained by improving quality at the earliest times in a product life cycle. Design of experiment procedures according to Ross [10] will be stating a problem or area concern (problem formulation), stating an objective of experiment, selecting quality characteristics, selecting factors that may influence selected quality characteristics, identifying control and noise factors (Taguchi-specific), selecting levels for factors, selecting appropriate orthogonal array (OA), selecting interactions that may influence selected quality characteristics, assigning factors to OA and locating interactions, conducting tests, analysing and lastly conducting confirmation experiment.

3 Grey Hazy Set

GHS exemplify itself in several stages: the embryonic state, the hazy state, the whitening state and the verifiable state. The embryonic state represents a beginning phase of grey hazy set, which is the limited available data of system. Incomplete information follows from the limited availability of data, named the hazy state, the basic characteristics of starting point to investigate grey systems. The whitening state forms a main melody of grey system theory to supply information so that the greyness can be whitened. The verifiable state is a final state where we may define by grading the kind of information of systems, whether it is a qualitative and/or quantitative appearance.

3.1 Data pre-processing

Data pre-processing is needed, since the range and unit in one data sequence may differ from others, also when the sequence scatter range is too large, or when the directions of the target in sequences are different. Data pre-processing is a tool for converting an original sequence to a comparable sequence. Depending on the characteristics of a data sequence, there are various methodologies of data pre-processing available for the GHS relational analysis.

If the target value of original sequence is infinite, then it has a characteristic of the "higher is better (HB)". The original sequence can be normalised as follows:

$$x_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{1}$$

In case the characteristic of the original sequence is the "lower is better (LB)", the original sequence should be normalised as follows:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{2}$$

Otherwise, if there is a definite target value to be achieved, called "nominal is best (NB)", the original sequence will be normalised in form:

$$x_i^*(k) = 1 - \frac{\left|x_i^0(k) - x^0\right|}{\max x_i^0(k) - x^0} \tag{3}$$

or the original sequence can be simply normalised by the most basic methodology, i.e. let the values of original sequence are divided by the first value of the sequence:

$$x_i^*(k) = \frac{x_i^0(k)}{x_i^0(1)} \tag{4}$$

where i=1,…, m; k=1, …, n. m is the number of experimental data items, and n is the number of parameters. $x_i^{\mathrm{O}}(k)$ denotes the original sequence, $x_i^*(k)$ the sequence after the data pre-processing, max $x_i^{\mathrm{O}}(k)$ the largest value of $x_i^{\mathrm{O}}(k)$, min $x_i^{\mathrm{O}}(k)$ the smallest value of $x_i^{\mathrm{O}}(k)$ and x^{O} the nominally desired value. A good example of lower-is-better characteristics is the waiting time for your order delivery at a fast-food restaurant or error-minimisation (in this work). Efficiency, ultimate strength or fuel economy are examples of higher-is-better. Additionally taken from Taguchi's principals, if we are not looking for a specific objective, then we take S/N ratio based on mean squared deviation (MSD) for analysis of repeated results. MSD expression combines variation around the given target and is consistent with Taguchi's quality objective. The relationships among observed results, MSD and S/N ratios are:

$$\begin{aligned}
&\mathrm{MSD} = \left((Y_1 - m)^2 + (Y_1 - m)^2 + \ldots + (Y_n - m)^2\right)\Big/n \\
&\qquad \text{for norminal} - \text{is} - \text{best;} \\
&\mathrm{MSD} = \left(Y_1^2 + Y_2^2 + \ldots + Y_n^2\right)\big/n \quad \text{for lower} - \text{is} - \text{better;} \\
&\mathrm{MSD} = \left({}^1\!/_{Y_1^2} + {}^1\!/_{Y_2^2} + \ldots + {}^1\!/_{Y_n^2}\right)\Big/n \\
&\qquad \text{for higher} - \text{is} - \text{better;} \\
&\mathrm{S/N} = -10 \cdot \log(\mathrm{MSD}) \quad \text{for all characteristics;}
\end{aligned}$$

with m as the target value of the quality characteristic, Y a measured value of the quality characteristic and n the number of data.

3.2 Grey hazy set leveling

In GHS relational analysis, the measure of the relevance between two systems or two sequences is defined as the GHS relational grade. When only one sequence, $x_0(k)$, is available as the reference sequence and all other sequences serve as comparison sequences, it is called a local GHS relation measurement. After data pre-processing is carried out, the GHS relation coefficient $\xi_i(k)$ for the k-th performance characteristics in the i-th experiment can be expressed as:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{0i}(k) + \zeta \Delta_{\max}} \tag{5}$$

where, Δ_{0i} is the deviation sequence of the reference sequence and the comparability sequence.

$$\begin{aligned}
\Delta_{0i} &= \left\| x_0^*(k) - x_i^*(k) \right\| \\
\Delta_{\min} &= \forall j^{\min} \in i \forall k^{\min} \left\| x_0^*(k) - x_j^*(k) \right\| \\
\Delta_{\max} &= \forall j^{\max} \in i \forall k^{\max} \left\| x_0^*(k) - x_j^*(k) \right\|
\end{aligned}$$

$x_0^*(k)$ denotes the reference sequence and $x_i^*(k)$ denotes the comparability sequence. ζ is distinguishing or identification coefficient: $\zeta \in [0, 1]$ (the value may be adjusted based on the actual system requirements). The smaller the value of ζ, the larger the distinguished ability. ζ=0.5 is generally used as an average of its value in range, which is accommodated unclearly definition of distinguish coefficients. This distinguish coefficient might also be determined by using several 'system identification'-based approaches such as regression method, least-square method, etc.

