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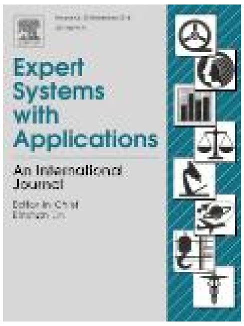

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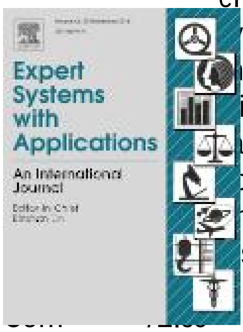

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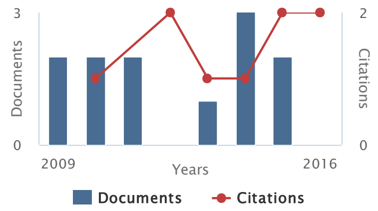

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Experimental PC based TGPID control method for 2D CNC machine

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ABSTRACT

An important problem in the control of circular motion of CNC machine is to let *X* and *Y* axes move simultaneously. This article addresses this problem for the performance of desktop-scale CNC milling machine for reducing roundness error (REB), minimizing position time difference (ΔTt). An approach that can solve those problems will be introduced. Our approach uses a Taguchi–Grey System–Proportional Integral Derivative (TGPID). This method emphasizes an improvement of system performance through this controller's robustness, such as a faster initialization in gaining as appropriate local minima and also high responsive. In this paper, it is aimed to enhance on multi-performance characteristics, namely actual radius (*R*_act) and position time (Tt). The improvement of roundness error in counter-clockwise (CCW) direction is from 0.151 mm by default, being 0.140 mm by TPID (Taguchi–PID; without grey system), and 0.133 mm by TGPID. The method can reduce the roundness error significantly, also the difference of position time for 100%. This proposed method also offers a simple experimental-based approach. An improvement of its performance indicated that this proposed approach is applied successfully to multi-linear motion performance optimization which is determined by many parameters at multi-quality performances. Performances of the proposed controller scheme, as well as some practical design aspects, are demonstrated by the control of a circular motion of CNC machine.

1. Introduction

A multi-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 optimization for linear table motion is proposed. This work posits a solution to the problem of optimizing a linear table motion where optimization requirements are conflicted between primary task motions and maintaining a sufficiently accurate position estimate to facilitate primary task motion. The proposed method is applied to improve the performances of table motion which are minimization of roundness error (REB) and position time's difference (ΔTt). A typical common industry application, namely CNC machine, which is often seen in machining industry, is selected as a test model. Experimental results show that the TGPID method effectively optimizes three responses of the system: response of roundness (*XY*), error and velocity. Therefore, the contribution of this work is of engineering significance. The method can reduce the roundness error significantly from 0.15 mm to 0.13 mm, also the difference of position time for 100%. This proposed method also offers a simple experimental-based approach.

Hybrid method of using grey and PID controller was illustrated in Yang and Li (2007), and of using a Taguchi and grey relational analysis in Nurhadi and Tarng (2008); also in Ping, Liu, Li, and Zhou (2007), Wei and Fei (2007), Peng (2006), Wu and Chen (2005), Huang and Huang (2000) and Chen and Li (2003) were described a grey theory and its applications in many fields, and in Yamaguchi, Li, and Nagai (2005) and Yamaguchi, Li, and Nagai (2007) were derived a grey relational analysis for other implementation of finding an invariable structure.

Recently, Liu, Luo, and Rashid (2004), Duelger and Kirecci (2007) and Gordon and Hillery (2005) proposed control developments of *XY* or multi-axes linear system. Lee and Lee (2004) introduced an approach of compensation of chucking compliance. He used only a controller of PID that causes the system not to be reliable enough. Bang and Lee (2004) and Kim and Dohmeki (2007) mentioned application of mechanical force that resulted by dynamical characteristics of the system, without applying any controller. This energy will be used to actuate the mechanism, example ejector mechanism. Others, Zhang, Chen, Ai, and Zhou (2007) and Yan and Cheng (2009) discussed artificial tools namely BP

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and neural. Both have a major drawback: slow convergence speed and problem of local minima. TGPID method is hence proposed to overcome problem of gain-positioning in machine tool applications. The originality of this method is a hybrid TGPID never used before, where grey facilitated a faster initialization in gaining an appropriate local minimum, and together with PID will guarantee system's stability while the reliability is high. Application area of this TGPID in machine tools such CNC machine is never done before.

In this paper, previous works are discussed shortly, and then used approach in this research is introduced. After that, the experimental setup will be mentioned. Result and discussion will follow hereafter. Finally, it will be closed by conclusion. The purpose of the present work is introducing a usage of created TGPID method in optimizing a multi-linear table motion on multi-performance characteristics. Thus, by properly adjusting the control factors, we can improve performance effectively and may produce high motion quality.

2. Grey system

Often a grey quantity can be described as an interval number, and a branch of mathematics (called interval mathematics) can be used to deal with this problem. Interval mathematics began with the goal of automating computational error analysis, and now has grown to include a much broader range of topics. The application of interval mathematics to computing has two objectives: to provide efficient computer algorithms for finding sets of unknown solution and to make these sets as small as possible. Toward these objectives, set-to-set mappings replace point-to-point mappings, and set inclusions replace approximate equalities. The optimization of a grey system is a problem in which both the objective function and constraint condition include grey quantities. As far as the authors are aware, there is no general approach for an optimization problem involving an interval number system. Therefore, we have almost no existing methods to follow in the field of interval mathematics. In this paper, an optimization concept of grey systems is proposed, and the problem of grey optimization is changed into a general optimization problem in the common meaning.

2.1. Grey prediction method (GPM)

Grey prediction theory aims to find the optimized systems parameters of grey differential equation and small amounts of data are required. The differential equation of grey modeling (GM) can be derived by three basic steps: (a) ratio checking (RC) and accumulated generation operations (AGO); (b) build a grey prediction model (GPM) and inverse accumulated generation operations (IAGO) and (c) error examination.

First, check the delay sequence $X^{(0)} = (x^{(0)}1, x^{(0)}2, \ldots, x^{(0)}n)$ ratio, where $x^{(0)}i$ corresponds to the system output at time i, and transform the original sequences into new sequence with AGO

$$\text{RC}: \quad \sigma^{(0)}(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)} \tag{1}$$

$$\text{AGO}: \quad x^{(1)}(k) = \sum_{m=1}^{k} x^{(0)}(m) \tag{2}$$

where $k = 1, \ldots, n$ is the sequence number; the new ratio sequence overlay area is $(e^{-2/(n+1)}, e^{2/(n+1)})$. When the ratio sequences are in overlay area, we can transform the original sequences into new more smooth sequences with AGO. Otherwise, we should take some pretreatment, such as logarithmic transformation, root-squaring transformation, or translational method. In this process, new generating sequences $X^{(1)} = (x^{(1)}1, x^{(1)}2, \ldots, x^{(1)}n)$ obtained from Eq. (2).

Second, build a grey model GM(1, 1), that is a single variable first-order grey model. The model can be constructed by establishing a first order differential equation. Set up this equation as follows:

$$x^{(0)}(k) + a \cdot z^{(1)}(k) = u \tag{3}$$

Where a and u are estimation parameters. $z^{(1)}$ is affected by $X^{(1)}$, i.e.

$$z^{(1)}(k) = \theta \cdot x^{(1)}(k) + (1-\theta) \cdot x^{(1)}(k-1) \tag{4}$$

Here, we appoint

$$Y_N = \begin{bmatrix} x_1^{(0)}(2) & x_1^{(0)}(3) & \cdots & x_1^{(0)}(n) \end{bmatrix}^T$$

$$B = \begin{bmatrix} -\frac{1}{2}(x^{(1)}(2) + x^{(1)}(1)) & 1 \\ -\frac{1}{2}(x^{(1)}(3) + x^{(1)}(2)) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(x^{(1)}(n) + x^{(1)}(n-1)) & 1 \end{bmatrix} = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}; \quad P = \begin{bmatrix} a \\ u \end{bmatrix}$$

So, Eq. (3) can be substituted as:

$$Y_N = B \cdot P \tag{5}$$

Then the optimal parameters P can be obtained by the minimum least square estimation algorithm:

$$\begin{bmatrix} a \\ u \end{bmatrix} = P = (B^T B)^{-1} B^T \cdot Y_N \tag{6}$$

According to first order differential equation, a single variable first-order GM(1, 1) can be derived in Eq. (7)

$$x^{(0)}(k) + a[\theta \cdot x^{(1)}(k) + (1-\theta) \cdot x^{(1)}(k-1)] = u \tag{7}$$

When $k > 2$, Eq. (8) is obtained

$$x^{(0)}(k) = \left(\frac{1 + (a \cdot \theta) - a}{1 + a \cdot \theta}\right) x^{(0)}(k-1) \tag{8}$$

$$x^{(0)}(k) = \left(\frac{1 + (a \cdot \theta) - a}{1 + a \cdot \theta}\right)^m x^{(0)}(k-m) \tag{9}$$

