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CONTROLLER PARAMETER OPTIMIZATION FOR AN ELECTRO-HYDRAULIC ACTUATOR SYSTEM BASED ON PARTICLE SWARM OPTIMIZATION TECHNIQUE

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Abstract

Motion control applications are widely applied in the industrial field with the assistance of electro-hydraulic actuator (EHA) system. EHA system is well known to be disclosed to the parameter variations, disturbances and uncertainties which are affected by the changes in the operating conditions such as friction, internal and external leakage. The complexity and nonlinear characteristic of the EHA system leads to a great challenge for controller development and system modelling. The performance of the utilized controller can be improved in order to achieve its best capability. In this paper, the basic knowledge in optimization of the proportional-integral-derivative (PID) controller through Gradient Descent (GD) and Particle Swarm Optimization (PSO) techniques are discussed. The PID parameters obtained through Ziegler-Nichols (ZN) tuning method has been optimized by using the GD method and is compared with PSO optimization technique via MATLAB/Simulink software. The findings show significant improvement in positioning tracking performance when the developed optimization technique is applied. Therefore, the issues degrading the EHA system performance have been reduced.

Keywords: Electro-hydraulic actuator system; gradient descent optimization; particle swarm optimization; PID controller; position tracking

1.0 INTRODUCTION

In recent years, various engineering works that are categorised as heavy and harmful work have been accomplished with the help of a number of engineering system applications such as electro-hydraulic actuator (EHA) system. Power sources in the EHA system, for instance, electric motor or engine drives generate the dynamics of hydraulic pump that deliver fluid under pressure. The fluid delivered through pressure is used to create the necessary movements in linear or rotary. The movement is the desired end function such as, lifting, pressing and clamping [1].

The advanced design of EHA system with versatile electronic and hydraulic components offers a great enhancement in an application's performance [2-3]. The integration of both electronic and hydraulic equipment that absorbs both advantages has been extensively used nowadays. Due to the ability to create a large force, torques, and high energy density, different applications such as fatigue testing system [4], aircrafts [5], automotive applications [6-7], hydraulic excavator [8], manufacturing machines [9-10], and sheet metal forming process [11] have established that the electro-hydraulic actuator system can be more crucial and well-known nowadays.

However, the dynamic features of the EHA system is known to be highly nonlinear and these existing nonlinearities and uncertainties yield to the constraint in the control of EHA system. Such characteristics, when appeared in the system, degrade its performance significantly. These disturbances simultaneously influence the position tracking accuracy and are commonly affected by the occurrences of leakage and friction in the system.

In order to overcome these issues, the utilized controller should be robust enough to overcome the entire operating range that is against such disturbances, uncertainties, and parameter variations. Due to the complexity of the EHA system and a great challenge to control it, a nonlinear and intelligent control approach should be designed in order to encounter these difficulties.

Various control strategies have been reported and proposed in the literature to overcome the difficulties in the control of EHA system. There is a raise in the number of works dealing with EHA system over the past decades which apply linear control, nonlinear control and intelligent control such as sliding mode control (SMC) [1][12], neural network (NN) [13], self-tuning Fuzzy PID [14-15], model reference adaptive control (MRAC) [16-17], and generalized predictive control (GPC) [18]. The nonlinear control strategy is found to be efficient and extensively applied to the nonlinear system.

In recent years, many studies related to the EHA system problems have been conducted to surmount these problems. One of the ways is to optimize the system controller performance. As the optimization technique becomes popular nowadays, it can be utilized to optimize various types of controller such as proportional-integral-derivative (PID) controller that is employed in this paper.

Optimization is described as the cognitive operation of searching for the solution that is the most useful among the solutions. This condition implies that an outcome of using optimization technique to the problem or design must yield a number of solutions that will define our problem [19]. It is well-known that an optimum response of the overall system performance is affected by various tuning methodologies in the tuning of controller for the system control loop. Many excellent optimization methods have been proposed in different systems, such as genetic algorithm (GA), particle swarm optimization (PSO), and ant colony optimization (ACO) method.