After the GHS relational coefficient is derived, it is usual to take the average value of the GHS relational coefficients

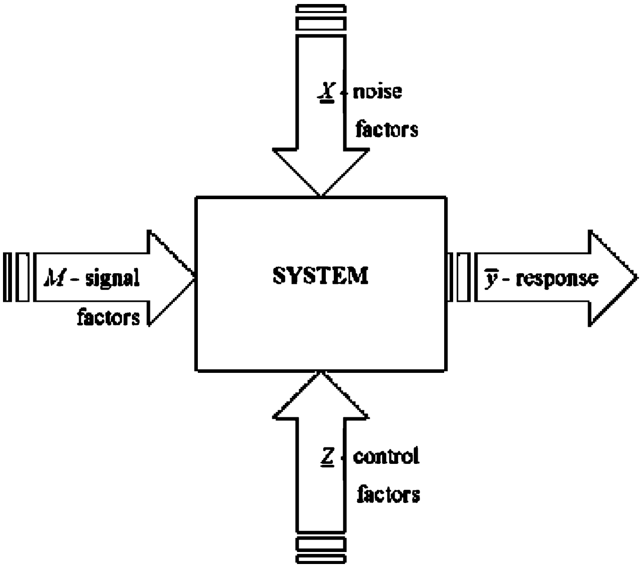


Fig. 1 Parameter diagram of system

as the GHS relational grade. The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{6}$$

However, in a real engineering system, the importance of various factors to the system varies. In the real condition of unequal weight being carried by the various factors, the GHS relational grade in Eq. 6 was extended and defined as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}w_k\xi_i(k) \qquad \sum_{k=1}^{n}w_k = 1 \tag{7}$$

where w_k denotes the normalised weight of factor k. Given the same weight, Eqs. 6 and 7 are equal.

The GHS relational grade γ_i represents the level of correlation between the reference sequence and the comparability sequence. If the two sequences are identical, then the value of GHS relational grade is equal to 1. The GHS relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference sequence, then the GHS relational grade for that comparability sequence and reference sequence will be higher than other GHS relational grades.

Table 1 Leveling factors and noise

	Level 1	Level 2	Level 3
Driver parameter			
A Speed loop proportional gain	10	250	500
B Speed loop integral gain	10	150	300
C Torque command smoothing	0	150	300
D Position gain	10	150	300
E Position smoothing time	0	150	300
F Speed loop differential gain	0	150	300
G Acceleration	100	300	500
Noise parameter			
External load	0 Nm	18.7 Nm	37.4 Nm

4 Taguchi parameters

The seven input parameters in this research that have three levels of each to be observed and analysed will be speed loop (proportional) gain, speed loop integral gain, torque command smoothing time, position gain, position smoothing time, speed loop differential gain and acceleration. An external load is being a disturbance.

