Sensors & Transducers, Vol. 160, Issue 12, December 2013, pp. 590-601

www.sensorsportal.com

Sensors & Transducers

© 2013 by IFSA

http://www.sensorsportal.com

The Position Control of the Hydraulic Cylinder Controlled by the High-Speed On-off Valve

Zhi-Hao LIU, Qin-He GAO, Hai-Long NIU
Xi'an Research Institution of High Technology,
Xi'an, People's Republic of China
Tel.: +86-15102951659
E-mail: liuzhihaoainana@126.com

Received: 22 September 2013 /Accepted: 22 November 2013 /Published: 30 December 2013

Abstract: This paper aims to research the position control of the hydraulic cylinder controlled by the high-speed on-off valve to realize the precise position control. A compound algorithm of proportional integral & speed feedforward- displacement feedback is put forward based on the research on the relationship between the duty ratio and the past flow for the high speed on-off valve. The speed feedforward-displacement feedback algorithm can solve the hysteresis resulting from the feedback control and be considered as the certain duty ratio is given ahead, and the proportional integral control algorithm is designed and utilized to deal with the position error by adjusting to the duty ratio of high speed on-off valve. The genetic algorithm is used to tune the control parameters, including speed forward coefficient, proportional and integral coefficient of displacement feedback, output coefficient to gain the optimization result, on terms of the performance of the position control system. The mathematics modeling is analyzed and simulated with MATLAB/Simulink using the bulk-cavity-node method, and the hydraulic loop is established to verify the simulation result with the optimized results on the FESTO platform. The research finds that the proposed position scheme is effective to increase the position precision, and the position control parameters optimized by genetic algorithm can decrease the position error more. *Copyright © 2013 IFSA.*

Keywords: Position control, Speed feedforward-displacement feedback algorithm, High-speed on-off valve, Genetic algorithm; PI control.

1. Introduction

High-speed on-off valve (HSV) is a new kind of electro-hydraulic digital valve, which has the advantage of fast switching capability, anti-pollution and high repeatability, and the past flow can be changed by adjusting the open and closed time of the valve [1]. HSV can be controlled by the pulse signal, and combines effectively the computer control technology and hydraulic fluid technology, and it is widely used in the speed, position, force control and other occasions [2].

In order to solve the inherent nonlinear dynamic and uncertainties associated with the hydraulic system, many researchers have done some works. Many woks are focused on the feedback control, which compensates the effect brought by the interference to deal with the error between the realistic value and the reference value after detected. PID control is widely utilized for its agility, effect, and wide application. W. Wei [3] utilized the PID control to control the automotive suspension system to decrease the body vibration and improve the vehicle comfort. L. B. Wang [4] used the PI to

Article number P_1661

control the speed of the brushless DC motor by comparing the target speed and the actual speed for input to improve the stability of control system, while the control parameters are initial artificially and can't be adjusted with the changing condition.

These control algorithms mentioned above belong to the feedback control, and the control signal lags behind the interference, and it may leads to the steady error during the regulation process, while the feedforward control strategy is widely used in the occasions with much interference, which keeps the controlled parameters changeless to compensate the influence of the interference, and it is timely compared with the feedback control strategy, but with weak anti-interference ability. The feedforward control strategy should be combined with the feedback control strategy, which can be considered as the compound compensated control method based on the input. M. H. Dong [5] proposes the compound algorithm PD & feedforward-feedback, and utilized to the speed control for elevator. L. Z. Bao [6] used the feedback term and feedforward term to control the optimized tracking performance of vehicle active suspension.

The initiation parameters of the PID control algorithm influence largely the performance of the control system, many researches are done to optimize the parameters, some intelligence algorithms are used to adjusting the parameters on-line or off-line. C. Jiefan [7] designs a PID controller tuned by fuzzy algorithm which made use of the PID control and the intelligence of fuzzy control to achieve the position control of double cylinders by compensating the variants and no-linear characteristic. Xiaodong. C [8] proposes a new PID tuning algorithm based on Widrow-Hoff neural network learning algorithm, which can decrease the respond time and improve the control precision. While the on-line tuning algorithm increase the complexity of the system. The genetic algorithm (GA) is used to tune the control parameters off-line, Karam M. Elbayomy [9] used the genetic algorithm to adjust the PID parameters to control the movable surface of space vehicles. This paper analyses and utilizes the genetic algorithm to optimize the control parameters to gain the optimization result, including speed forward coefficient, proportional and integral coefficient of displacement feedback and output coefficient.