Recently, the PSO optimization technique which has been realized able to tune the PID controller efficiently, is implemented in various types of system such as vehicle steering system [20], pulley transmission system [21], waste-water treatment system [22], and electro-hydraulic actuator system [23]. With cost effective and efficient computational optimization methods, many complex engineering control issues have been improved and solved to achieve an optimal solution for a specific system [24].

This paper continues the work done in [25]. In order to obtain the optimal parameters of PID controller, three different approaches, which include Ziegler-Nichols (ZN) tuning method, Gradient Descent (GD) optimization technique, and Particle Swarm optimization (PSO) technique are utilized. An intensive computer simulation works is performed to evaluate the proposed technique.

The paper is organized as follow: Section 2 illustrates the mathematical modelling of the developed system. The process to develop the simulation studies are explained in Section 3. The results are discussed, compared, and presented in Section 4. Finally, conclusion and summary of the observation are drawn in Section 5.

2.0 EHA SYSTEM MODELLING

The EHA system configuration consists of servo valve, hydraulic actuator and computer control unit, as depicted in Figure 1. Servo valve that is connected to the hydraulic cylinder through the pipeline formed the dynamic equation of the EHA system. The oil flow in the cylinder chamber will be regulated by the servo valve and generating cylinder actuator displacement. The counter force against the cylinder actuator is generated from the spring and damper that is attached to the mass.

To produce a mechanical motion of the spool valve, electrical current is supplied to the coil that is connected to the servo valve. The torque of the motor that receives the power source will drive the servo spool valve to the desired position.

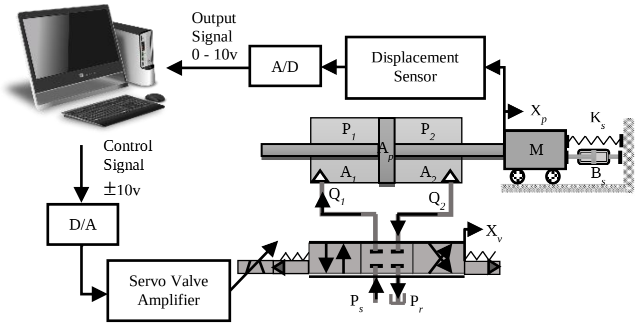

Figure 1 The EHA system configuration

The torque motor electrical signal is given as in Equation (1), [26].

$$V = \frac{dI}{dt}L_c + R_c I \tag{1}$$

where R_c and L_c are the coil resistance and inductance respectively.

The dynamics of the servo valve are represented by a second order differential equation that related to electric current drive from the torque motor as expressed in (2).

$$\frac{d^2x_v}{dt^2} + 2\xi\omega_n\frac{dx_v}{dt} + \omega_n^2 = I\omega_n^2 \tag{2}$$

where ξ is the ratio of the damping, while the natural frequency of servo valve is represented by ω_n.

In the mechanical design of each port in the servo valve, the spool valve is un-exposed to the dead-zone and flow leakages problems. Critical centred on the spool valve is considered. The flow Q in each of the chambers controlled by servo valve can be modelled from the equations related to the orifice of spool valve displacement x_v and pressure difference P_v. The ideal orifice equation is written in (3).

$$Q = Kx_v\sqrt{\Delta P_v} \tag{3}$$

The flow relations that neglect the internal leakages in servo valve for each chamber are given in (4) and (5).

$$Q_1 = \begin{cases} K_1 x_v \sqrt{P_s - P_1} & ;x_v \geq 0, \\ K_1 x_v \sqrt{P_1 - P_r} & ;x_v < 0, \end{cases} \tag{4}$$

$$Q_2 = \begin{cases} -K_2 x_v \sqrt{P_2 - P_r} & ;x_v \geq 0, \\ -K_2 x_v \sqrt{P_s - P_2} & ;x_v < 0, \end{cases} \tag{5}$$

The hydraulic actuator volumes for each chamber are modelled in (6) and (7).

$$V_2 = V_{line} + A_p(x_s - x_p) \tag{6}$$

$$V_1 = V_{line} + A_p(x_s + x_p) \tag{7}$$

where V_{line} is the volume between hydraulic cylinder and pipeline.