Fig. 2 Measurement setup

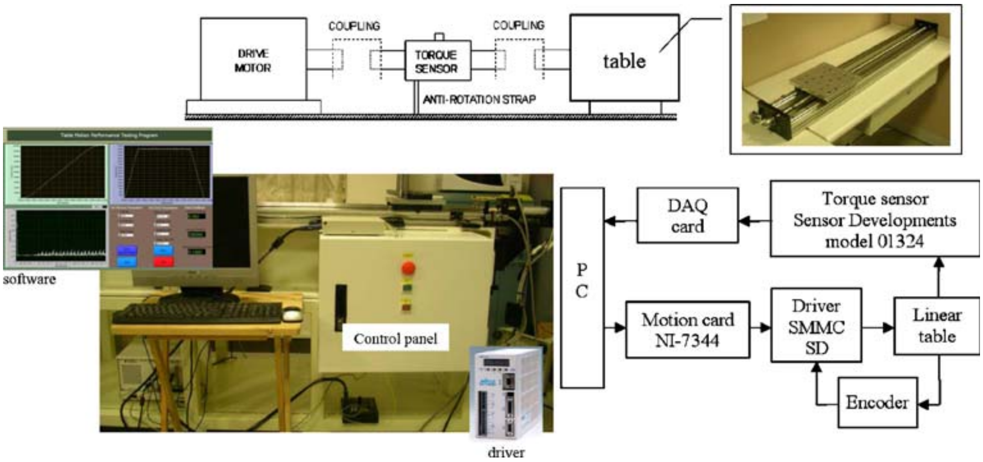


Fig. 3 Research flow

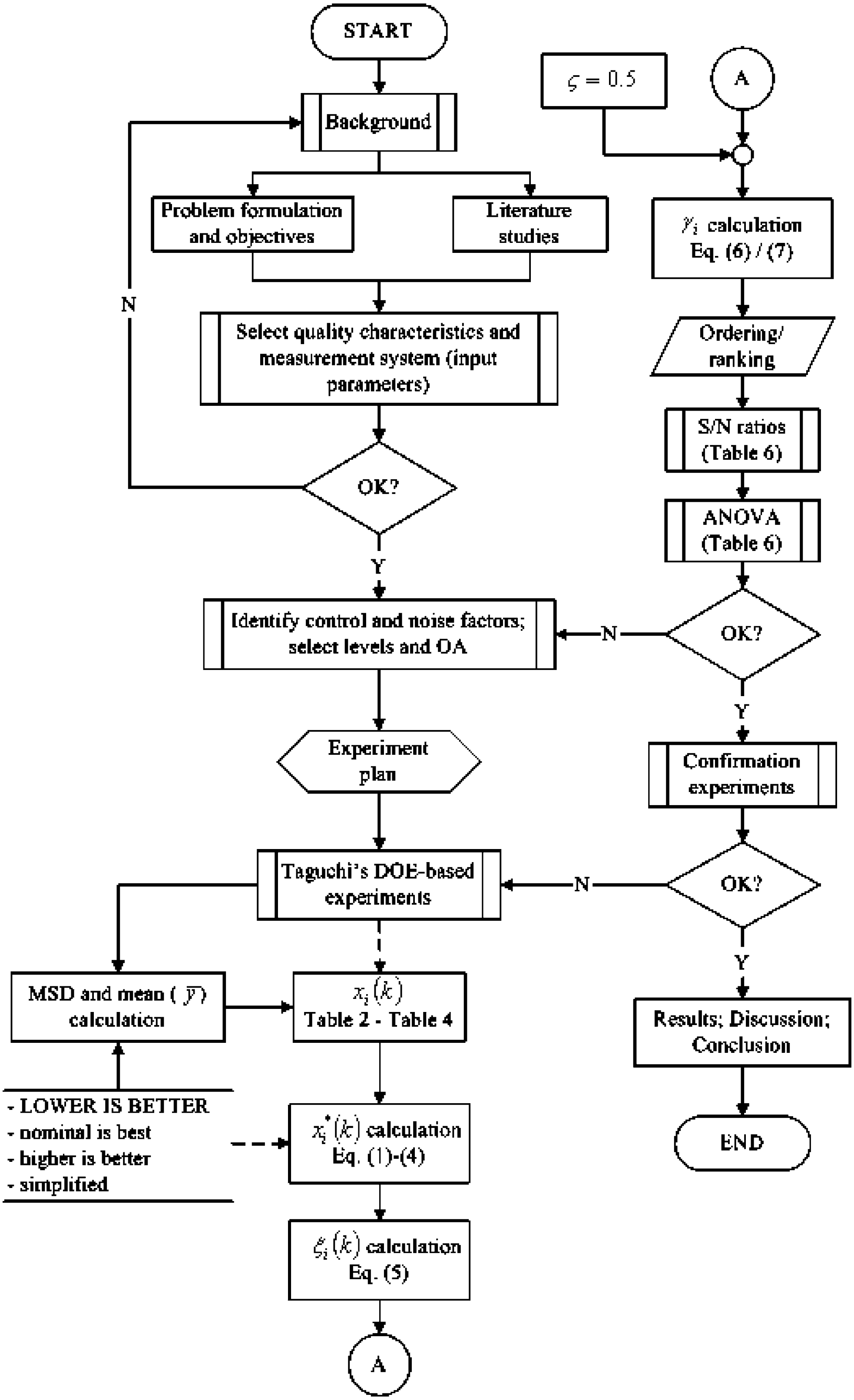


Table 2 Response for position accuracy

Exp.	A	B	C	D	E	F	G	MSD			$\bar{y}$	STD	S/N (dB)
								M1	M2	M3			
1	1	1	1	1	1	1	1	0.086	0.046	0.088	0.261	0.073	11.362
2	1	2	2	2	2	2	2	56.924	39.632	41.843	6.704	1.130	−16.640
3	1	3	3	3	3	3	3	4.597	4.616	4.582	2.144	0.014	−6.626
4	2	1	1	2	2	3	3	2.120	2.116	2.143	1.458	0.005	−3.276
5	2	2	2	3	3	1	1	0.005	0.005	0.005	0.072	0.001	22.872
6	2	3	3	1	1	2	2	2.914	2.802	2.897	1.694	0.030	−4.580
7	3	1	2	1	3	2	3	16.545	16.492	16.577	4.067	0.013	−12.185
8	3	2	3	2	1	3	1	0.000	0.001	0.001	0.025	0.004	31.950
9	3	3	1	3	2	1	2	0.003	0.003	0.002	0.052	0.003	25.662
10	1	1	3	3	2	2	1	30.615	24.533	21.179	4.986	0.788	−14.056
11	1	2	1	1	3	3	2	73.441	56.448	48.769	7.496	1.900	−17.749
12	1	3	2	2	1	1	3	0.582	0.513	0.965	0.725	0.416	1.633
13	2	1	2	3	1	3	2	0.001	0.001	0.002	0.037	0.004	28.714
14	2	2	3	1	2	1	3	0.916	2.762	3.767	1.514	0.451	−3.948
15	2	3	1	2	3	2	1	0.019	0.019	0.018	0.137	0.003	17.243
16	3	1	3	2	3	1	2	13.126	13.213	13.484	3.643	0.046	−11.230
17	3	2	1	3	1	2	3	0.000	0.000	0.000	0.011	0.002	38.903
18	3	3	2	1	2	3	1	0.267	0.549	0.541	0.651	0.175	3.445

4.1 Speed loop proportional gain

Speed loop proportional gain, that is, the higher this gain is, the faster will be the motor response in speed, also might promote the control efficiency to have an optimum performance and effectively suppresses the vibration. In PID controller, this proportional term has the most important role countering proportionally occurring (overall) error but not the steady-state error. The proportional term makes a change to the output that is proportional to the current error value.