The main contributions of this paper are:

1) The flow characteristic is studied with the mathematical model of HSV, and the pulse width modulation (PWM) method is proposed to control the past flow of HSV;

2) The compound algorithm of PI & speed feedforward-displacement feedback is researched and adapted to precise position control;

3) GA is analyzed and used to optimize the control algorithms and the optimized results are verified by simulation and experiment.

The rest of the paper is organized as follows: the experimental system of the position control for the hydraulic cylinder controlled by HSV is presented in "Design of Hydraulic Loop" Section. The mathematical model of flow characteristic for HSV and the hydraulic system is analyzed and presented in "Mathematics Modeling" section. The position control strategy is presented in "Position Control Algorithm" section. The optimization and simulation for the control parameters optimized by GA is presented in "Parameters Optimization and Simulation" section. The "Experimental Studies" section verifies the proposed control strategy and the optimized result by experiment. Finally, the study is ended with several concluding remarks of the research work.

2. Design of Hydraulic Loop

Hydraulic position control loop designed in this paper as shown in Fig. 1 is mainly composed of the Lenovo computer with the data acquisition card PCI-6221, the displacement sensor for the hydraulic cylinder, HSV, and three position four-way reversing valve and so on.

The displacement sensor is installed to measure the hydraulic cylinder displacement which is gathered by the AI port of PCI-6221 data acquisition card (DAQ). HSV controls the flow to the hydraulic cylinder no-stem cavity by adjusting the open time of HSV. HSV is controlled by the amplified PWM signal, which was produced by the AO port of data acquisition card.

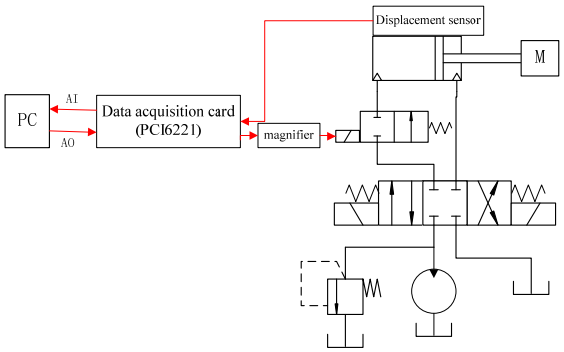


Fig. 1. The experimental hydraulic loop.

3. Mathematics Modeling

3.1. Mathematics Modeling for HSV

The relationship between the spool displacement and PWM signal is determined by the switching characteristic of HSV, and the spool displacement decides directly the past flow [10]. The equations of the valve opening area and the past flow are needed to analyze the flow characteristic.

The area of valve opening is shown in Eq. (1):

$$\overline{A}_{hsv} = \pi D \overline{x}_{hsv} \sin(2\theta) / 2 , \quad (1)$$

where $\bar{A}_{hsv}$ is the average valve-port area of HSV; D is the diameter of valve ball; θ is the half-angle of valve seat; $\bar{x}_{hsv}$ is the average displacement of valve ball, which can be referred in [11-12].

The past flow of HSV is shown in Eq. (2):

$$Q_{hsv} = C_d \bar{A}_{hsv} \sqrt{2(p_y - p_w)/\rho}\,, \tag{2}$$

where Q_{hsv} is the past flow of HSV; C_d is the flow coefficient; p_y is the pressure of rod cavity; p_w is the pressure of no-stem cavity; ρ is the oil density.