When $k = 2$, Eq. (10) is obtained

$$x^{(0)}(2) = \frac{u - (a \cdot x^{(0)}(1))}{(1 + a \cdot \theta)} \tag{10}$$

Then we use inverse accumulated generation operations (IAGO) to obtain the grey prediction model (GPM) as follows.

$$\hat{x}^{(0)}(k) = \left(\frac{1 + (a \cdot \theta) - a}{1 + a \cdot \theta}\right)^{(k-2)} \cdot \left(\frac{u - (a \cdot x^{(0)}(1))}{1 + a \cdot \theta}\right) \tag{11}$$

The relative error percentage $\varepsilon(k)$, the mean of error percentage $\bar{\varepsilon}(k)$ and the small error probability P_ε can be separately calculated by Eqs. (12)–(14)

$$\varepsilon(k) = \frac{x^{(0)}(k) - \hat{x}^{(0)}(k)}{x^{(0)}(k)} \times 100\% \tag{12}$$

$$\bar{\varepsilon}(k) = \frac{1}{n-1} \sum_{k=2}^{n} |\varepsilon(k)| \tag{13}$$

$$P_\varepsilon = (1 - \bar{\varepsilon}(k)) \times 100\% \tag{14}$$

Where $x^{(0)}(k)$ means original data, and $\hat{x}^{(0)}(k)$ means GPM data. When $P_\varepsilon > 90\%$, the predicting accuracy is excellent; for $P_\varepsilon > 80\%$, the predicting accuracy is good; for $P_\varepsilon > 70\%$, the predicting accuracy is just qualified enough.

Obviously, it is known that the grey differential equation (3) is employed to imitate the following first-order differential equation

$$\frac{dx^{(1)}(t)}{dt} + a \cdot z^{(1)}(t) = u \tag{15}$$

which is called the whitening equation of the GM(1, 1) model. By directly modifying the solution of Eq. (15), the term $x^{(1)}(k)$ of the GM(l, 1) model can be estimated as

$$\hat{x}^{(1)}(k) = \left(x^{(0)}(1) - \frac{u}{a}\right)e^{-a(k-1)} + \frac{u}{a}, \quad k = 1, 2, \ldots, n \tag{16}$$

Further using the IAGO in Eq. (11) yields

$$\hat{x}^{(0)}(k) = (1 - e^{*})\left(x^{(0)}(1) - \frac{u}{a}\right)e^{-a(k-1)}, \quad k = 2, 3, \ldots, n \tag{17}$$

Clearly, $\hat{x}^{(0)}(k)$ for $k > n$ are the predictive data of the sequence $X^{(0)} = (x^{(0)}1, x^{(0)}2, \ldots, x^{(0)}n)$, which can be expressed as

$$\hat{x}^{(0)}(n+p) = (1 - e^{*})\left(x^{(0)}(1) - \frac{u}{a}\right)e^{-a(n+p-1)}, \quad p = 1, 2, \ldots, n \tag{18}$$

For $p = 1$, we have the one-step-ahead predictive value

$$\hat{x}^{(0)}(n+1) = (1 - e^{*})\left(x^{(0)}(1) - \frac{u}{a}\right)e^{-an} \tag{19}$$

For $p = n$, we have the predictive value

$$\hat{x}^{(0)}(2n) = (1 - e^{*})\left(x^{(0)}(1) - \frac{u}{a}\right)e^{-a(2n-1)} \tag{20}$$

which is the first predictive value coming after sequence $X^{(0)} = (x^{(0)}1, x^{(0)}2, \ldots, x^{(0)}n)$.

The grey prediction theory above is used to determine the optimized system parameters in three levels where results are listed in Table 2.

The manufacturer of driver provides ranges of minimum to maximum values of seven experimental parameters. In order to weigh an appropriate value within the range, one other value is needed where it will be determined by grey prediction method. Every parameter will be used for five times in experiments. After all experiments are done, the data will be used to get one value within a range. In other word, x is each parameter itself. Since the grey will facilitate a faster initialization in finding a local minimum of optimization and it will be combined with PID be the controller; therefore, the stability of control system is guaranteed by both these methods.

Table 1
Orthogonal array L18.

Exp.	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2
3	1	3	3	3	3	3	3
4	2	1	1	2	2	3	3
5	2	2	2	3	3	1	1
6	2	3	3	1	1	2	2
7	3	1	2	1	3	2	3
8	3	2	3	2	1	3	1
9	3	3	1	3	2	1	2
10	1	1	3	3	2	2	1
11	1	2	1	1	3	3	2
12	1	3	2	2	1	1	3
13	2	1	2	3	1	3	2
14	2	2	3	1	2	1	3
15	2	3	1	2	3	2	1
16	3	1	3	2	3	1	2
17	3	2	1	3	1	2	3
18	3	3	2	1	2	3	1

Table 2
Parameter level.

Parameter		L1	L2	L3
A	KPP	10	35	100
B	PFG	100	5000	10,000
C	PFF	2	5	50
D	KVP	100	500	1000
E	KVI	10	100	1000
F	SFG	0	5	100
G	ACL	75	150	300

2.2. Grey relational analysis (GRA)

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 of 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 grey relational analysis. If the target value of original sequence is infinite, then it has a characteristic of the "higher is better". The original sequence can be normalized as follows:

$$x_i^{*}(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{21}$$

Incase of the "lower is better" (case of this work) is a characteristic of the original sequence; the original sequence should be normalized as follows:

$$x_i^{*}(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{22}$$

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

$$x_i^{*}(k) = 1 - \frac{\left|x_i^0(k) - x^0\right|}{\max x_i^0(k) - x^0} \tag{23}$$

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

$$x_i^{*}(k) = \frac{x_i^0(k)}{x_i^0(1)} \tag{24}$$

where $i = 1, \ldots, m$; $k = 1, \ldots, n$. m is the number of experimental data items and n is the number of parameters. $x_i^0(k)$ denotes the original sequence, $x_i^{*}(k)$ the sequence after the data pre-processing, $\max x_i^0(k)$ the largest value of $x_i^0(k)$, $\min x_i^0(k)$ the smallest value of $x_i^0(k)$ and x^O is the nominally desired value.

In grey relational analysis, the measure of the relevancy between two systems or two sequences is defined as the grey 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 grey relation measurement. After data pre-processing is carried out, the grey relational coefficient $\xi_i(k)$ for the kth performance characteristics in the ith experiment can be expressed as:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{oi}(k) + \zeta\Delta_{\max}} \tag{25}$$

where Δ_{0i} is the deviation sequence of the reference sequence and the comparability sequence referred to Eq. (22).

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

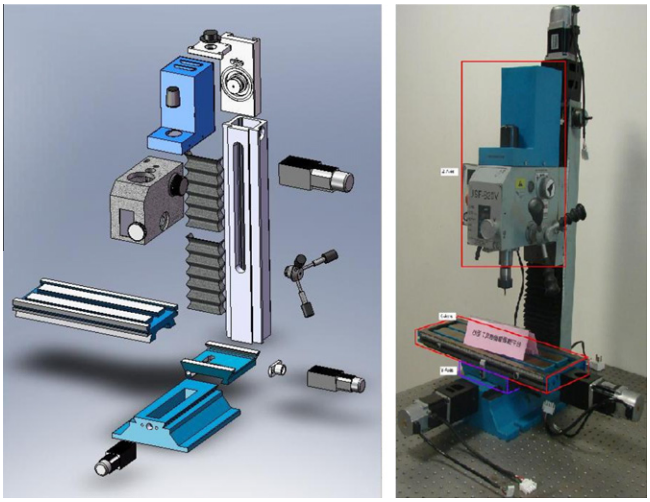

Fig. 1. Desktop-scale CNC machine.

$x_0^*(k)$ denotes the reference sequence ($\bar{y}$); 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). A value of ζ is the smaller and the distinguished ability is the larger. $\zeta = 0.5$ is commonly used. When only one sequence $x_0^*(k)$ is available as the reference sequence, and all other sequences are comparability sequences, it is called the localized grey relational grade. In this work, the localized grey relational grade is applied.

2.3. Grey relational grade (GRG)

After the grey relational coefficient is derived, it is usual to take the average value of the grey relational coefficients as the grey relational grade. The grey relational grade is defined as follows:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{26}$$

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 grey relational grade in Eq. (26) was extended and defined as:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k\xi_i(k) \quad \sum_{k=1}^{n} w_k = 1 \tag{27}$$

where w_k denotes the normalized weight of factor k. Given the same weight, Eqs. (26) and (27) are equal.

The grey 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 grey relational grade is equal to 1. The grey 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 grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades.

3. Taguchi

The Taguchi method utilizes orthogonal arrays from experimental design theory to study a large number of variables with a small number of experiments. In this work, based on number of input parameter and its level, is OA L18 defined (Table 1).