Pressure for each chamber can be obtained by defining the relationship between bulk modulus, volume, and flow rate as expressed in (8) and (9).

$$P_1 = \frac{\beta}{V_{line} + A_p(x_s + x_p)} \int (Q_1 - q_{12} - q_1 - \frac{dV_1}{dt})dt \tag{8}$$

$$P_2 = \frac{\beta}{V_{line} + A_p(x_s - x_p)} \int (\frac{dV_2}{dt} - Q_2 - q_{21} - q_2)dt \tag{9}$$

Through the overall dynamics equation of moving mass, damper, and spring, the total force produced from hydraulic actuator can be obtained in (10).

$$F_p = A_p(P_1 - P_2) = M_p \frac{d^2 x_p}{dt^2} + B_s \frac{dx_p}{dt} + K_s x_p + F_f \tag{10}$$

In a simulation study, the parameters used in a nonlinear model of EHA system are tabulated in Table 1.

Table 1 EHS system parameters [26]

Symbol	Description	Value
R_c	Servo-valve coil resistance	100 Ω
L_c	Servo-valve coil inductance	0.59 H
I_{sat}	Torque motor saturation current	0.02 A
ξ	Servo-valve damping ratio	0.48
ω_n	Servo-valve natural frequency	543 rad/s
K	Servo-valve gain	$2.38\text{x}10^{-5}$ $m^{5/2}/kg^{1/2}$
β	Hydraulic fluid bulk modulus	$1.4\text{x}10^{9}$ N/m^2
P_s	Pump pressure	$2.1\text{x}10^{7}$ Pa
P_r	Return pressure	0 Pa
K_s	Spring stiffness	10 Nm
X_s	Total actuator displacement	0.1 m
A_p	Piston area	$645\text{x}10^{-6}$ m^2
M_p	Total mass	9 kg
B_s	Damping coefficient	2000 Ns/m

3.0 METHODOLOGY

Basically, the idea of conducting this study is illustrated in the block diagram of Figure 2. The parameters tabulated in Table 1 will be applied to the equations in the modelling Section to form an EHA system. Disturbances and uncertainties such as friction and leakage in the EHA system is not considered.

PID controller is then connected to the models to control the displacement of the cylinder actuator according to the desired reference input. The parameter values for K_p, K_i, and K_d are first obtained through the ZN tuning method. This is followed by the GD optimization technique that takes the values of ZN parameters as the initial value. The obtained optimal result is then compared with the PSO optimization technique.

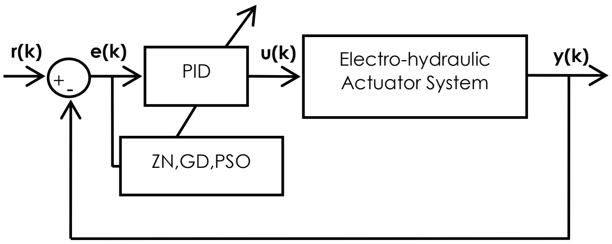

Figure 2 The block diagram of EHA system

3.1 Ziegler-Nichols (ZN) PID Tuning Method

PID controller is commonly enveloped with three important controller terms provided treatment of transient as well as steady state responses. The transfer function of the PID controller is usually expressed in (11).

$$C_s(s) = K_p + \frac{K_i}{s} + K_d s = K_p(1 + \frac{1}{\tau_i s} + T_d s) \tag{11}$$

where, K_p is the proportional gain, K_i is an the integral gain and the derivative gain is described as K_d. The proportional terms provide rapid control to the transient response proportional to the possible steady state error signal while the integral terms reduce or eliminate steady state errors through the low frequency compensation. The derivative terms improve transient response through high frequency compensation [27].

The controller gains are then obtained by applying the ultimate gains value and corresponding sustained oscillations period to the formula as tabulated in Table 2.

Table 2 PID controller formula [28]

PID Type	K_p	T_i	T_d
P	$0.5\ K_U$	Inf	0
PI	$0.45\ K_U$	$T_U/1.2$	0
PID	$0.6\ K_U$	$T_U/2$	$T_U/8$

The obtained ZN parameter will then be utilized as an initial value for the GD Optimization toolbox to generate an optimal PID controller parameters.

