Position Tracking Optimization for an Electro-hydraulic Actuator System

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***Abstract*—Electro-hydraulic actuator (EHA) system has received a positive admission and widely utilized in the industrial field for the process such as lifting, clamping and pressing. It is well known that the EHA system is exposed to the disturbances, uncertainties, and parameter variations which are caused by various factors for instance the changes in load or total moving mass, supply pressure, friction and leakage coefficient. These problems consequently pose to a great challenge in EHA system modelling and controller development in order to achieve a good performance in the system positioning control. In this paper, a comparative study in different trajectories that represents the desired positioning which are multi-step and multi-sine reference signal is applied to the system in order to access the capability of the proportional-integral-derivative (PID) controller that is tuned by using the Ziegler-Nichols (ZN) and Particle Swarm Optimization (PSO) tuning methods. The finding shows that the PID controller variables obtained through the PSO tuning method performs better than the conventional ZN tuning method. From the simulation study, it can be concluded that the PSO technique was able to obtain a better PID controller parameter and provides a much satisfying positioning tracking capability.**

***Index Terms*—Electro-Hydraulic Actuator System; Particle Swarm Optimization; PID Controller; Positioning Tracking.**

I. INTRODUCTION

In recent years, various engineering works that are categorised as a heavy and harmful work has been accomplished with a number of engineering system application such as electro-hydraulic actuator (EHA) system. The advanced design of EHA system with the versatile electronic and hydraulic components offers a great enhancement in an application's performance [1]. The integration of both electronic and hydraulic equipment that absorbed both advantages have 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 [2], aircrafts [3], automotive applications [4-6], hydraulic excavator [7], manufacturing machines [8-10], and sheet metal forming process [11] 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 the existing nonlinearities and uncertainties yield to the constraint in the control of EHA system. Such characteristics appeared in the system degrade its performance significantly. These disturbances simultaneously influence the position tracking accuracy and commonly affected by the occurrences of leakage and friction in the system.

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

Many studies related to the EHA system problems have been conducted to figure out a right direction to surmount these problems. One of the ways is, optimizes 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 employed in this paper [12].

Optimization is described as the cognitive operation of searching for the solution that is more useful among the solutions. This condition implies that an outcome of using optimization technique to the problem or design must yield a numbers of solution that will define our problem [13].

This paper continues the work done in [14]. In order to obtain the optimal parameters of PID controller, two tuning approaches which are Ziegler-Nichols (ZN) tuning method, and Particle Swarm optimization (PSO) technique will be applied. An intensive computer simulation works will be performed to evaluate the proposed techniques.

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

II. EHA SYSTEM MODELLING

The EHA system configuration consists of servo valve, hydraulic actuator and the 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 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 cylinder actuator generated from the spring and damper that attaches to the mass.

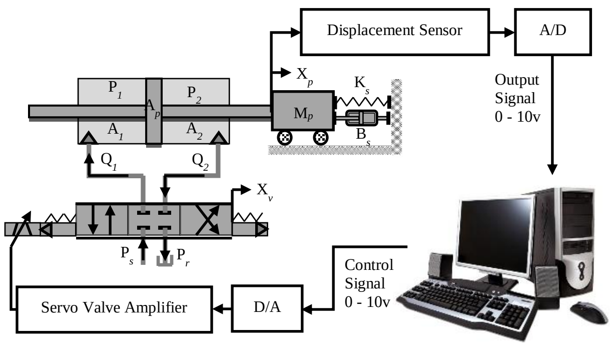

Figure 1: Configuration of the EHA system

To produce a mechanical motion of the spool valve, the electrical current is supplied to the coil that connected to the servo valve. The torque motor that received the power source will drive the servo spool valve to the desired position. The torque motor electrical signal is given as in Equation (1), [15]

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

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 an electric current drive from the torque of the motor as expressed in Equation (2).

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

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

In the mechanical design of each port in 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 relates to the orifice of spool valve displacement x_v and pressure difference P_v. The ideal orifice equation is written in Equation (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 Equation (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 Equation (6) and (7).

$$V_1 = V_{line} + A_p(x_s + x_p) \tag{6}$$

$$V_2 = V_{line} + A_p(x_s - x_p) \tag{7}$$

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 Equation (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 Equation (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 have been tabulated in Table 1.