Loss function measures quality. The loss function establishes a financial measure of the user dissatisfaction with a product's performance as it deviates from a target value. Thus, both average performance and variation are critical measures of quality. Selecting a product design or a manufacturing process that is insensitive to uncontrolled sources of variation improves quality. The loss function can also be applied to product characteristics other than the situation in which the nominal value is the best value: where lower (or smaller) is better; or higher (or larger) is better, for instance. A good example of lower-is-better characteristics is the waiting time for your order delivery at a fast-food restaurant. Efficiency, ultimate strength, or fuel economy are examples of higher-is-better. Loss (L) for an individual part is:

$$\text{Nominal-is-best}: \quad L(y) = k(y - m)^2 \tag{28.1}$$

$$\text{Lower-is-better}: \quad L(y) = k(y^2) \tag{28.2}$$

$$\text{Higher-is-better}: \quad L(y) = k(1/y^2) \tag{28.3}$$

with L is the quality loss, y is a product quality characteristics, m is a nominal value, and k is a constant of cost factor. The average quality loss Q with n be a number of experiments will be $Q = \frac{\sum_{i=1}^{n} k(y_i-m)^2}{n} = k\left[\frac{\sum_{i=1}^{n}(y_i-m)^2}{n}\right]$ where $\sum_{i=1}^{n} k(y_i - m)^2 =$ total quality loss. The S/N ratio consolidates several repetitions (at least two data points are required) into one value that reflects the amount of variation present. They are the S/N ratios for lower-is-better, higher-is-better, and nominal-is-best systems. The nominal-is-best MSD is

$$\text{Nominal-is-best MSD}: \quad \text{MSD} = \left[\frac{\sum_{i=1}^{n}(y_i - m)^2}{n}\right]^2 \tag{29.1}$$

$$\text{Lower-is-better MSD}: \quad \text{MSD} = \left[\frac{\sum_{i=1}^{n} y_i^2}{n}\right] \tag{29.2}$$

$$\text{Higher-is-better MSD}: \quad \text{MSD} = \left[\frac{\sum_{i=1}^{n} 1/y_i^2}{n}\right] \tag{29.3}$$

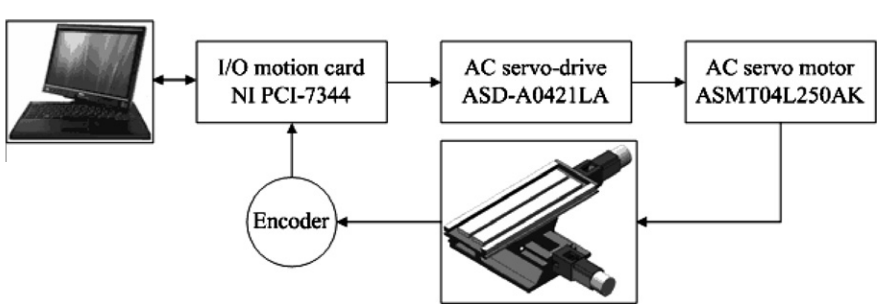

Fig. 2. System structure.

$$S/N \text{ ratio}: \quad S/N = -10\log(\text{MSD}) \tag{30}$$

The relative magnitude of the effect of different factors can be obtained by the decomposition of variance, called ANOVA. The object of ANOVA is to identify the influence of individual factors by applying statistical approaches and summarizing the effect of the experiment. In addition, the Taguchi method could not determine the effect of individual factors in the experimentation, and ANOVA can be used to compensate for that effect. Sum of squares will be:

$$SS = \left[\sum_{i=1}^{k_A}\left(\frac{A_i^2}{n_{A_i}}\right)\right] - \frac{\left(\sum_{i=1}^{N} S/N\right)^2}{N} \tag{31}$$

with SS is sum-of-squares, k_A number of factor under investigation (level 1, level 2 and level 3), A_i factor under investigation (A_1 at level 1, A_2 at level 2 and A_3 at level 3), n_{A_i} number of observations under A_i level, S/N signal-to-noise ratio, N number of observations. If v is degree of freedom (DOF),

$$\text{Mean } (V) \text{ is } V = \frac{SS}{v} \tag{32}$$

$$F\text{-ratio will be } F = \frac{V}{V_e} \text{ with } V_e = \frac{SS_e}{v_e} \tag{33}$$

$$\text{The percentage is } P = \frac{SS}{TSS}100\% \text{ with } TSS = \sum_{i=1}^{n} SS \tag{34}$$

4. PID

PID control is the major process control method. It uses the error $e(t)$ of reference input, the integral of $e(t)$ and the derivation of $e(t)$ to produce the control signal. Among them, proportion item reflects the error of system in time, integral item can eliminate static error and increase precision and deviation item can suppress the vibrating of output and improve the stability. The ideal discrete digital PID control equation is

$$u^*(k) = K_P \cdot e(k) + K_I \cdot \sum_{j=0}^{k} e(j) \cdot T + \frac{K_D}{T} \cdot (e(k) - e(k-1)) \tag{35}$$

with $K_I = K_P/T_I$ and $K_D = K_P \cdot T_D$

where K_P is the coefficient of proportionality, K_I is the coefficient of integral, T_I is the time constant of integral, K_D coefficient of derivation, T_D is the time constant of derivation, $e(k)$ is the deviation between the set value and the real output; and T is the sampling period.

The position and speed responsiveness selection is depending on and determined by the control stiffness of machinery and conditions of applications. The characteristics of robust and rapidity are the main requirements of speed closed loop. The characteristics of the position closed loop are good linear and high stable precision. Since the speed closed loop has fast response speed and insulates most of disturbances of the system, the position closed loop takes emphasis on increasing the tracking precision. Generally, high responsiveness is essential for the high frequency positioning control of mechanical facilities and the applications of high precision process system. However, the higher responsiveness may easily result in the resonance of machinery system. Therefore, for the applications of high responsiveness, the machinery system with control stiffness is needed to avoid the resonance. Especially when adjusting the responsiveness of unfamiliar machinery system, the

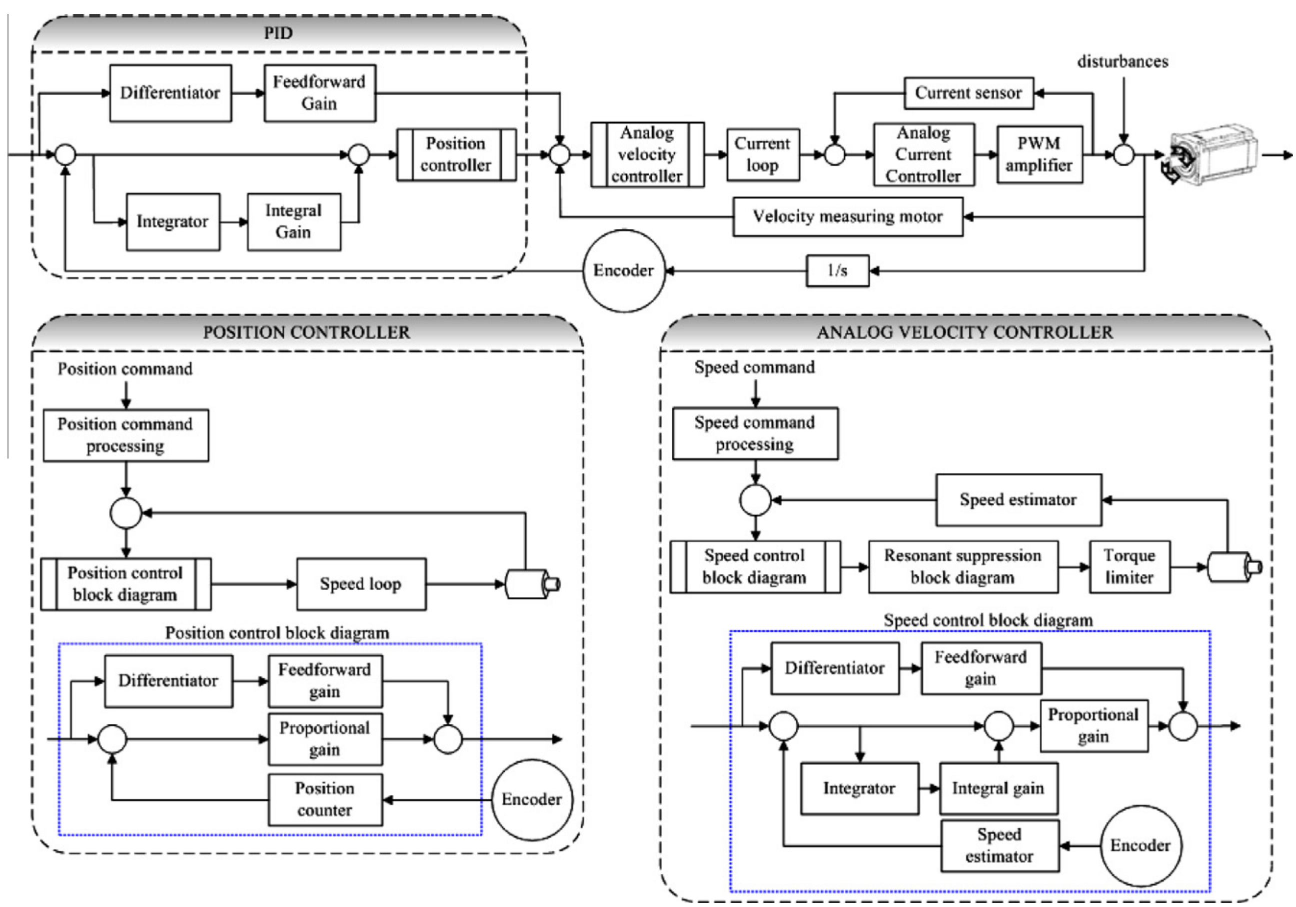

Fig. 3. Block diagram of PID control system (dual loops: position and velocity).

users can gradually increase the gain setting value to improve responsiveness until the resonance occurs, and then decrease the gain setting value.