3.2 Gradient Descent (GD) Optimization Technique

The method of steepest descent, GD is an algorithm applied to obtain a minimum point for the particular function. Conversely, gradient ascent is an algorithm that is used to find a maximum point nearest to the current result. In any starting point of the function, GD algorithm shifts the solution to the negative direction of the gradient to reach a minimum point as indicated in Figure 3. The function value will be diminished at the fastest rate when running along the slope direction. The negative sign of the gradient vector indicates the direction of the steepest descent. Hence, the GD method is expected to arrive at the minimum point faster than other non-gradient based optimization methods [29]. The iteration process is repeated according to Equation (12):

$$X_{i+1} = X_i - \lambda_i \nabla f(X_i) = X_i - \lambda_i g(X_i) \tag{12}$$

where λ denotes the step size, and gradient operator ∇ of the function $f(X)$. While $g(X_i)$ is the gradient at the current point.

By moving to the point where function f takes on a minimum value, the directional derivative is given as:

$$\frac{d}{d\lambda_i} f(X_{i+1}) = \nabla f(X_{i+1})^T . \frac{d}{d\lambda_i} X_{i+1} = -\nabla f(X_{i+1})^T g(X_i) \tag{13}$$

Let Equation (14) equals to zero, and by applying step size λ to the function $\nabla f(X_{i+1})$ and $g(X_i)$, the directional derivative of the function will be obtained in orthogonal form or in a zigzag pattern as illustrated in Figure 3.

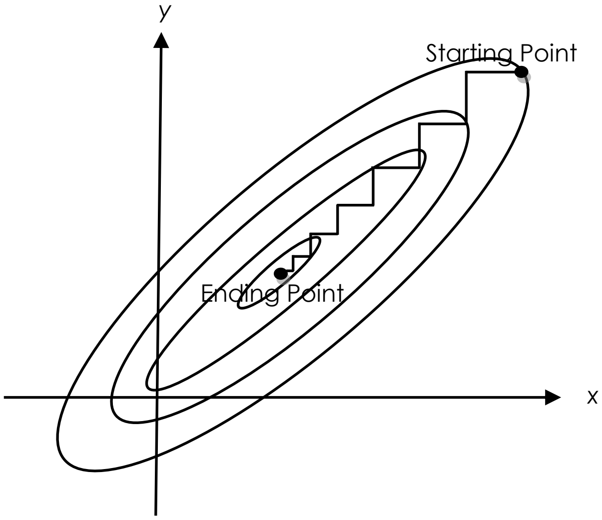

Figure 3 The direction to reaching local minimum

$\lambda>0$ is a minor value that leads a small step to the function. An appropriate value for λ is very significant. A smaller value could increase convergence time and a higher value may lead to divergence. The appropriate value of λ that yields to stable condition is:

$$f(X_{i+1}) \leq f(X_i) \tag{14}$$

Alternatively, the algorithm can be started by choosing a fix value for step size λ. The step size λ will need to be regulated if necessary to make sure that the function decreases at each iteration [30].

The proposed controller parameter will be transformed until the stopping criteria is met. These criteria include the variation of the parameters, the variation of the gradient, the function reached lower bound, the Euclidean norm of the gradient and the fixed maximum for the number of iterations [31]. The best controller parameters are expected to be achieved when all the criteria of GD is fulfilled.

3.3 Particle Swarm Optimization (PSO) Technique

Particle swarm optimization (PSO) was first introduced by Kennedy and Eberhart in 1995 as an evolutionary algorithm. PSO was inspired by swarming behaviours perceived in a swarm of bees, a flock of birds, or a school of fish [32]. PSO is a popular optimization algorithm since it is applicable to various types of application which is a population based optimization tool. By solving the continuous nonlinear problems, this method is found to be outperformed by simulating the simplified social system [33].

In the development of PSO technique, the XY coordinates within a two dimensional search space will be crossed by each particle or in other words, known as an agent. The new position of each particle will be realized by the current velocity and position information [34]. The XY position and best value obtained will be saved by each particle. The saved data are then compared to the personal experience information of each particle and a personal best value is formed. Among the personal best value saved in each iteration, global best value will be concluded. Information such as the distance between the current position of each agent and its personal best position, the distance between the current position of each agent and its global best position, and the current velocity of each particle will be used to moving forward to their new position [33].