Table 1
Parameters applied to the system [16]

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	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/m2
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

III. Implementation of PSO Algorithm to the PID Controller

In this study, the idea was conducted as illustrated in the block diagram of Figure 2. Parameter that is tabulated in Table 1 will be applied to the equation in the modelling Section and formed an EHA system. Disturbances and uncertainties such as friction and leakage in the EHA system is not considered.

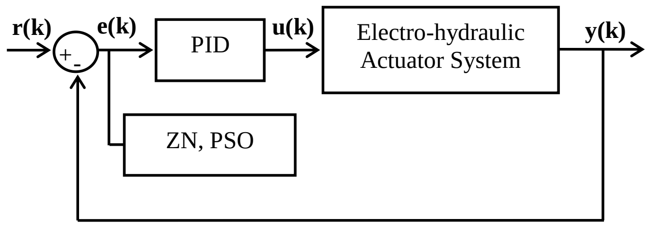

Figure 2: Block-diagram for the concept of the proposed tuning method

A. The overview and concept of PSO technique

In the early of 1995, Kennedy and Eberhart discovered an evolutionary algorithm which is Particle swarm optimization (PSO). The inspiration of this idea was coming from the swarming behaviour in a swarm of bees, a flock of birds, or a school of fish [17]. 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 [18].

In the development of PSO technique, the XY coordinates within a two dimensional search space will be cross by each particle or other word know as an agent. The new position of each particle will be realized by the current velocity and position information [19]. The XY position and the best value obtained will be saved by each particle. The saved data are then compared to the personal experience information of each particle and formed a personal best value. Among the personal best value saved in each iteration, global best value will be concluded. The 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 [18].

Each particle changes their position according to Equation (11) and (12) respectively [19].

$$v_i^{k+1} = wv_i^k + c_1 rand_i x(pbest_i - s_i^k) + \cdots + c_2 rand_i x(gbest_i - s_i^k) \tag{11}$$

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{12}$$

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 represent 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, 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 [20] implement the inertia weight decreased over time. The inertia weight decreased over time minify the seaching area to induce a shift from an exploratory to an exploitative mode [21]. In order to control the convergence of the swarm, the inertia weight function proposed by [20] was expressed as Equation (13).

$$w = \left(w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \right) \times \left(iter \right) \tag{13}$$

where, w denotes the inertia weight, w_{max} is the initial weight coefficient, w_{min} represent the final weight coefficient, $iter_{max}$ is the number of iterations, and *iter* represent 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 3. The s^k and s^{k+1} is the current and future searching point, v^k and v^{k+1} denotes the current and future velocity, while the v_{pbest} and v_{gbest} is the velocity based upon personal best and global best respectively.

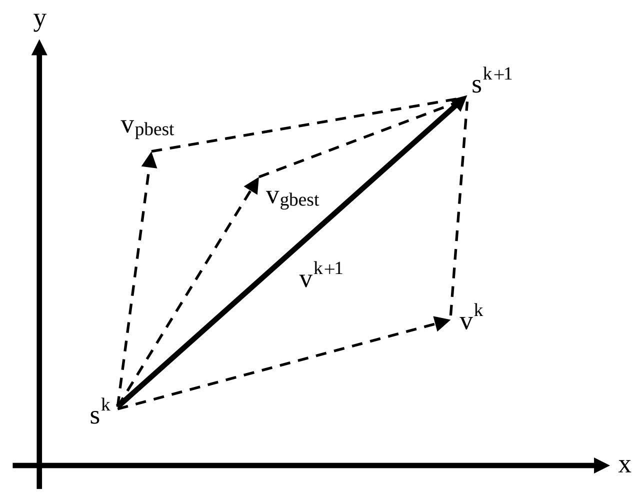

Figure 3: The concept of searching point alteration for PSO technique

In this paper, the implementation of PSO is using the following parameters included, the number of particles is 30, 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 is set to 0.4 and 1.4 respectively.

Figure 4 illustrates the general process of flowchart for the PSO technique. Sequence of the process 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 the process in Step 1.