4.2 Speed loop integral gain

Speed loop integral gain works similarly as an integral gain by a PID controller. In the concept of PID controller, the

Table 3 Response for position time

Exp.	A	B	C	D	E	F	G	MSD			$\bar{y}$	STD	S/N (dB)
								M1	M2	M3			
1	1	1	1	1	1	1	1	0.305	0.294	0.342	0.559	0.020	5.039
2	1	2	2	2	2	2	2	592.336	537.995	652.604	24.266	2.425	−27.740
3	1	3	3	3	3	3	3	19.505	19.570	19.584	4.422	0.005	−12.912
4	2	1	1	2	2	3	3	0.724	0.741	0.724	0.854	0.009	1.370
5	2	2	2	3	3	1	1	12.372	12.586	12.405	3.529	0.023	−10.953
6	2	3	3	1	1	2	2	2.610	2.578	2.605	1.612	0.015	−4.146
7	3	1	2	1	3	2	3	16.297	16.273	16.275	4.035	0.007	−12.117
8	3	2	3	2	1	3	1	0.002	0.001	0.002	0.044	0.008	27.077
9	3	3	1	3	2	1	2	2.927	2.949	2.949	1.715	0.009	−4.686
10	1	1	3	3	2	2	1	87.483	78.376	75.098	8.785	1.834	−19.048
11	1	2	1	1	3	3	2	169.214	177.726	177.490	13.208	0.625	−22.426
12	1	3	2	2	1	1	3	36.455	30.641	41.358	5.995	0.480	−15.581
13	2	1	2	3	1	3	2	0.002	0.002	0.002	0.042	0.003	27.432
14	2	2	3	1	2	1	3	73.695	73.995	74.353	8.603	0.019	−18.693
15	2	3	1	2	3	2	1	15.702	15.655	15.650	3.958	0.007	−11.950
16	3	1	3	2	3	1	2	6.462	6.462	6.462	2.542	0.000	−8.104
17	3	2	1	3	1	2	3	0.001	0.001	0.001	0.028	0.008	30.735
18	3	3	2	1	2	3	1	4.650	9.895	9.865	2.814	0.482	−9.105

Table 4 Response for torque standard deviation

Exp.	A	B	C	D	E	F	G	MSD			$\bar{y}$	STD	S/N (dB)
								M1	M2	M3			
1	1	1	1	1	1	1	1	0.006	0.005	0.006	0.075	0.002	22.448
2	1	2	2	2	2	2	2	0.401	0.425	0.445	0.651	0.017	3.729
3	1	3	3	3	3	3	3	0.002	0.002	0.003	0.051	0.006	25.754
4	2	1	1	2	2	3	3	0.003	0.003	0.004	0.055	0.005	25.113
5	2	2	2	3	3	1	1	0.006	0.006	0.007	0.079	0.002	22.065
6	2	3	3	1	1	2	2	0.003	0.003	0004	0.056	0.003	24.993
7	3	1	2	1	3	2	3	0.002	0.002	0.002	0.046	0.001	26.666
8	3	2	3	2	1	3	1	0.003	0.003	0.004	0.058	0.002	24.661
9	3	3	1	3	2	1	2	0.004	0.004	0.004	0.062	0.004	24.186
10	1	1	3	3	2	2	1	0.528	0.528	0.554	0.732	0.018	2.703
11	1	2	1	1	3	3	2	0.002	0.002	0.002	0.044	0.001	27.080
12	1	3	2	2	1	1	3	0.080	0.094	0.101	0.303	0.018	10.361
13	2	1	2	3	1	3	2	0.006	0.005	0.005	0.074	0.002	22.671
14	2	2	3	1	2	1	3	0.002	0.002	0.002	0.047	0.003	26.490
15	2	3	1	2	3	2	1	0.003	0.003	0.004	0.058	0.008	24.595
16	3	1	3	2	3	1	2	0.002	0.003	0.003	0.052	0.003	25.748
17	3	2	1	3	1	2	3	0.003	0.004	0.004	0.061	0.003	24.219
18	3	3	2	1	2	3	1	0.003	0.003	0.003	0.055	0.002	25.234

contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously.

4.3 Torque command smoothing time

Torque (or torsion) command smoothing time is a parameter of AC servo driver, where the lesser the setup time, the higher an accuracy to have the current torque.

Table 5 Response of GHS relational

Number	Data pre-processing			GHS relational coefficient			GHS relational grade	Rank
	Position accuracy	Position time	Torque stand. dev.	Position accuracy	Position time	Torque stand. dev.		
1	0.9666	0.9781	0.9547	0.9374	0.9580	0.9169	0.9374	5
2	0.1058	0.0000	0.1186	0.3586	0.3333	0.3619	0.3513	18
3	0.7150	0.8187	0.9898	0.6369	0.7339	0.9801	0.7836	11
4	0.8067	0.9659	0.9839	0.7212	0.9362	0.9689	0.8754	9
5	0.9919	0.8556	0.9498	0.9840	0.7759	0.9087	0.8895	7
6	0.7751	0.9347	0.9826	0.6898	0.8844	0.9664	0.8469	10
7	0.4581	0.8347	0.9969	0.4799	0.7515	0.9937	0.7417	14
8	0.9982	0.9994	0.9793	0.9963	0.9987	0.9603	0.9851	1
9	0.9945	0.9304	0.9747	0.9892	0.8778	0.9518	0.9396	4
10	0.3353	0.6387	0.0000	0.4293	0.5805	0.3333	0.4477	17
11	0.0000	0.4562	1.0000	0.3333	0.4790	1.0000	0.6041	16
12	0.9046	0.7538	0.6242	0.8398	0.6701	0.5709	0.6936	15
13	0.9966	0.9994	0.9575	0.9933	0.9988	0.9216	0.9712	3
14	0.7992	0.6462	0.9956	0.7135	0.5856	0.9912	0.7635	13
15	0.9831	0.8378	0.9793	0.9674	0.7551	0.9603	0.8943	6
16	0.5147	0.8963	0.9894	0.5075	0.8282	0.9793	0.7716	12
17	1.0000	1.0000	0.9750	1.0000	1.0000	0.9523	0.9841	2
18	0.9145	0.8850	0.9848	0.8540	0.8131	0.9705	0.8792	8