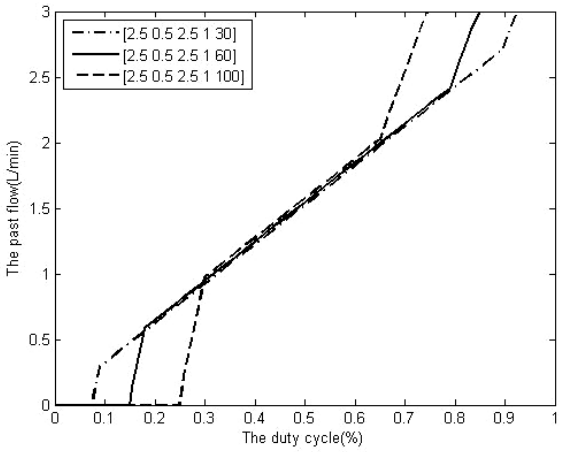
Table 1. List of component parameters.

Component	Parameters	Value
HSV	Maximum spool displacement	0.0013 [m]
	Diameter of valve ball	0.005 [m]
	Half-angle of valve seat	20 [deg]
Relief valve	Adjustment pressure	3.5 [MPa]

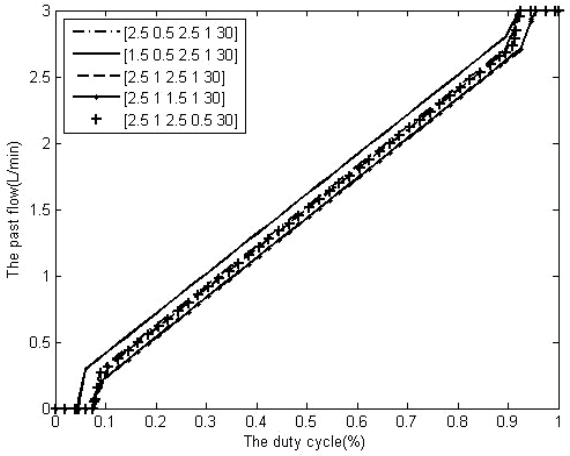
The mathematics modeling is simulated with the same switching parameters and different frequency firstly, the initial parameters are $[t_1,t_2,t_3,t_4]=[2.5,1,2.5,1]$, $f = 30/60/100$ and the simulation result is shown in Fig. 2 (a). The mathematics modeling is also simulated with the same frequency and different switching parameters, the initial parameters are $[t_1,t_2,t_3,t_4,f]=[2.5,0.5,2.5,1,30]$ $[t_1,t_2,t_3,t_4,f]=[1.5,0.5,2.5,1,30]$ $[t_1,t_2,t_3,t_4,f]=[2.5,1,2.5,1,30]$, $[t_1,t_2,t_3,t_4,f]=[2.5,1,1.5,1,30]$, $[t_1,t_2,t_3,t_4,f]=[2.5,1,2.5,0.5,30]$ respectively and the simulation result is shown in Fig. 2 (b).

The mathematic analysis result shows that: 1) The switching characteristic parameters and the frequency of pulse signal affect directly the flow characteristic of HSV; 2) On occasion of the mechanism and electromagnetism characteristics of the spool ,the past flow has linear relationship with the duty ratio of the control signal within the duty ratio range $[0.1 \sim 0.9]$; 3) The dead and sutured zone exists as the frequency of the pulse signal becomes bigger, the linear zone decreases, and the flow of HSV magnifies, when the duty ratio of pulse signal becomes bigger. Dead zone, saturated zone, and none-linear zone become bigger as switching characteristic parameters of HSV getting bigger with frequency of pulse signal fixed. The minimal responding duty ratio of HSV is $dc_{\min} = \frac{t_1 + t_2}{T}$ and the maximal responding duty ratio is $dc_{\max} = 1 - \frac{t_3 + t_4}{T}$.

Based on the analysis of the flow characteristic, the pulse signal with the fixed frequency 60 Hz is utilized and the past flow is adjusted with the duty ratio by PWM method.



(a)



(b)

Fig. 2. The mathematics modeling result for HSV.