In Fig. 3, the input reference to the controller will be a reference radius of 6 mm driven by certain velocity. The position control mode Driver's user manual of manufacturer, 2006 is usually used for the applications requiring precision positioning, such as industry positioning machine, indexing table, etc. The speed control mode is usually used on the applications of precision speed control. When the value of proportional position loop gain (KPP) is too large, the position loop responsiveness will increase, i.e. the rotor of motor will oscillate. At this time, KPP need to be reduced, until the rotor of motor stop to be oscillated. If an external torque command interrupted, over low value of KPP will lead the motor not be able to overcome an external strength and will fail to meet the requirement of reasonable position track error demand. By adjusting feed forward gain (PFG) can reduce the dynamic position track error effectively. The speed control block diagram Driver's user manual of manufacturer, 2006 manages the gain parameters of the servo drive and calculates the current input provided to motor instantaneously. The resonance suppression block diagram suppresses the resonance of mechanical system. Construction of PID embedded controller design including seven parameters taken for this experiment is shown in Fig. 3, and the tuning procedure is shown by Fig. 4.

The tuning procedures (Fig. 4) provided by the manufacturer of servo Driver's user manual of manufacturer, 2006 consist of three options: manual mode, easy mode and auto mode. In this work, manual mode is chosen to meet the need of applying grey system in defining a parameter's value. At the beginning, i.e. the driver is never tuned before, performing a trial run and then the 'J_load/J_motor' is estimated. After deciding to use a manual mode, setting position and/or speed control mode are necessary to be conducted. Carelessly selection of parameter's values effected performance reduction. This process of selection is done by GPM.

5. TGPID

Since every single component of TGPID control method is introduced above, therefore, in this section an intersection among them will be discussed. Begin with defining experimental parameters $x_i^*(k)$ based on DOE (Design of Experiment) is which done by the Taguchi method (lower-is-better MSD), the definition of experimental parameters will be:

$$Y = \Phi(\alpha) = \Phi(\xi_i(k), u^*(k)) \tag{36}$$

with Y is the properties of output, α is experimental parameters which consists of $\xi_i(k)$ in Eq. (25) is a grey-relational-coefficient and $u^*(k)$ in Eq. (35) is a PID-controller output. The goal of control method development is minimizing an error ΔY as time goes to infinity. In this case, error is a difference between reference and actual values. It is also called a variation equation that will be defined as:

$$\begin{aligned} \Delta Y &= e(t) = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u \\ \Delta Y &\to 0 \quad \text{as } t \to \infty \end{aligned} \tag{37}$$

where $\partial\alpha$ is disturbance sensitivity, $\Delta\alpha$ is disturbances, ∂u is control sensitivity, and Δu is control inputs. An alternative to minimize ΔY is by regulating u to compensate disturbances. So, the TGPID control algorithm is represented in Eqs. (36) and (37). This development is the essential innovation of proposed approach.

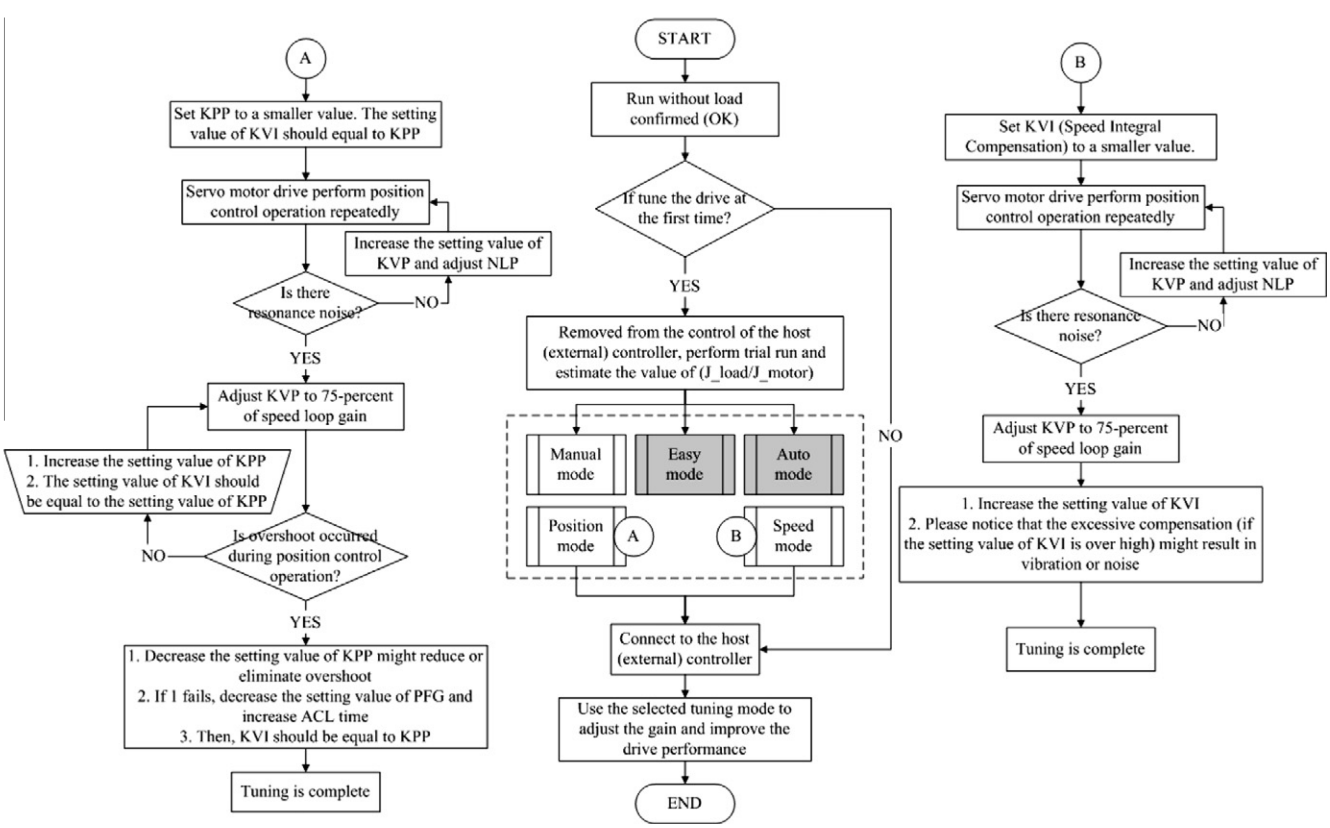

Fig. 4. Tuning procedure.

6. Experimental setup

The actuators used for X- and Y-axis in this work were supported by DELTA AC Servomotor ASMT04L250AK with power of 400 W, current 3.3 A and 3000 rpm, and the drivers were DELTA AC Servodrive ASD-A0421LA. Motor resolution is 10,000 pulses/rev, and the pitch is 4 mm/rev, therefore, 10,000 pulses/rev/4 mm/rev = 2500 pulses/mm, while 1 mm = 2500 pulses and 1 pulse = 0.4 μm. The system is interfaced to the PC by NI PCI-7344 motion card. The machine used was CNC from Jih-Shun Machine Co. Ltd. JSF-820 V, which is shown in Fig. 1, and CNC software was by Heidenhain-iTNC-530, Siemens-840D, Fanuc-CNC. Fig. 2 illustrated a CNC semi closed loop control system. To bridge the communication between machines with the post-processor, it is used 1394 bus computer's connection port and 68-pin Very High Density Cable Interconnect (VHDCI). A motion control card from National Instrument NI PCI 7344 is implemented to interface machine and computer. Start from programing at the PC, the command signal to perform a circular motion on two dimensionally XY axes is sent via motion control card to the drivers. The driver will forward a command signal to the actuators (motors). Motion will be read by the encoders, and then the signal sent back to the drivers and will be forwarded to the PC via a motion control card.