Table 6 S/N Ratio and ANOVA for multi performance characteristics of GHS relational

	Control factors (diver parameters)	S/N ratio (dB)					ANOVA table				
		Level 1	Level 2	Level 3	Max–Min	Rank	Sum of Square (SS)	DOF (v)	Mean (V)	*F* ratio (*F*)	Percentage (P)
A	Speed loop proportional gain	0.6363	0.8735	0.8836	0.2473	1	0.2350	2	0.117	19.546	42.90
B	Speed loop integral gain	0.7909	0.7629	0.8395	0.0766	6	0.0180	2	0.009	1.500	3.29
C	Torque command smoothing	0.8725	0.7544	0.7664	0.1181	4	0.0507	2	0.025	4.216	9.25
D	Position gain	0.7955	0.7619	0.8360	0.0741	7	0.0165	2	0.008	1.374	3.01
E	Position smoothing time	0.9031	0.7094	0.7808	0.1936	2	0.1150	2	0.058	9.570	21.00
F	Speed loop differential gain	0.8326	0.7110	0.8498	0.1388	3	0.0687	2	0.034	5.713	12.54
G	Acceleration	0.8389	0.7475	0.8070	0.0914	5	0.0258	2	0.013	2.149	4.72
	Error						0.0180	3	0.006	–	3.29
	T						0.5478	17			100.00

4.4 Position (proportional) gain

Position (proportional) gain is a factor of AC servo driver, where the higher its position gain, the faster will be the response to reach its reference value of position, but consequently the higher will be the risk of vibration.

4.5 Position smoothing time

Position smoothing time, is a parameter of AC servo driver, where the lesser is the setup time, the higher will be the accuracy to have the current speed value.

4.6 Speed loop differential gain

Principally is identical to the derivative term of PID controller. The derivative term slows the rate of change of the controller output, and this effect is most noticeably close to the controller set point. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability.

4.7 Acceleration (and deceleration)

In common speech, the term acceleration is only used for an increase in speed; a decrease in speed is called deceleration. It is used accordingly to get an optimum accuracy and stability of movement of the system. The higher its value of acceleration and/or deceleration, the higher the risk of inaccuracy and instability; the lesser the value of acceleration and/or deceleration, the slower is the speed response.

The above parameters are taken based on previous experiments, which apply other parameters that have less significant relationship among them due to analysis of variance (ANOVA) method. The strategy on how to perform the experiment is by doing all experiments with $2^1 \times 3^7 = L_{18}$ orthogonal array (OA) three levels (number of experiment will total $18 \times 15 = 270$ experiments) using Taguchi method and utilising LabVIEW as a means for helping us to write the program and execute the experiment.

Furthermore, using both methods, GHS relational analysis and Taguchi, may combine them to become one reliable experimental approach in optimising a linear table motion, the so-called GHST analysis method, flowcharted by Fig. 3.

5 Experimental procedures

Before presenting the analysis, the experimental setup will be described first. Parameter diagram of system is shown in Fig. 1, and measurement setup is shown in Fig. 2, which is PC-based using LabVIEW from NI (National Instruments) with RS-232 communication with the following hardware: NI-7344 (Motion Control), UMI-7764 (Universal Motion Interfaces) and DAQ Signal Accessory of PXI-6221 [PCI extensions for instrumentation, peripheral component inter-

Table 7 Confirmation experiment for (a) initial parameters; (b) multi performance parameters