3.2. Mathematics Modeling of Hydraulic Cylinder

The flow equation can illuminate the relationship between the pressure and the total flow with the bulk-cavity-node method [13], which is shown in Eq. 3.

$$P = \int \frac{E_0}{V} \sum Q_i dt\,, \tag{3}$$

where $\sum Q_i$ is the total flow of the cavity; P is the pressure of the cavity; E_0 is the elastic modulus of oil; V is the volume of rodless cavity.

The hydraulic system model is established with the bulk-cavity-node method according to hydraulic system schematic diagram, and the application is modeling respectively, as shown in Eq. 4-7.

The flow equation of rodless cavity:

$$\frac{dp_w}{dt} = \frac{\beta_e}{V_{w0} + A_w x}(\bar{Q}_{hsv} - Q_x - A_w \dot{x})\,, \tag{4}$$

where β_e is the elastic modulus of oil, Q_{hsv} is the flow that flow into the rod cavity; Q_x is the flow that leakage from rod cavity to rodless cavity; V_{w0} is the initial volume of rodless cavity; A_w is the effective stress area of piston in rodless cavity.

The equation of rod cavity:

$$\frac{dp_y}{dt} = \frac{\beta_e}{V_{y0} + A_y x}(Q_x + A_y \dot{x} - Q_{out}), \quad (5)$$

where A_y is the effective stress area of piston in rod cavity; V_{y0} is the initial volume of rod cavity, Q_{out} is the flow that flow out of rodless cavity.

The equation of force balance:

$$m\ddot{x} = p_y A_y - p_w A_w - mg - \beta_c \dot{x}, \quad (6)$$

where m is the equivalent mass of piston; β_c is the viscous damping coefficient of oil; g is the gravity acceleration.

The equation of the leakage flow:

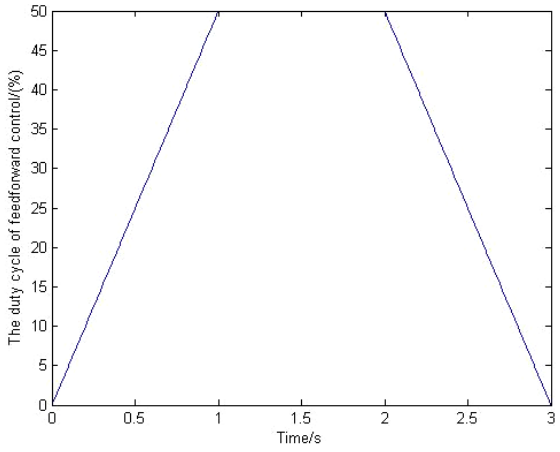
$$Q_x = k_c(p_y - p_w), \quad (7)$$

where k_c is the leakage flow coefficient; p_p is the pressure of system.

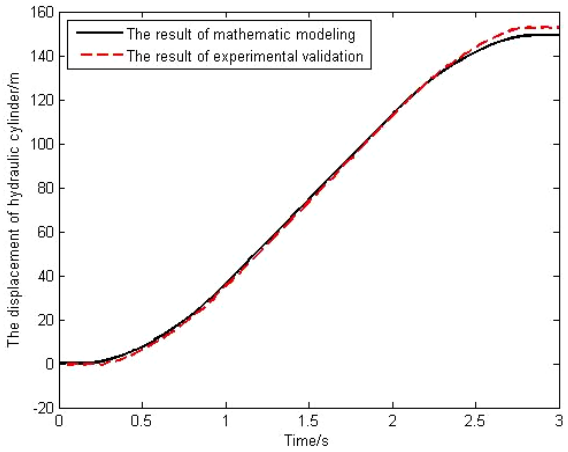
Table 2. List of component parameters.

	Parameters		Value	Unit
1	Elastic modulus of oil	β_e	750	MPa
2	The pressure of system	p_p	3.5	MPa
3	The density of oil	ρ	850	kg/m^3
4	Maximal displacement	x_{xc}	200	mm
5	The area of the rod cavity	A_y	120	mm^2
6	The area of the rodless cavity	A_w	200	mm^2
7	The mass of piston	m	9	kg
8	viscous damping coefficient of oil	β_c	250	N·s/m
9	The initial volume of rod cavity	V_{y0}	2827.5	mm^3
10	The initial volume of rodless cavity	V_{w0}	5696.5	mm^3
11	The leakage flow coefficient	k_c	0.0033	m^3/(Pa·s)

The open loop experiment is done to validate the mathematics modeling by measure the displacement of the hydraulic cylinder with the control signal for HSV given ahead and the open loop control signal and the displacement are shown in Fig. 3.