Referred to PID parameterizations before, following are the parameters taken for performing works. They are proportional position loop gain (KPP), position feed forward gain (PFG), smooth constant of position feed forward gain (PFF), proportional speed loop gain (KVP), speed integral compensation (KVI), speed feed forward gain (SFG), and acceleration and/or deceleration (ACL). These abbreviations of KPP, PFG, PFF, KVP, KVI, SFG and ACL are already

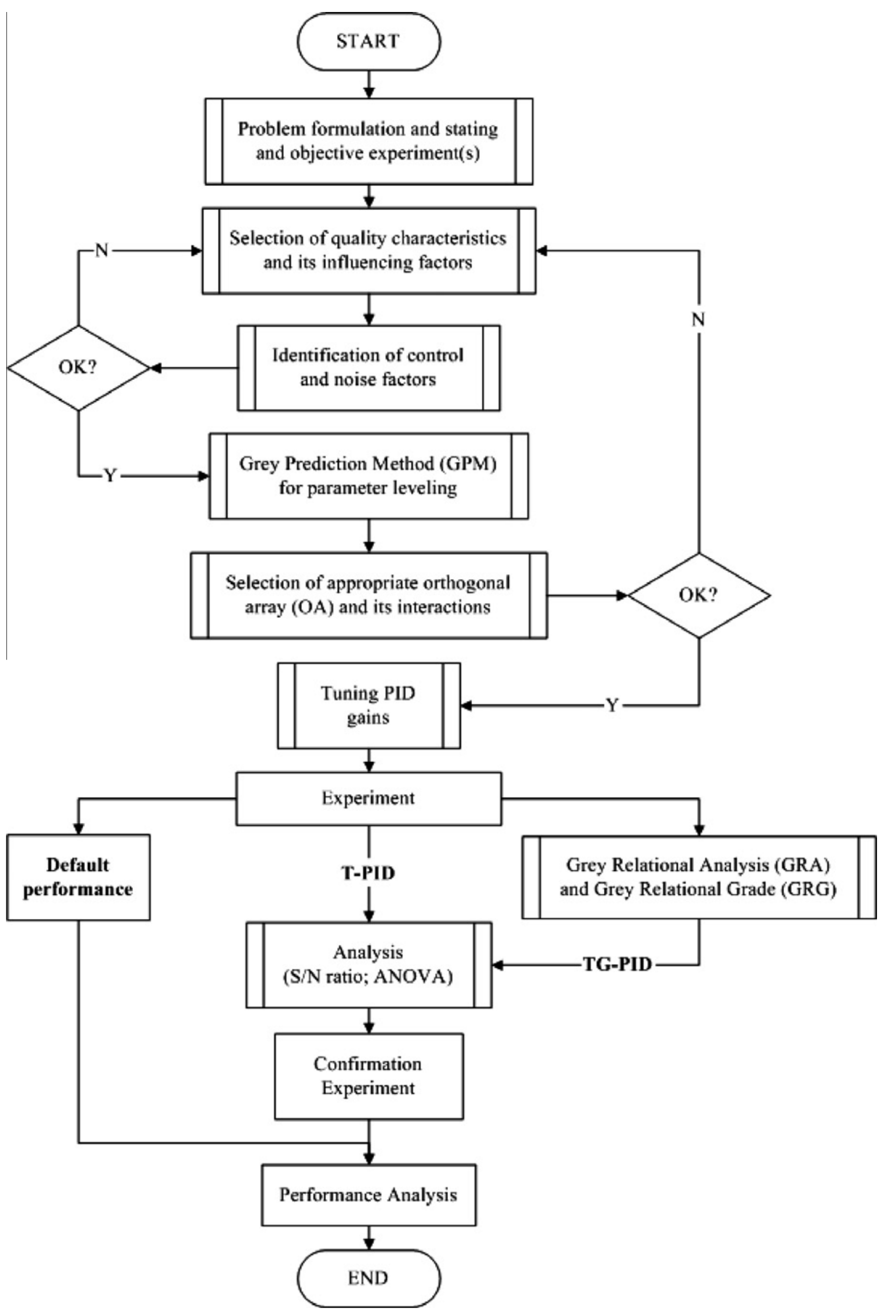

Fig. 5. Experimental procedure.

provided by driver's manufacturer Driver's user manual of manufacturer, 2006.

6.1. Proportional position loop gain (KPP)

This parameter is used to set the position loop gain. It can increase stiffness, expedite position loop response and reduce position error. However, if the setting value is over high, it may generate vibration or noise. In easy mode, the value of this parameter is determined by the system automatically.

6.2. Position feed forward gain (PFG)

This parameter is used to set the feed forward gain when executing position control command. When using position smooth command, increase gain can improve position track deviation. When not using position smooth command, decrease gain can improve the resonance condition of mechanical system. However, if the setting value is over high, it may generate vibration or noise.

6.3. Smooth constant of position feed forward gain (PFF)

When using position smooth command, increase gain can improve position track deviation. When not using position smooth command, decrease gain can improve the resonance condition of mechanical system.

6.4. Proportional speed loop gain (KVP)

This parameter is used to set the speed loop gain. When the value of proportional speed loop gain is increased, it can expedite speed loop response. However, if the setting value is over high, it may generate vibration or noise. In easy mode, the value of this parameter is determined by the system automatically.

6.5. Speed integral compensation (KVI)

This parameter is used to set the integral time of speed loop. When the value of speed integral compensation is increased, it can improve the speed response ability and decrease the speed

Table 3
Calculation data at circle *XY*.

Circle	A	B	C	D	E	F	G	REB		Mean ($\bar{y}$)	Std. dev. S	MSD LB	S/N (in dB)
								CCW	CW				
1	10	100	2	100	10	0	75	1.727861	1.593839	1.66085	0.0947679	2.7629132	−4.413672
2	10	5000	5	500	100	5	150	0.2845639	0.2985741	0.291569	0.0099067	0.0850616	10.702667
3	10	10,000	50	1000	1000	100	300	0.187211	0.1900668	0.1886389	0.0020194	0.0355867	14.487126
4	35	100	2	500	100	100	300	0.16879	0.1589797	0.1638849	0.0069369	0.0268823	15.705335
5	35	5000	5	1000	1000	0	75	0.1413674	0.1259385	0.133653	0.0109099	0.0179226	17.465984
6	35	10,000	50	100	10	5	150	1.36666	1.215856	1.291258	0.1066345	1.6730327	−2.235044
7	100	100	5	100	1000	5	300	0.226209	0.263771	0.24499	0.0265603	0.0603728	12.191585
8	100	5000	50	500	10	100	75	0.1806269	0.178413	0.17952	0.0015655	0.0322286	14.917581
9	100	10,000	2	1000	100	0	150	0.1730907	0.1653702	0.1692305	0.0054592	0.0286538	15.428171
10	10	100	50	1000	100	5	75	0.2677873	0.2704905	0.2691389	0.0019115	0.0724376	11.400361
11	10	5000	2	100	1000	100	150	0.2469719	0.2780606	0.2625163	0.021983	0.0691564	11.601676
12	10	10,000	5	500	10	0	300	0.549115	0.550391	0.549753	0.0009023	0.3022288	5.196642
13	35	100	5	1000	10	100	150	0.1967407	0.1925813	0.194661	0.0029411	0.0378972	14.213925
14	35	5000	50	100	100	0	300	0.375058	0.425822	0.40044	0.0358956	0.1609964	7.9318373
15	35	10,000	2	500	1000	5	75	0.1800351	0.160751	0.1703931	0.0136359	0.0291268	15.357078
16	100	100	50	500	1000	0	150	0.1473686	0.1514609	0.1494148	0.0028937	0.022329	16.511316
17	100	5000	2	1000	10	5	300	0.1740166	0.1706704	0.1723435	0.0023661	0.0297051	15.271693
18	100	10,000	5	100	100	100	75	0.221972	0.226297	0.2241345	0.0030582	0.050241	12.989422

Table 4
Calculation data at velocity.

Velocity	A	B	C	D	E	F	G	ΔTt		Mean ($\bar{y}$)	Std. dev. S	MSD LB	S/N (in dB)
								CCW	CW				
1	10	100	2	100	10	0	75	0.546875	0.03125	0.2890625	0.3646019	0.1500244	8.2383806
2	10	5000	5	500	100	5	150	1.421875	1.453125	1.4375	0.0220971	2.0666504	−3.15267
3	10	10,000	50	1000	1000	100	300	0	0.015625	0.0078125	0.0110485	0.0001221	39.133899
4	35	100	2	500	100	100	300	0	0	0	0	0	0
5	35	5000	5	1000	1000	0	75	1.40625	0.046875	0.7265625	0.9612233	0.9898682	0.0442264
6	35	10,000	50	100	10	5	150	1.4375	1.53125	1.484375	0.0662913	2.2055664	−3.435201
7	100	100	5	100	1000	5	300	0	0	0	0	0	0
8	100	5000	50	500	10	100	75	1.4375	0.03125	0.734375	0.9943689	1.0336914	−0.143909
9	100	10,000	2	1000	100	0	150	1.4375	1.4375	1.4375	0	2.0664063	−3.152157
10	10	100	50	1000	100	5	75	0.484375	0.046875	0.265625	0.3093592	0.1184082	9.2661821
11	10	5000	2	100	1000	100	150	1.421875	1.4375	1.4296875	0.0110485	2.0440674	−3.104952
12	10	10,000	5	500	10	0	300	0	0	0	0	0	0
13	35	100	5	1000	10	100	150	0.796875	1.4375	1.1171875	0.4529903	1.350708	−1.305615
14	35	5000	50	100	100	0	300	0.015625	0.015625	0.015625	0	0.0002441	36.123599
15	35	10,000	2	500	1000	5	75	1.390625	0.03125	0.7109375	0.9612233	0.9674072	0.1439067
16	100	100	50	500	1000	0	150	1.4375	1.4375	1.4375	0	2.0664063	−3.152157
17	100	5000	2	1000	10	5	300	0	0	0	0	0	0
18	100	10,000	5	100	100	100	75	1.40625	0.03125	0.71875	0.9722718	0.9892578	0.0469051

Table 5
Grey system.