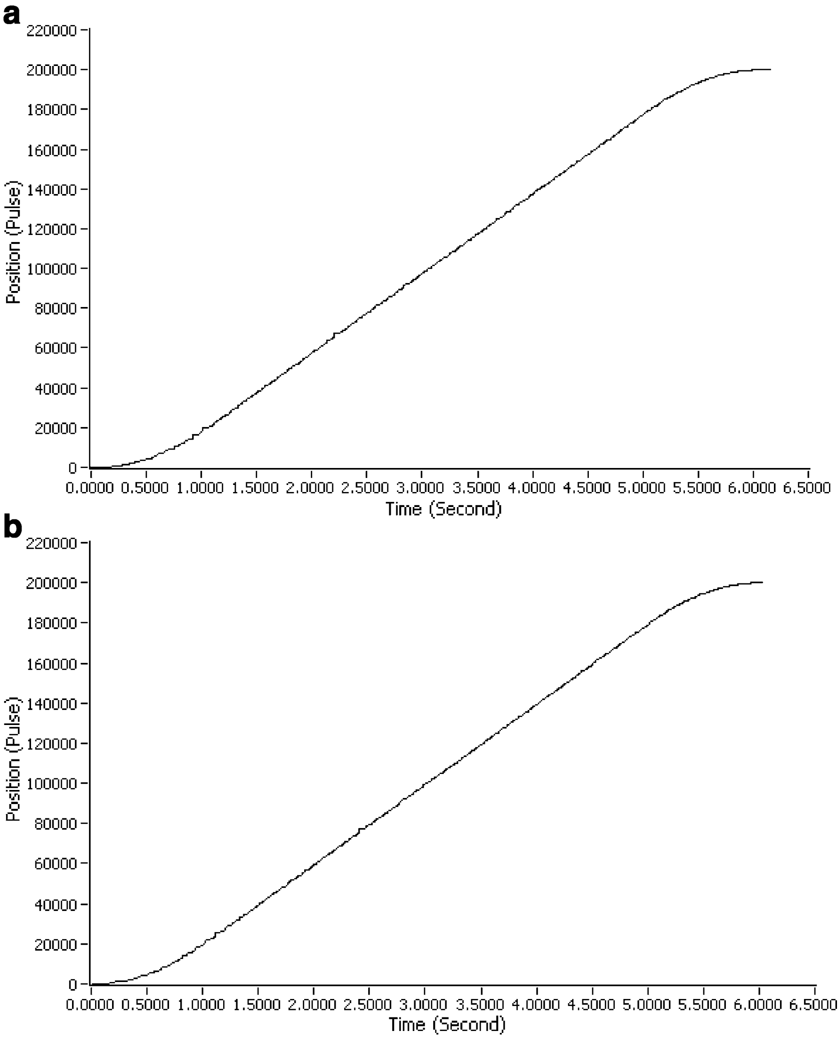
	Average	Mean square deviation (MSD)	Signal-to-noise ratio (S/N)
PA.M (mm)			
(a) Initial (default)	0.2100	0.0457	13.4023
(b) mpp (GHST)	0.0137	0.0002	37.1935
PT.M (s)			
(a) Initial (default)	0.1599	0.0256	15.9229
(b) mpp (GHST)	0.0293	0.0010	29.9305
TSD.M (Nm)			
(a) Initial (default)	0.0924	0.0087	20.5970
(b) mpp (GHST)	0.0481	0.0023	26.3447

PA position accuracy, *PT* position time, *TSD* torque standard deviation, *M* noise connect (PCI)]; Driver from SMMC (SMart Motion Controller) company with type SMART AC servo SD; Torque sensor from Sensor Developments company Model 01324; ball-screw table type from SMI company type SFE-2020 500 mm long with 70 μm tolerance (C7). All computation processes will be done using a processing unit of PXI-1031 from NI. Leveling parameter and noise are referred to Table 1. Measurement setup information are as follows: pulse command and semi closed-loop, motor with 8,000 pulses/rev; screw rod accuracy, 20 mm/rev; $(8,000\,\mathrm{pulses/rev})/(20\,\mathrm{mm/rev}).(20\,\mathrm{mm/rev}) = 400\,\mathrm{pulses/mm}$; 1 mm=400 pulses; 1 pulse=2.5 μm.

Procedure of experimental-based research is shown in Fig. 3. After the experimental plan is developed, calibration of the measurement setup and the software are necessary and then setup the initial values to be taken as reference values. As the design parameter using Taguchi method with all of experimental conditions, running the experimental will be the next task to do after setting the initial, eventually reference values. By running the experiment, sampling data are also consequently done. Data pre-processing, as discussed above, hereafter is used to convert values into specific range. Data pre-processing is normally required, since the range and unit in one data sequence may differ from the others. Data preprocessing is also necessary when the sequence scatter range is too large or when the directions of the target in the sequences are different. Data pre-processing is a means of transferring the original sequence to a comparable sequence. Depending on the characteristics of a data sequence, there are various methodologies of data pre-processing available for the grey relational analysis.

According to the calculation of MSD based on Taguchi's concept, which is continuously used to determine S/N ratio, originally, there are only three conditions to be applied; they are lower-is-better, nominal-is-best and higher-is-better. Simple normalisation of data pre-processing is used once in a while and the original sequence be simply normalised by the most basic methodology, which means that values of the original sequence is divided by the first value of the

Fig. 4 Displacement responses of **a** initial parameters; **b** multi performance parameters



sequence, i.e. the value is setup to be the reference. In this paper, lower-is-better is applied to minimise errors.

To get an optimum result with regard to fast process and precise positioning, as well as minimisation of error, therefore, three responses are necessary to be plotted. They are responses of position accuracy (PA), position time (PT) and torque standard deviation (TSD). Response of PA is needed in determining precise positioning, response of PT is required in determining process time and response of TSD is noticed in determining an error minimisation. Optimum results will have less error (±1%) and fast process time, depending on the time calculation desired.

As an example: the total distance of motion is 500 mm= 200.00 pulses; an assumed velocity of 100 mm/s is equal to 40,000 PPS(pulse/s). Acceleration, constant velocity and deceleration are three proportional divided standard regions of velocity response in time. Supposed that the acceleration and deceleration are similarly assumed, then acceleration and/or deceleration of 500 mm/s^2 will be 200,000 PPS/s^2 equally. Furthermore, the theoretically estimated time is 5.2 s.