Followed by the assessment on searching point of each particle. Each particle will be processed through 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 Equation (11), (12) and (13). Modification of each particle will be repeated 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.

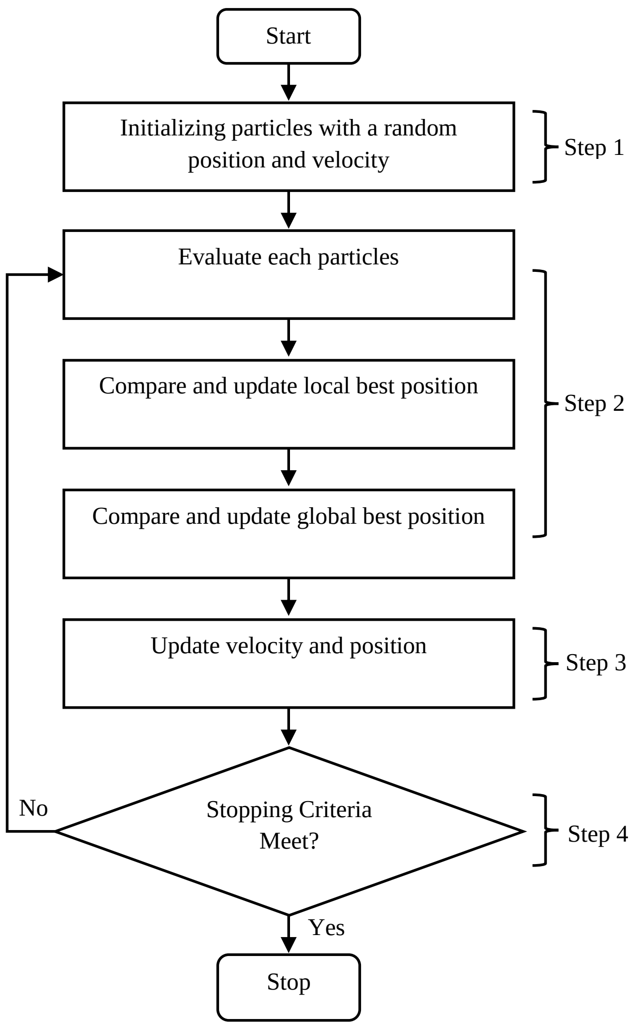

Figure 4: The execution process of PSO algorithm

IV. RESULTS AND DISCUSSION

In order to evaluate the performance of the variables obtained through the proposed tuning method, two different reference signal has been fed to the EHA system which are multi-step and multi-sine input reference signal. The simulation work has been done by using MATLAB/Simulink 2013a software. The PID controller variables were first tuned by using the conventional ZN tuning method. Referring to the multi-step output result as illustrated in Figure 5, through the conventional ZN tuning procedure, the parameter that fed into the EHA system yield the output waveform as depicted in pink dotted line. Obviously, the signal has been overshoot before reaching steady state condition. This is an unwanted phenomenon in the control system that could be very harmful if applied to the real applications. For instance, an inaccurate positioning control could cause a damage in the development of the product. Hence, the controller with no overshoot or a minimum overshoot with fast settling time is a target for every type of controller. By utilizing PSO optimization technique, a set of K_p, K_i and K_d parameters for the PID controller has been obtained where the overshoot and settling time has been reduced as illustrated in dark blue dotted line depicted in Figure 5.

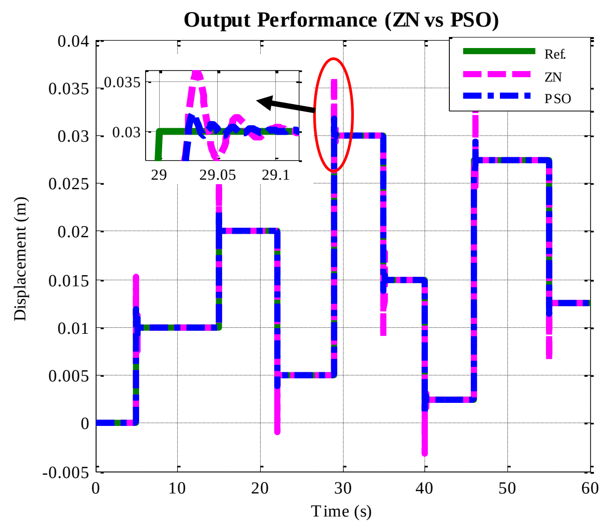

Figure 5: The output response for the multi-step input reference signal

To provide a clearer view for the gap between the ZN and PSO output result, Table 2 below provided the Root Mean Square Error (RMSE) analysis of ZN and PSO to the reference signal. The result of PSO indicated the improvement of 4.55% as compared to the ZN tuning method.