	REB		ΔTt		Grey rel. grade
	Data pre-proc.	Grey rel. coef.	Data pre-proc.	Grey rel. coef.	
1	0	0.333333333	0.805263158	0.71969697	0.526515152
2	0.896597463	0.828634235	0.031578947	0.340501792	0.584568014
3	0.963995511	0.932828008	0.994736842	0.989583333	0.961205671
4	0.980204323	0.961916426	1	1	0.980958213
5	1	1	0.510526316	0.505319149	0.752659574
6	0.242006753	0.397458414	0	0.333333333	0.365395873
7	0.927097129	0.872748288	1	1	0.936374144
8	0.969966548	0.943336685	0.505263158	0.502645503	0.722991094
9	0.976704054	0.955482273	0.031578947	0.340501792	0.647992033
10	0.911284565	0.849306763	0.821052632	0.736434109	0.792870436
11	0.915621039	0.855609174	0.036842105	0.341726619	0.598667896
12	0.727540038	0.647282739	1	1	0.82364137
13	0.960052274	0.926015567	0.247368421	0.399159664	0.662587615
14	0.825309347	0.741080372	0.989473684	0.979381443	0.860230908
15	0.97594279	0.954094306	0.521052632	0.510752688	0.732423497
16	0.989679262	0.979775978	0.031578947	0.340501792	0.660138885
17	0.974665646	0.951774801	1	1	0.975887401
18	0.940753192	0.894059641	0.515789474	0.50802139	0.701040516

control deviation. However, if the setting value is over high, it may generate vibration or noise. In easy mode, the value of this parameter is determined by the system automatically.

6.6. Speed feed forward gain (SFG)

This parameter is used to set the feed forward gain when executing speed control command. When using speed smooth command, increase gain can improve speed track deviation. When not using speed smooth command, decrease gain can improve the resonance condition of mechanical system.

6.7. Acceleration and/or deceleration (ACL)

Acceleration refers to the rate of change in instantaneous velocity. In common speech, the term acceleration is only used for an increase in speed; a decrease in speed is called deceleration. Any increase or decrease in speed is referred to as acceleration and similarly, motion in a circle at constant speed is also acceleration, since the direction component of the velocity is changing. The instability is affected by the acceleration. The higher acceleration is the higher instability.

Experimental procedure is shown by Fig. 5. In general, the whole procedure of experiments is done by Taguchi method. Starting by formulating a problem and objective of experiments followed by selection of characteristics, and then identification of control and noise factors will be performed. Valuing characteristics is done by GPM. Afterward, selection of appropriate orthogonal array (OA) and its interactions will be mentioned, and then tuning gains of experiments will be the next. When previous procedures are all done, the experiments can be performed. In this work, three performances will be observed: default performance (PID), TPID (Taguchi–PID) performance and lastly TGPID performance. A pre-processing on data calculation is additionally needed to be done for TGPID. In Table 3, a calculation of data circle *XY* is tabulated. In Table 4 a calculation data at velocity is displayed. Closely, the results will be observed by an analysis procedure using *S/N* ratio and ANOVA (Analysis of Variance). Confirmation experiments are, therefore, needed to be conducted to make sure of its reliability, robustness and stability. Finally, a performance analysis of performance's comparison is a 'dessert' of all experimental procedure.

Table 6
S/N ratio and ANOVA for T-PID.

Parameter		*S/N* ratio (dB)			Max–min
		L1	L2	L3	
A	KPP	8.1624665	11.406519	14.551628	6.3892
B	PFG	10.934808	12.981906	10.203899	2.7780
C	PFF	11.491713	12.126704	10.502196	1.6245
D	KVP	6.3443005	13.065103	14.71121	8.3669
E	KVI	7.1585206	12.359632	14.602461	7.4439
F	SFG	9.686713	10.448057	13.985844	4.2991
G	ACL	11.286125	11.037118	11.79737	0.7603
Source	*SS*	*v*	*V*	*F*	*P* (%)
ANOVA of S/N ratio					
A	122.4739	2	61.237	10.680	18.89
B	24.8843	2	12.442	2.170	3.84
C	8.0428	2	4.021	0.701	1.24
D	235.7681	2	117.884	20.559	36.37
E	174.9882	2	87.494	15.259	26.99
F	63.1562	2	31.578	5.507	9.74
G	1.8027	2	0.901	0.157	0.28
Error	17.2016	3	5.734	–	2.65
T	648.3178	17			100.00

Table 7
S/N Ratio and ANOVA for TG-PID.

Parameter		*S/N* ratio (dB)			Max–min
		L1	L2	L3	
A	KPP	0.7145781	0.7257093	0.7740707	0.0595
B	PFG	0.7599074	0.7491675	0.7052832	0.0546
C	PFF	0.7437407	0.7434785	0.7271388	0.0166
D	KVP	0.6647041	0.7507868	0.7988671	0.1342
E	KVI	0.6795031	0.7612767	0.7735783	0.0941
F	SFG	0.711863	0.7312532	0.7712418	0.0594
G	ACL	0.70475	0.5865584	0.9230496	0.3365
Source	*SS*	*v*	*V*	*F*	*P* (%)
ANOVA of S/N ratio					
A	0.0120	2	0.006	2.364	2.51
B	0.0100	2	0.005	1.979	2.10
C	0.0011	2	0.001	0.214	0.23
D	0.0554	2	0.028	10.917	11.59
E	0.0314	2	0.016	6.178	6.56
F	0.0110	2	0.006	2.166	2.30
G	0.3497	2	0.175	68.857	73.12
Error	0.0076	3	0.003	–	1.59
T	0.4783	17			100.00

Table 8
Performance comparison.

Comparison table	PID (default)	T-PID	TG-PID
(h, k) CCW	(−0.00635, −0.00273)	(−0.00096, 0.00081)	(−0.00180, −0.00038)
R_act CCW	5.99227	5.99463	6.00074
e_max CCW	0.08757	0.07394	0.06431
e_min CCW	−0.06323	−0.06632	−0.06913
REB CCW	0.15079	0.14025	0.13344
Tt(X) CCW	2.40625	2.21875	2.21875
Tt(Y) CCW	3.8125	2.21875	2.21875
ΔTt CCW	1.40625	0	0
(h, k) CW	(−0.00792, 0.00158)	(0.00104, 0.00235)	(−0.00246, −0.00383)
R_act CW	5.99322	5.99708	5.99498
e_max CW	0.11244	0.08000	0.07597
e_min CW	−0.07818	−0.06525	−0.06600
REB CW	0.19062	0.14524	0.14197
Tt(X) CW	2.390625	2.234375	2.25
Tt(Y) CW	2.421875	2.234375	2.25
ΔTt CW	0.03125	0	0
Comment(s)	Good	Better	Optimal

Notes: (h, k) is an actual center.
R_act is an actual radius of circle.
REB is roundness-error based on best-fit-circle-method.
ΔTt is a position time difference.

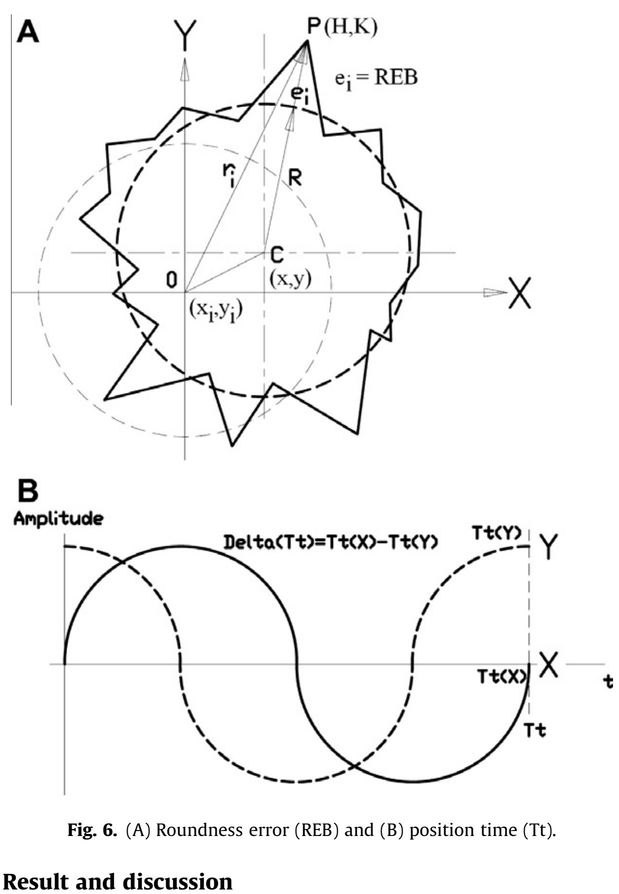

Fig. 6. (A) Roundness error (REB) and (B) position time (Tt).