Each particle changes its position according to (15) and (16) respectively [34].

$$v_i^{k+1} = wv_i^k + c_1 rand_i x\left(pbest_i - s_i^k\right) + c_2 rand_i x\left(gbest_i - s_i^k\right) \tag{15}$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{16}$$

where, w is the inertia weighting coefficient, v_i^k denotes the current velocity for agent i at iteration k, v_i^{k+1} is a new velocity for agent i at iteration $k+1$, c_1 is an acceleration for cognitive or the particle itself, c_2 represents an acceleration for social or the entire swarm, $rand_i$ denotes a random value between 0 and 1 for current iteration, *pbest* represent personal best value for agent i, *gbest* is a global best value for agent i, s_i^k indicates a current position of agent i at iteration k, and s_i^{k+1} represent the position of agent i at the iteration $k+1$.

For PSO optimization technique, the inertia weight is a crucial factor that controls the impact of each particle in the previous velocity. A small inertia weight favours exploitation while the large inertia weight controls the impact of each particle in the previous velocity. The researcher in [35] stated that inertia weight decrease over time. The inertia weight decrease over time minify the searching area to induce a shift from an exploratory to an exploitative mode [36]. In order to control the convergence of the swarm, the inertia weight function proposed by [35] is expressed as (17).

$$w = \left(w_{max} - \frac{w_{max} - w_{min}}{iter_{max}}\right) x\left(iter\right) \tag{17}$$

where, w denotes the inertia weight, w_{max} is the initial weight coefficient, w_{min} represents the final weight coefficient, $iter_{max}$ is the number of iterations, and *iter* represents the current iteration.

Simply to say that, the PSO process was done in the alteration of searching point according to the concept as illustrated in Figure 4. The s^k and s^{k+1} is the current and future searching point, v^k and v^{k+1} denote the current and future velocities, while v_{pbest} and v_{gbest} are the velocities based on personal best and global best respectively.

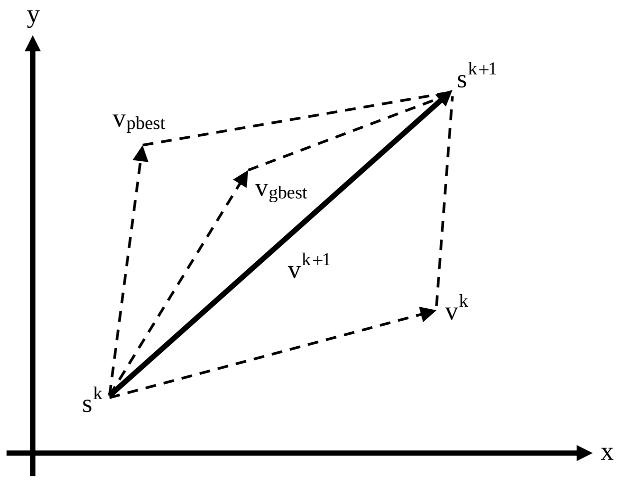

Figure 4 The concept of searching point alteration for PSO technique

In this paper, the implementation of PSO uses the following parameters, the number of particles is 100, the number of maximum iterations is 20, the dimension of the problem is 3, the speed of convergence or known as the inertia weighting coefficient is set to 0.9, the acceleration coefficient of c_1 and c_2 are set to 0.3 and 1.3 respectively.

Figure 5 illustrates the general process of flowchart for the PSO technique. The sequence of the process is described as follows. First, the generation of initial conditions for searching point, the condition of each particle, and the velocities v_i^0 generated randomly within the specified range. A current best searching point for each particle is set to *pbest*. While the best evaluated parameter of *pbest* will be set to *gbest* and the stored parameter will be the particle number with the best parameter as in Step 1.