Table 2
RMSE for the multi-step input reference signal

Technique	Root Mean Square Error (Multi-Step)
ZN	0.000704
PSO	0.000672

The multiple sinusoidal input reference signal has been applied to the system as depicted in Figure 6. As shown in the zoomed in Figure 6, PSO output (dark blue dotted line) had provides much closer result to the reference signal as compared to the ZN output (pink dotted line). The Root Mean Square Error (RMSE) analysis for the ZN and PSO to the reference signal was indicated in Table 3. Simulation result of the PSO tuning method indicated the improvement of 4.88% as compared to the ZN tuning method.

Since the controller variables was influenced the transient response of the system for instance the rise time, settling time, overshoot and the steady state error, appropriate variable must be obtained for the particular controller. In this study, a comparative PID controller variable obtained through ZN and

PSO tuning methods for the multi-step and multi-sine input reference signal was tabulated in Table 4.

Table 3
RMSE for the multi-sinusoidal input reference signal

Technique	Root Mean Square Error (Multi-Sine)
ZN	0.000041
PSO	0.000039

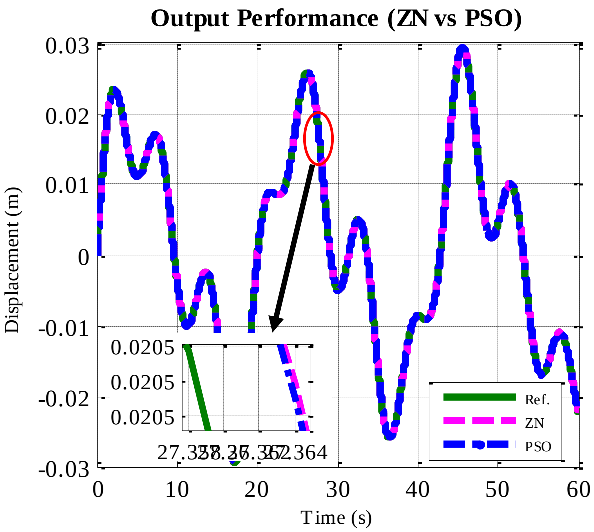

Figure 6: The output response for the multi-sine input reference signal

Table 4
Obtained PID variables for the ZN and PSO tuning methods

Technique	PID Controller Parameters		
	K_p	K_i	K_d
ZN	1020	0.0150	0.0038
PSO	1064.6476	1.9668	3.5906

V. Conclusion

In this paper, the mathematical modelling of the EHA system has been derived and implemented in the simulation study. Two different tuning methods which are Ziegler-Nichols (ZN) and Particle Swarm Optimization (PSO) has been applied to the PID controller and evaluated its positioning tracking capability by insert a multiple step and sinusoidal input reference signal to the EHA system. A comparative results showed that the variables obtained through PSO tuning method improved 4.55% for the multiple-step and 4.88% for the multiple-sine reference signal compared to the conventional ZN tuning method. The PID variables obtained through PSO tuning method were capable to track the position much more accurate compared to the ZN method. In future work, the PSO tuning method that will optimize the controller variables recursively will be continued to produce an adaptive tuning method based on PSO algorithm.

Acknowledgment

The authors would like to thank to the Universiti Teknikal Malaysia Melaka (UTeM) and Ministry of Education (MOE) for their support. The research was funded by Short Term Grant No. (PJP/2015/FKE(8C)/S01440) and Fundamental Research Grant Scheme (FRGS) Grant No. FRGS/1/2014/TK03/FKE/02/F00214.

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