7. Result and discussion

Firstly, it defines the following terms, REB is a roundness-error that is determined by best-fit-circle method; Tt is a position-time which is a time needed to back to zeros plotted on velocity response; ΔTt is a position-time difference; CCW is a direction in counter-clock-wise; CW is a direction in clock-wise. A detailed procedure to get a final result of a grey relational grade was started by leveling parameter with grey prediction method (Table 2). Therefore, it will use these levels to continue applying grey relational coefficient (Eq. (25)) and grey relational grade (Eq. (26)). Data pre-processing (Eq. (22)) is necessary to be performed firstly before both of them. Table 5 shows the results of the whole calculation of getting grey relational grade. Based on leveling value of experiment parameters in Table 2, it is found that thefourth experiment has a maximum of grey relational grade of 0.981, and sixth experiment has a minimum one 0.365. It means that the fourth experiment has closest optimum values, and vice versa for the sixth experiment. They are shown in Table 5.

Afterward, conducting all experiments should be the next task to be done. The results of those experiments will be analyzed by method of S/N ratio and completed by ANOVA (Tables 6 and 7). S/N ratio in will be resulting a differentiation of max and min value of each taken experimental parameter. The sequence of biggest to lowest 'max–min' should be the same to the sequence of P (%) in ANOVA. Based on S/N ratio values were followed by ANOVA (in Tables 6 and 7), that means a higher a difference of max–min S/N ratio, therefore, higher is the significance of that parameter. Also, a higher the P-percentage in ANOVA, means a higher the influence or effect to the performance of the system. The most significant factor of TPID method is proportional speed loop gain (KVP) then followed by KVI, KPP, SFG and PFG. Other two factors, PFF and ACL, have less significance were indicated by its values that less than 2%. It is different from TGPID with the sequence form that most is acceleration/deceleration (ACL) then followed by KVP, KVI, KPP, SFG and PFG. Another one factor, PFF, has less significance where indicated by its values that less than 2%. It indicated that PFF is less significance factor and ACL is the most significance in TGPID. The sequence of other parameters is the same, i.e. KVP, KVI, KPP, SFG and PFG. It shows that TPID, without grey (only Taguchi and PID), is the system independent to parameter of ACL, beside PFF. In TGPID (with grey), ACL becomes the key factor of system stability to minimize error.

Following are mathematical definitions of REB and Tt. REB (see Fig. 6A): given: (x_i, y_i) for $i = 1, \ldots, n$; best-fit-circle equation to be determined will be

$$r_i^2 = (x_i - H)^2 + (y_i - K)^2 \tag{38}$$

$$R^2 = (x - H)^2 + (y - K)^2 \tag{39}$$

$$\Rightarrow \text{ minimize } \sum e_i^2 \tag{40}$$

$$\Rightarrow \text{ minimize sum} = \sum \left(r_i^2 - R^2\right) \tag{41}$$

$$\Rightarrow \ e_i = \text{REB} = r_{i\_\max} - r_{i\_\min} \tag{42}$$

Tt and ΔTt (see Fig. 6B):

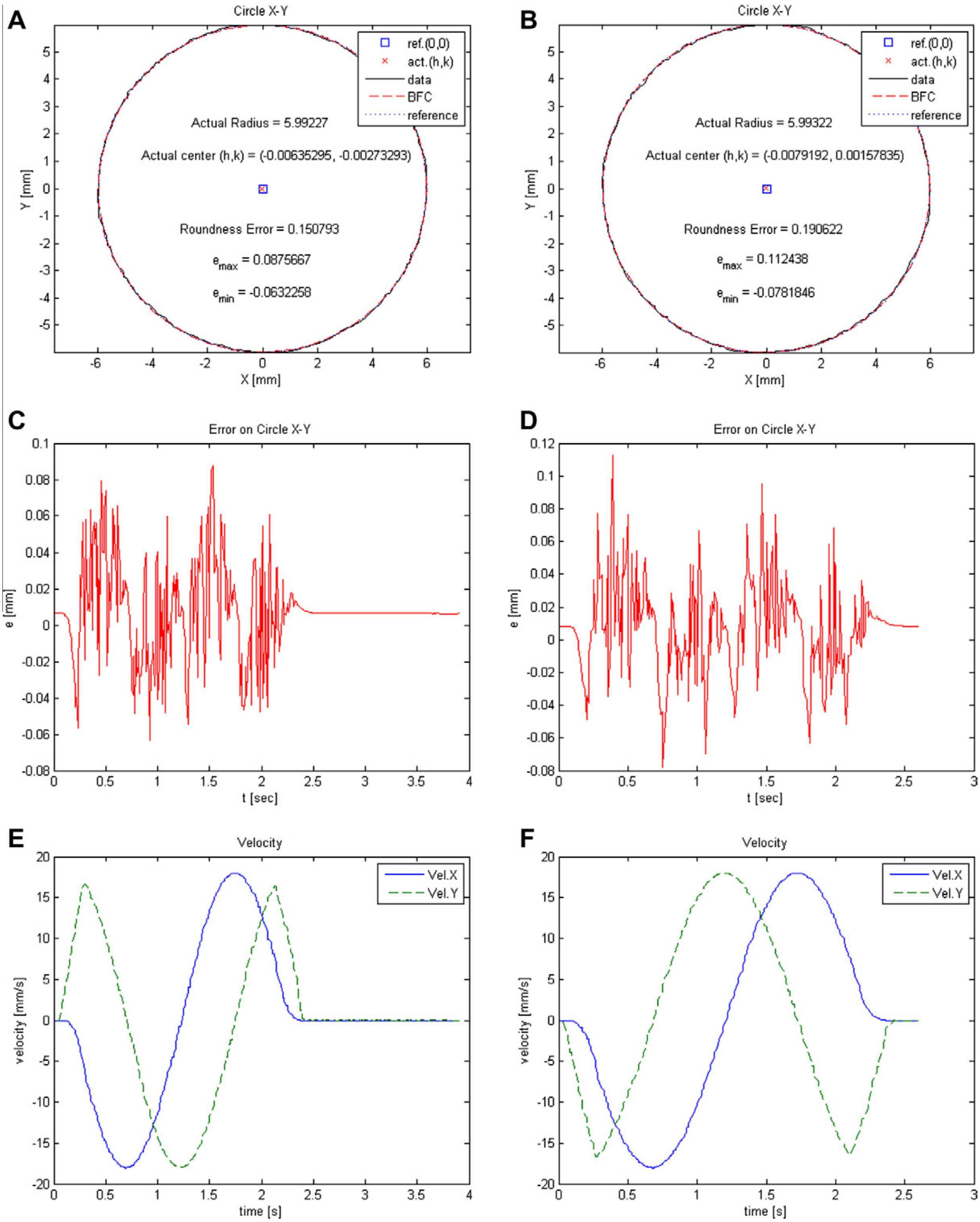

Fig. 7. Default responses.

$$\left.\begin{array}{l} x = \sin(t) \\ \dot{x} = \frac{dx}{dt} \\ \ddot{x} = \frac{d^2x}{dt^2} \end{array}\right\} \rightarrow t \cong \mathrm{Tt}(x) \tag{43}$$

$$\left.\begin{array}{l} y = \cos(t) \\ \dot{y} = \frac{dy}{dt} \\ \ddot{y} = \frac{d^2y}{dt^2} \end{array}\right\} \rightarrow t \cong \mathrm{Tt}(y) \tag{44}$$

$$\Delta\mathrm{Tt} = \mathrm{Tt}(x) - \mathrm{Tt}(y) \tag{45}$$

As mentioned in control philosophy, the error will supposedly go closed to zero as the time goes to infinity. In this work, REB and ΔTt will be the error parameters go closed to zero.

7.1. Roundness error based on best-fit-circle method (REB)

Roundness error is determined by best-fit-circle method of Eqs. (38)–(42). We can see in Table 8, comparison table of default, TPID