Detailed procedures of implementing GHST method is shown in Fig. 3, starting from defining Taguchi's DOE to conducting necessary confirmation experiments. Figure 3 detailed also the experimental procedure. All procedures mentioned by this project are shown in this figure, inclusively detailed how to integrate or to confirm the experimental results with the analysis results.

6 Results and discussions

The selection of quality characteristics to measure as experimental outputs greatly influences the number of tests that will be done to be statistically meaningful. Starting from taking seven parameters to be used for this experi-

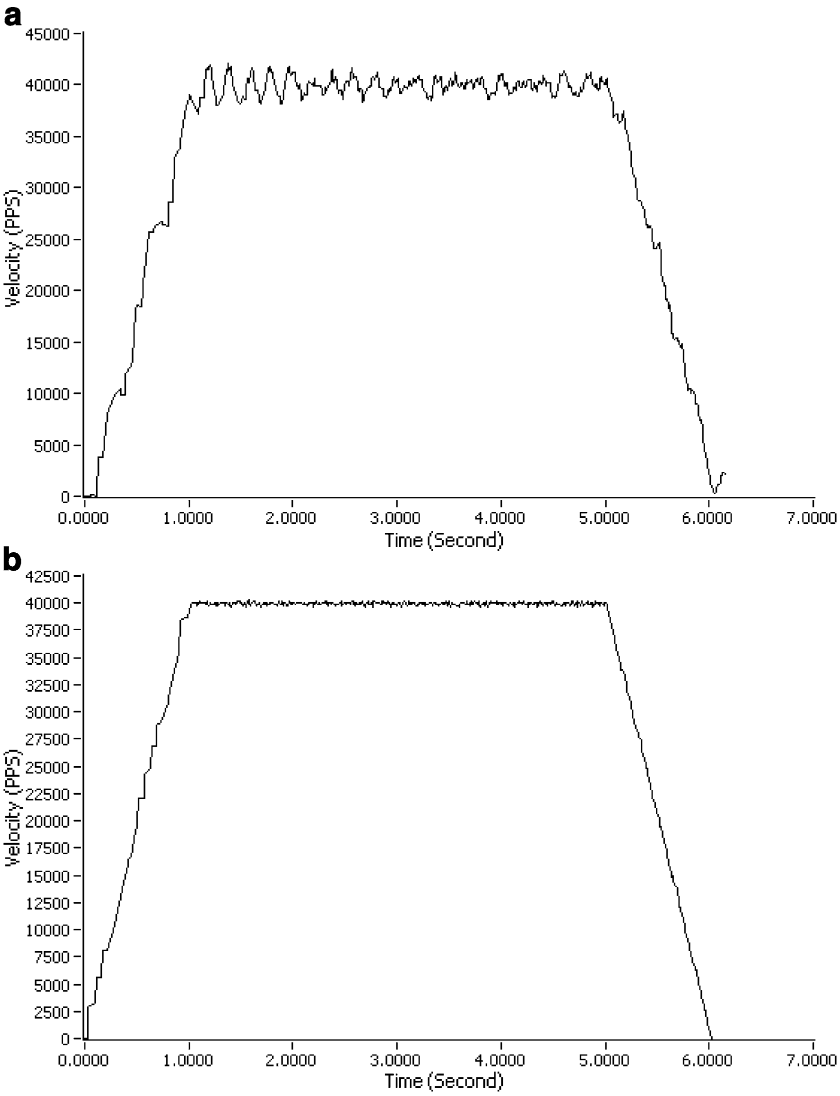


Fig. 5 Velocity responses of **a** initial parameters; **b** multi performance parameters

ment, in which each parameter has three levels, therefore, based on Taguchi method in defining an orthogonal array, then it might be used an L18 orthogonal array.

The S/N ratio (or log S value) is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. If an outer array is used, the noise variation is forced in an experiment; with pure repetitions (no outer array), the noise variation is unforced. S/N ratio is a response that consolidates repetitions and the effect of noise levels into one data point. A standard ANOVA can be done on the S/N ratio, which will identify factors significant in increasing the average value of S/N ratio and subsequently reducing variation. All responses of sampling data are tabularised in Table 2 for PA, Table 3 for PT and Table 4 for TSD.

Taking PA, PT and TSD of empirical datum as quality characteristics, then applying GHST analysis might discover optimum multi-performance characteristics. And then, Eq. 1, 2, 3 or 4 is used to do pre-processing, which depends on what kind of condition suitable to the parameter characteristics, whether HB, LB, NB or simply normalisation. After data pre-processing is carried out, Eqs. 5 and 6 are used to determine the relational coefficient and the relational grade, which represents the level of correlation between the reference sequence and the comparability sequence. All responses of sampling data of GHS relational are displayed in Table 5, in which the first rank has a grade of 0.9851 and last rank of 0.3513.

In Table 6, calculated S/N ratios are shown and will be followed up by statistically based ANOVA to get differences in average performance of variable tested. Obviously, experimental factors of speed loop proportional gain, position smoothing time, speed loop differential gain, torque command smoothing, position gain, acceleration and lastly speed loop integral gain are descend significance.

From Table 7, a comparison of confirmation-experiment performance between initial parameters with multi performance parameters might be found. There was an improvement of an average error of position accuracy from 0.2100 to 0.0137 mm and S/N from 13.4023 to 37.1935 dB, which means that it enhanced to 23.7912 dB. An average error of position time improved from 0.1599 to 0.0293 s and enhancement of S/N of 14.0076 to 29.9305 dB. The average error of torsion standard deviation from 0.0924 Nm is improved to 0.0481 Nm, enhancement of S/N of 5.7477 to 26.3447 dB.