(a) Duty ratio test signal.



(b) Displacement of the hydraulic cylinder.

Fig. 3. The result of the open loop experiment.

The result shows that the displacement error of the mathematics modeling and experiment result exists for the control dead zone of HSV during the experiment process, the changeable pressure leads to the instability switching parameters, while the switching parameters of simulating environment is fixed.

4. Position Control Algorithm

This paper proposes the compound algorithm of PI & speed feedforward-displacement feedback as the position control algorithm, which is shown in Fig. 4.

The feedforward value is referred as the control signal, which is shown in Fig. 5 (a), and the feedback algorithm is utilized to compensate the error between the reference input (Fig. 5 (b)) and the realistic output to deal with the uncertainties associated with the hydraulic system.

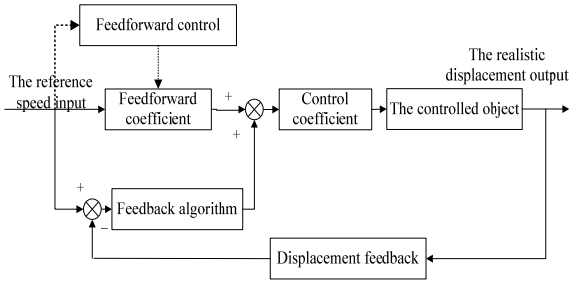
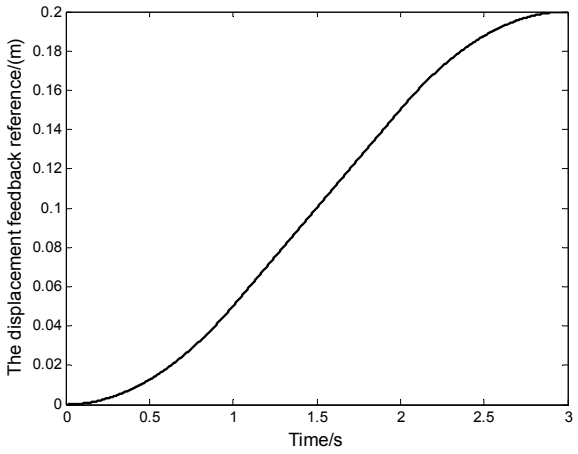
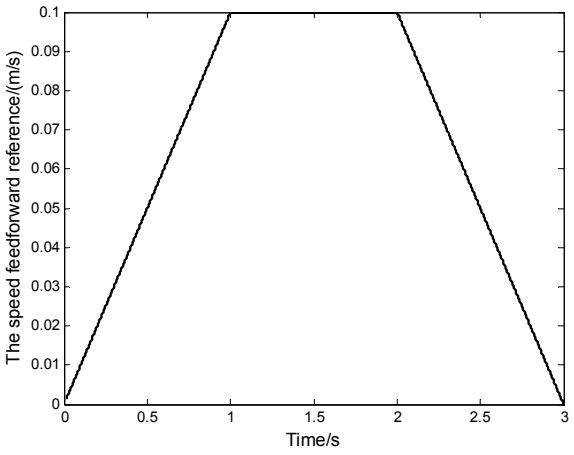


Fig. 4. The position control algorithm.



(a)The feedback displacement reference curve.



(b) The feedforward speed reference curve.

Fig. 5. The position control reference curve.

The feedforward input signal is multiplied by the PI feedback control so that the final control duty ratio can be expressed in Eq. 8:

$$u(t) = k_2[k_1 * v_{ideal}(t) + u_{PI}(t)], \quad (8)$$

where k_2 is the output control coefficient; k_1 is the speed feedforward coefficient; $u_{PI}(t)$ is the displacement feedback output based on the feedback algorithm.