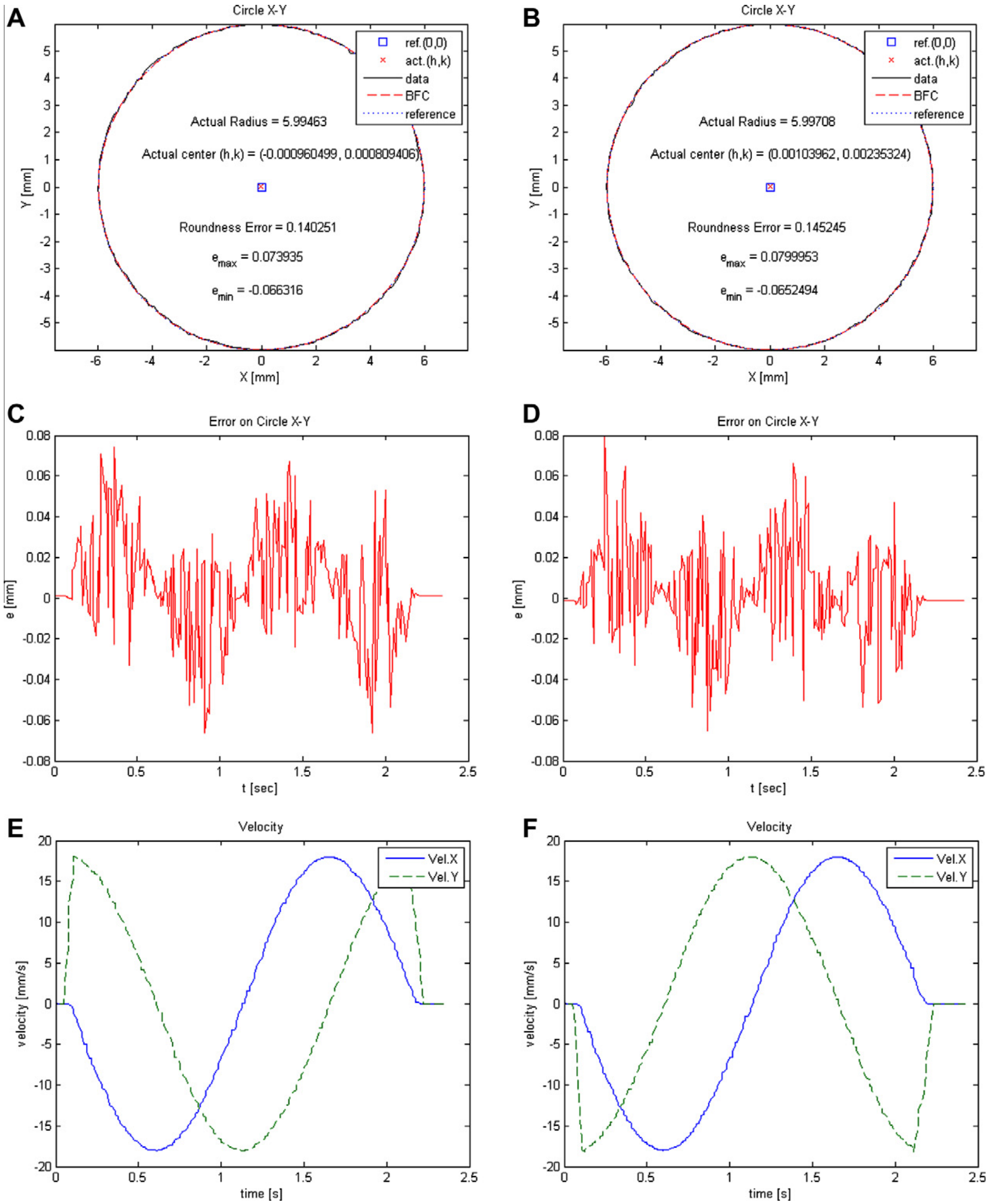

Fig. 8. T-PID responses.

and TGPID in different circular motion's direction, a roundness error will change to be less (quoted from Figs. 7–9). Firstly we obtain in CCW (counter clock wise) direction: an actual radius is 5.9 mm by default and TPID, while TGPID is 6.0 mm, i.e. equals to reference radius of 6 mm. A maximum roundness error among those three performances is 0.151 mm on the default-setting, minimum is on TGPID for 0.133 mm, while in-between TPID is 0.140 mm. In Fig. 7 is a default performance, Fig. 8 is a T-PID performance and Fig. 9 is a TG-PID performance which shows a roundness error reduction from 0.191 mm by default in CW which becomes 0.145 mm by TPID in CW, and 0.142 mm by TG-PID in CW. The actual radius by default CW is 5.99 mm, TPID 5.99 mm and TGPID 5.99 mm. It is shown that circle tracking error occurred is minimized, which means the performance is improved.

7.2. Position time difference (*ΔTt*)

A position time difference will be defined from Tt(*X*) subtracted by Tt(*Y*), Eqs. (43)–(45). It is a difference between them. Expectation is when ΔTt zero. From Table 8, it shows that Tt of TPID and

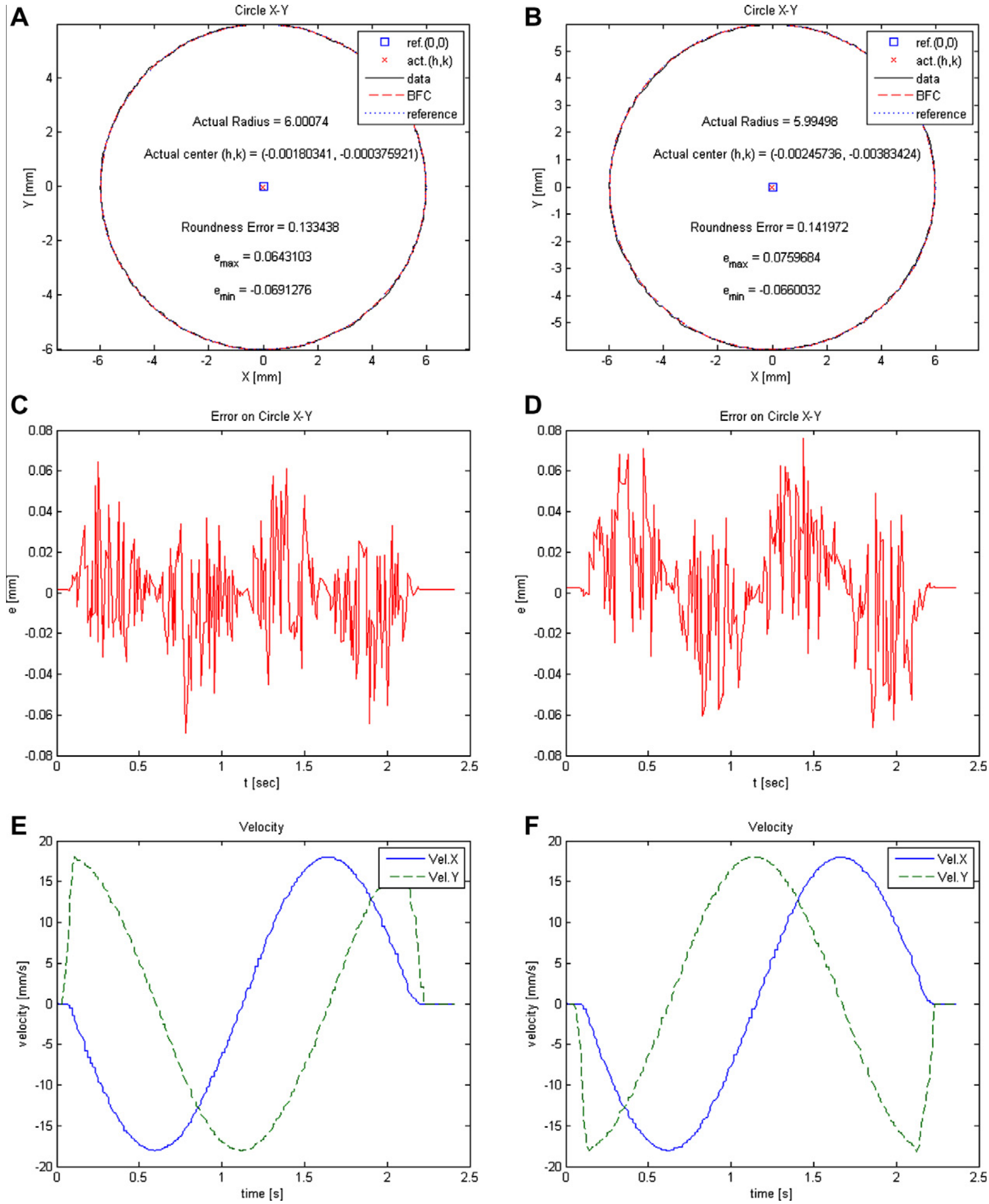

Fig. 9. TG-PID responses.

TGPID faster then default, also convinced by ΔTt of TPID and TGPID, the performance of TPID and TGPID have zero lag of time in both directions CW and CCW. ΔTt default CCW and CW are not zero, it indicated that *X*-axis and *Y*-axis did not move simultaneously.

8. Conclusion

The use of taken parameters using Taguchi method is a very efficient solution due to their simplicity to reduce number of experiments. Usage of grey prediction method for leveling the parameters is also useful instead of applying trial-and-error approach. The actual radius measured in difference performances shows its improvement and robustness of this approach. A reference radius is then reached, i.e. the error is closed to zero. The difference of position time also zero which means zero lag time between *X* and *Y*-axis in reaching a proper circular motion. In Tables 2–4, also following analyzed in Figs. 7–9, it is shown that circle tracking error occurred is minimized, which means the performance is improved. The less roundness error, then a closer is an actual radius to the desired radius. All improvements have been summarized in comparison table (Table 8) that indicates an improvement of a proposed method. The application of proposed method on real case (CNC machine) showed that this method is applicable. Among the scenarios of experimental discussed were that applying grey in TGPID brings an influence defining significance system's parameter rather than only TPID. The thing that distinguishes a proposed method of TGPID to other methods; it can overcome disadvantages of others. TGPID is, therefore, offering its simplicity, reliability and a robust optimization approach for local minima. The drawback of the system referred to the noise occurred, which shown in Figs. 7–9(C) and (D), is this desktop-scale CNC machine mounted improperly. The future work would focus on mounting and system identification so we can develop an expand controller algorithm.

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