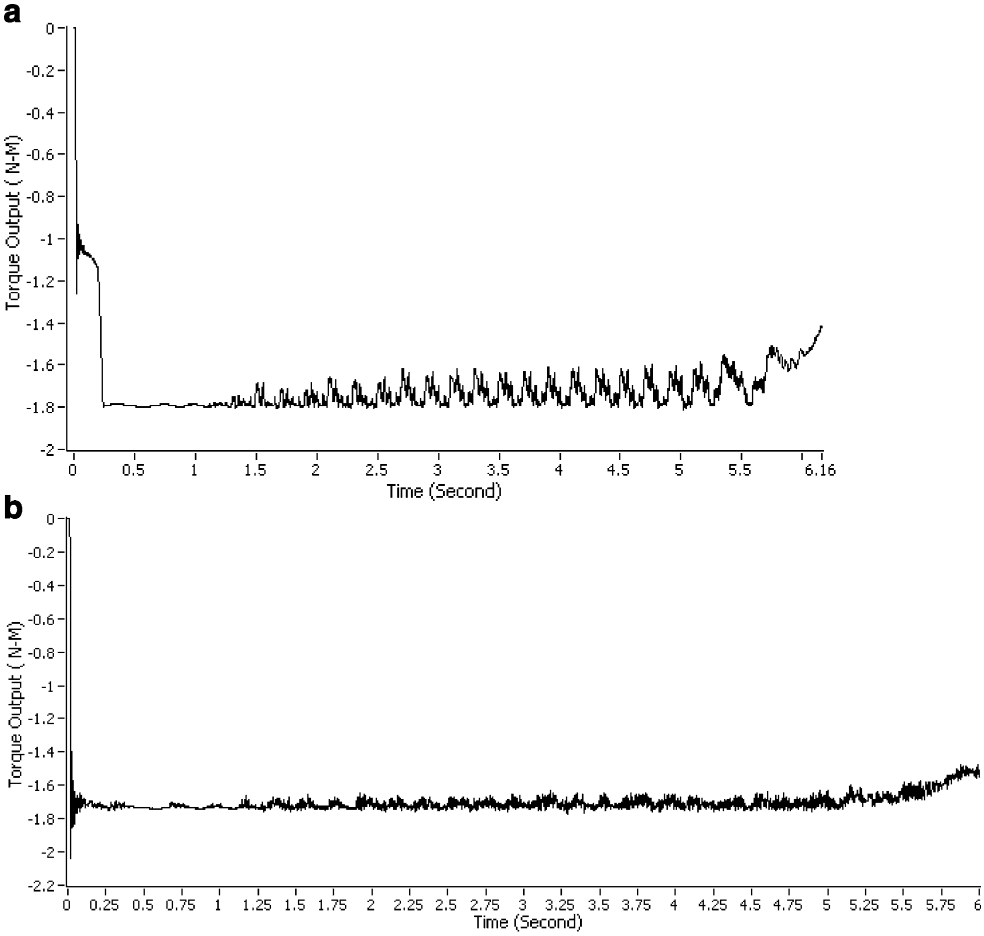


Fig. 6 Torque responses of **a** initial parameters; **b** multi performance parameters

Results of comparison between initial and multi-performance parameters are plotted in Fig. 4 for displacement–time response, Fig. 5 for velocity–time response, and Fig. 6 for torque–time response. From Fig. 4, it is shown that a multi-performance parameter has improved 0.16 s less delay time in achieving end-position rather than an initial parameter. In Fig. 5, it is shown that velocity–response by initial parameter is chattered more than multi-performance parameter. In other words, a multi-performance parameter has improved to a smoother motion. In Fig. 6, it is obviously seen that torque of multi-performance parameters is also better accommodated than initial parameters, even within the time range from 0.25 to 1 s, some small fluctuations might be observed, which was not observed in the initial solution, and currently is hypothesised as a phenomenon that is caused by having higher S/N ratio probably. There are further investigations necessary to clarify this, such as frequency analysis or other error analysis (e.g. pitch, yaw or rolling errors, etc.). Other possibility is hypothesised as a transient phenomenon, where it could be minimised by applying persistent excitation.

7 Conclusions

The aim of this paper is optimising a performance of motion of ball-screw table type based on multi-performance characteristics, namely displacement, velocity and torque.

From Table 7 and Figs. 4, 5 and 6, it is clearly shown that by using GHST, multi-performance parameter is improved into better performance and low cost effectively. This study indicated that GHST analysis approach might be applied successfully to table motion performance optimization, which is determined by many parameters at multi-quality performances.

In further research, it is advised to apply voltage or current command signal as a feedback to get more precise performance of motion; also further investigations are necessary to clarify the phenomenon shown in Fig. 6, such as frequency analysis or other error analysis (e.g. pitch, yaw or rolling errors, etc.). Lastly, it is also suggested to implement our developed control algorithm to be able to improve robustness, convergence and stability of the system.

Acknowledgements Honor appreciations are due to Chao-Wei Tang, Shuo-Jian Zhou and all colleagues of Opto-Mechatronics Laboratory for helping in developing the system. This work is supported by the OMTC of National Taiwan University of Science and Technology, Taipei, Taiwan, the Republic of China.

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