The PI control is used as the feedback algorithm with its agility, effect, and wide application to compensate the changing load and disturbance. The position error between the reference and reality is:

$$e = x_1 - x_2, \quad (9)$$

where x_1 is the reference displacement; x_2 is the realistic displacement of hydraulic cylinder.

The output of the PI control is:

$$u(k) = K_p e(k) + K_{ia}\sum_{i=1}^{k} e(j)T = K_p e(k) + K_i\sum_{i=1}^{k} e(j), \quad (10)$$

where $K_i = K_{ia}T$; K_p is the proportional coefficient; K_i is the integral coefficient; T is the sampling period; k is the sampling serial number.

1) The proportional coefficient K_p is used to control the system error e_s, while the increscent proportional coefficient may decrease the stability or cause the system instable;

2) The integral coefficient K_i is used to decrease the steady error and increase the steady precision.

The parameters are initialized as $K_p = 60$ $K_i = 2$ $k_1 = 4$ $k_2 = 1$ to verify the speed forward-displacement feedback algorithm, and the results are shown in Fig. 6.

The simulation result shows that: 1) the speed forward-displacement feedback algorithm is effective to decrease the tracking error, and the displacement error of position control is limited in 2 mm; 2) the tracking error of the start and end process is larger than the other process for the cycle ratio belongs to the dead zone of HSV; 3) the control parameters of the speed forward-displacement feedback algorithm is initialized personality, and the optimized method can be used to adjusting the control parameters to decrease the position error more.

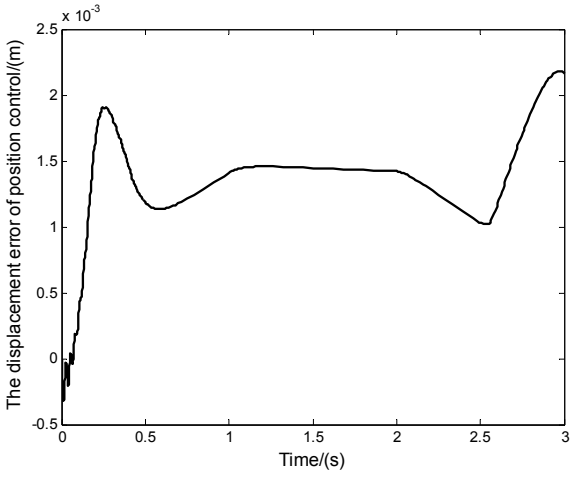


Fig. 6 (a). The performance of the position control: the displacement error.

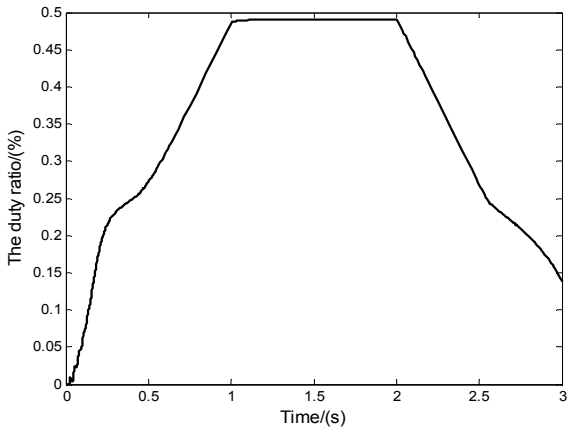


Fig. 6 (b). The performance of the position control: the duty ratio.

5. Parameters Optimization and Simulation

The four control parameters K_p, K_i, k_1 and k_2 are initialed based on the expert intelligence and different control parameters influence the dynamic performance of the position control. In order to decrease the position error, this paper utilizes the genetic algorithm to optimize the parameters off-line.

GA is based on natural selection and genetic theory, and it is the efficient global optimization search algorithm which is combination of the survival of fittest rules and the random information exchange mechanism of chromosomes within the group [14]. The possible solution of the problem domain is seen as an individual or chromosome, and the group is repeatedly operated with genetic operation as selection, crossover, and mutation. In order to achieve the optimal solution, GA uses the fitness function to evaluate each individual, and gains the better group based on evolutionary rules, the optimization process shown in Fig. 7.