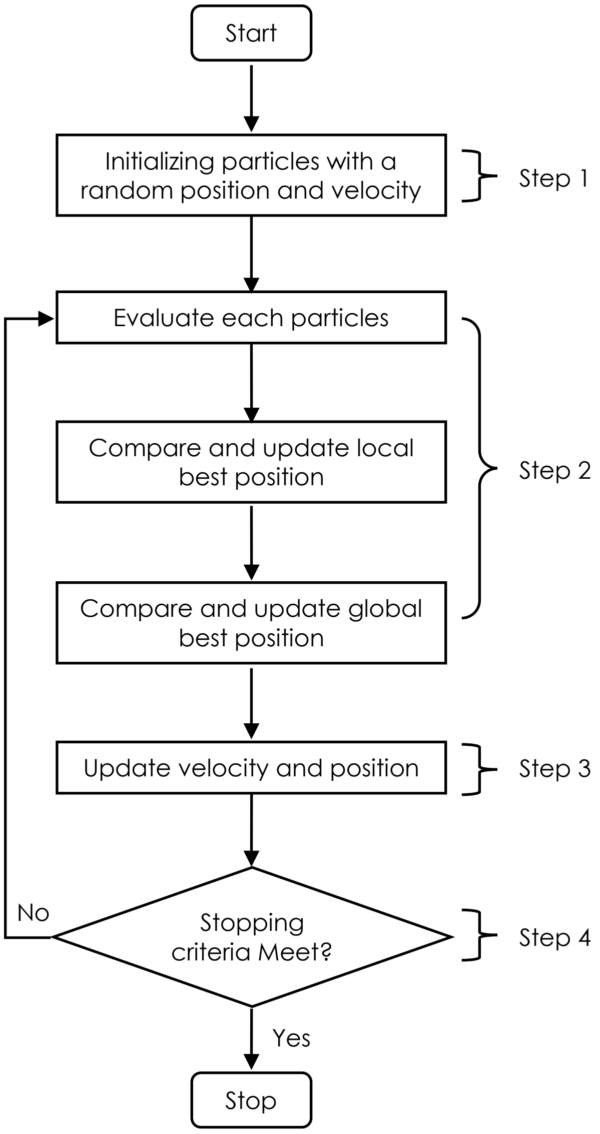

Figure 5 Flowchart of PSO technique

The searching point is where each particle will be processed by the objective function. If the parameter evaluated is better than the current particle *pbest* value taken from the previous result, then the best value will be replaced by the current particle value. After the process of determination on *pbest* value, *pbest* will be compared with the *gbest* value as illustrated in Step 2. The best value will be substituted into the current best and stored with the number of particles together with its parameter and conversely.

In Step 3, the current searching point for each particle is changed according to (15) and (16). Modification of each particle will be repeated alone until the stopping criteria is met.

Termination process will be checked according to the achievement of the initial conditions in Step 4. The process will be repeated to Step number 2 when the termination criteria is not met or otherwise the execution is ended.

4.0 RESULTS AND DISCUSSION

Simulation work has been done by using MATLAB/Simulink 2013a software. The PID controller parameter is first tuned by using ZN tuning method which is later improved in order to obtain a much better controller parameter. Referring to the output result for step input reference signal as illustrated in Figure 6, throughout the ZN tuning procedure, the parameters that are fed into the EHA system yield the output waveform as depicted by the pink line. Obviously, the signal has been overshoot before reaching steady state condition. This is an unwanted phenomena in the control system that could be very harmful if applied to real applications. Hence, the controller with no overshoot or a minimum overshoot with fast settling time is a target for every type of controller. By utilizing optimization technique based GD method in the controller, the overshoot of the PID controller has been eliminated as illustrated in the waveform of cyan line.