The speed feedforward-displacement feedback algorithm parameters are optimized in the following steps:

Step 1: Initialize the first generation with randomly population, and then evaluate each population;

Step 2:

(a) Select children from the set with the better performance;

(b) Apply crossover with a given rate;

(c) Apply mutation with a given rate;

(d) Repeat (a) to (d) generate the new generation;

Step 3: Repeat steps 2 until as topping criterion is satisfied.

The genetic algorithm parameters are shown in Table 3.

Table 3. The initial parameters of GA.

Parameters	Value	Parameters	Value
Population size	20	Crossover rate	0.7
Number of generations	200	Mutation rate	0.1
Generation gap	0.9		

In order to obtain the satisfied dynamic process characteristic, we use Eq. 11 as the object function:

$$y = \frac{1}{N}\sqrt{\sum_{i=1}^{N} e(i)^2} \quad N = size(e) \tag{11}$$

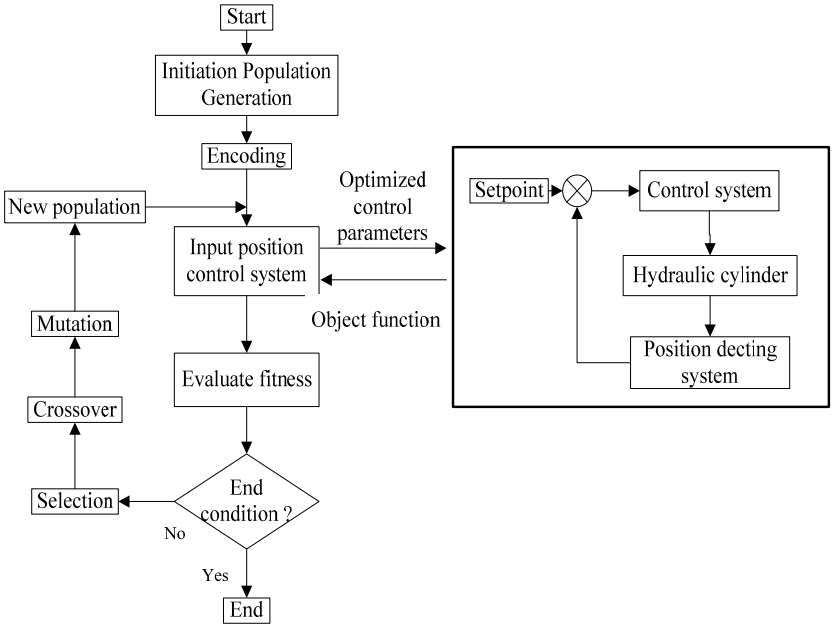


Fig. 7. The parameters optimization process.

The fitness is evaluated by the object function with the linear sorting and the difference is equal to 2.

The range of the variables when optimized is shown in Table 4.

Table 4. The range of the optimized variables.

Parameters	**Range**
k_1 (The speed feedforward coefficient)	[0 ~ 10]
K_p (The displacement feedback proportional coefficient)	[0 ~ 100]
K_i (The displacement feedback integral coefficient)	[0 ~ 10]
k_2 (The output coefficient)	[0 ~ 10]

This paper proposes three optimization processes for the position control system. The first is that the parameters K_p, K_i, k_2 is initialed and k_1 needs to be optimized by GA; The second is that the parameters k_2 is initialed and K_p, K_i and k_1 need to be optimized by GA; the third is the parameters k_2, K_p, K_i and k_1 need to be optimized by GA.