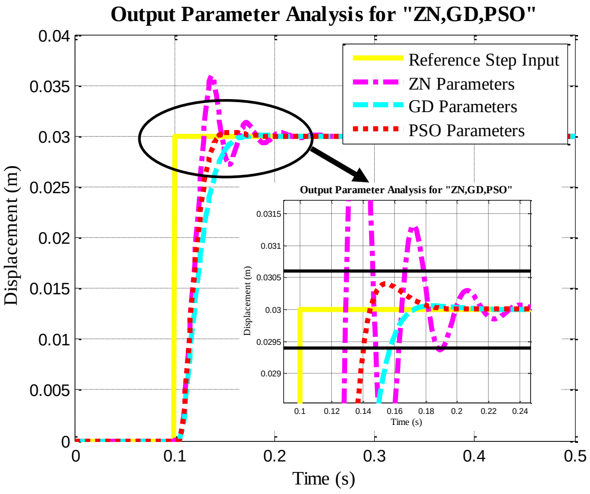

Figure 6 The output of step input reference signal

However, compared to the PSO optimization technique that yields to the red output waveform, it is obvious that the PSO technique have a faster settling time as compared to the ZN and GD methods. Although the PSO optimization technique seems to produce a little overshoot when reaching the reference signal, the overall performance produced by PSO is better than ZN and GD techniques as illustrated in Table 3.

The transient response analysis in terms of settling time, percentages of overshoot, and steady-state error for these three methods are tabulated as below:

Table 3 Transient response analysis for step input reference signal

Technique	Transient Response Analysis		
	Settling Time (s)	**Overshoot (%)**	**Steady-state error**
ZN	0.1910	19.67	0
GD	0.1471	1.00	0
PSO	0.1405	1.33	0

Through these three methods, the PID controller optimal parameter for the step input reference signal is tabulated in Table 4 below:

Table 4 The PID controller optimal parameter obtained through Ziegler-Nichols, Gradient Descent, and Particle Swarm Optimization technique

Technique	PID Controller Parameters (Step Ref. Signal)		
	K_p	K_i	K_d
ZN	1020	0.0150	0.0038
GD	249.9794	0.0142	0.0035
PSO	351.9716	7.3992	0.5068

The sinusoidal input reference signal has been applied to the system as depicted in Figure 7. As shown in the zoomed area in Figure 7, PSO output provides a much closer result to the reference signal compared to the ZN and GD outputs.

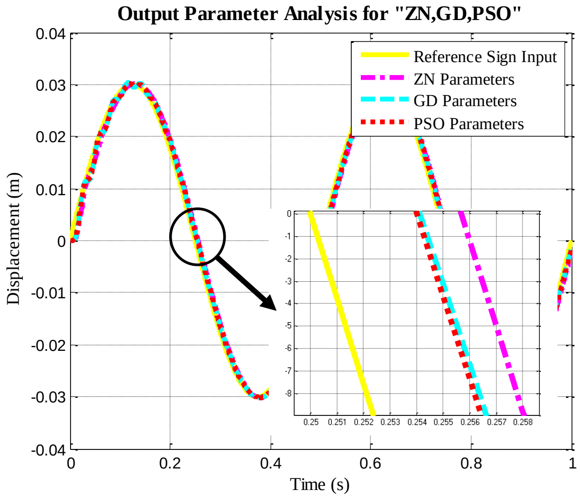

Figure 7 The output of sinusoidal input reference signal

To provide a clearer view to the gap between ZN, GD and PSO output, Table 5 provides a Root Mean Square Error (RMSE) analysis of ZN, GD and PSO to the reference signal. The result of GD indicates significant improvement which is 28.26%, while PSO has been improved to 34.63% compared to the ZN tuning method.

Table 5 RMSE for sinusoidal input reference signal

Technique	Root Mean Square Error
ZN	0.0015
GD	0.0011
PSO	0.0010

The PID controller's optimal value for sinusoidal input reference signal obtained through these three methods is tabulated in Table 6 below:

Table 6 PID controller optimal value for Ziegler-Nichols, Gradient Descent, and Particle Swarm Optimization technique

Technique	PID Controller Parameters (Sign Ref. Signal)		
	K_p	K_i	K_d
ZN	1020	0.0150	0.0038
GD	1487.6219	0.0037	0.0003
PSO	1571.4211	1.5832	4.0623

5.0 CONCLUSION

In this paper, the mathematical modelling of EHA system has been derived and implemented in the simulation study, followed by the controller tuning process which is the ZN tuning technique on PID controller. Then, the performances of PID controller is evaluated by considering the ZN, GD and PSO tuning technique that has been applied to the PID controller. Simulation result shows that the PSO optimization technique generates a significant improvement to the controller, and produces more precise trajectory tracking performance compared to GD optimization technique and conventional ZN tuning technique.

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