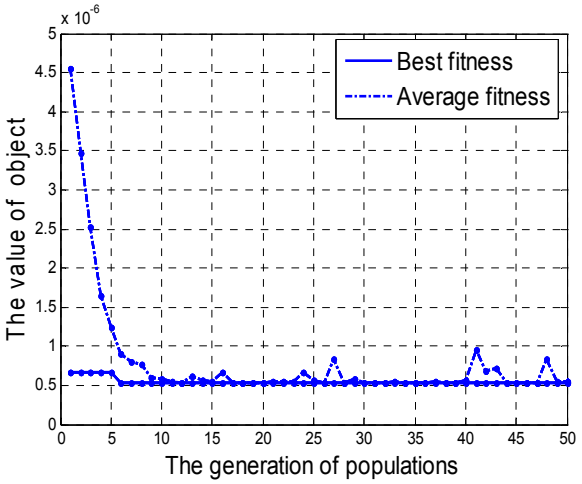
1) The parameter k_1 is optimized by GA with $K_p = 60$, $K_i = 2$ and $k_2 = 1$, and the value of object function is shown in Fig. 8 (a). The simulation is done with the optimal solution $k_1 = 5.45$, and the displacement error and the cycle ratio is shown in Fig. 8 (b, c).

The simulation result shows that 1) the optimized position control algorithm parameters can decrease effectively the position error from [0-2] mm to [0.9-1.5] mm; 2) the larger tracking error of the start and end process exists which results from the dead zone of HSV.

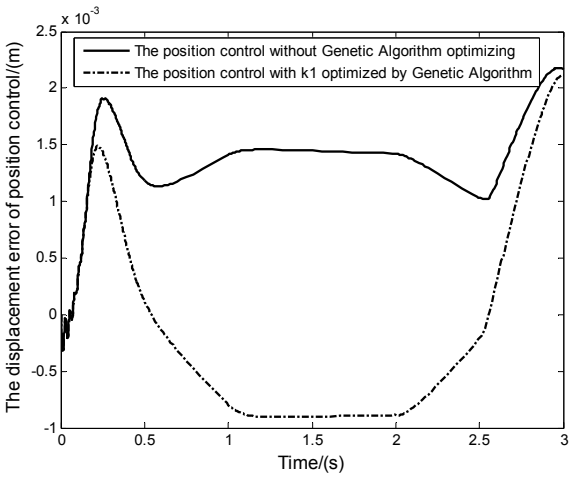
2) The parameters K_p, K_i and k_1 are optimized by GA with $k_2 = 1$, and the value of object function is shown in Fig. 9(a). The simulation is done with the optimal solutions $K_p = 96.24$, $K_i = 5.76$, $k_1 = 5.47$, and the displacement error and the cycle ratio is shown in Fig. 9 (b, c).

The simulation result shows that: 1) the optimized position control algorithms can decrease the position error from [0.9-1.5] mm to [-0.5-1] mm; 2) the larger tracking error of the start and end process also exists which results from the dead zone of HSV.

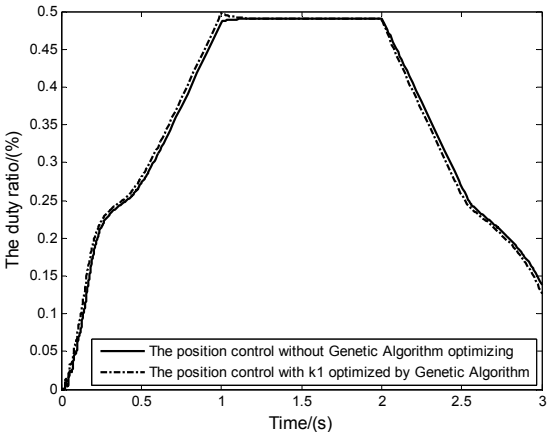
3) The parameters K_p, K_i, k_2 and k_1 are optimized by GA, and the value of object function is shown in Fig. 10 (a). The simulation is done with the optimal solutions $K_p = 68.68$, $K_i = 9.66$, $k_1 = 2.78$, $k_2 = 1.9657$, and the displacement error and the cycle ratio is shown in Fig. 10 (b, c). The simulation result shows that: 1) The optimized position control algorithm parameters can decrease the position error from [-0.5-1] mm to [-0.4-0.8] mm; 2) the larger tracking error of the start and end process and the light turbulence exists which results from the dead zone of HSV.



(a) Computational optimized curve of GA

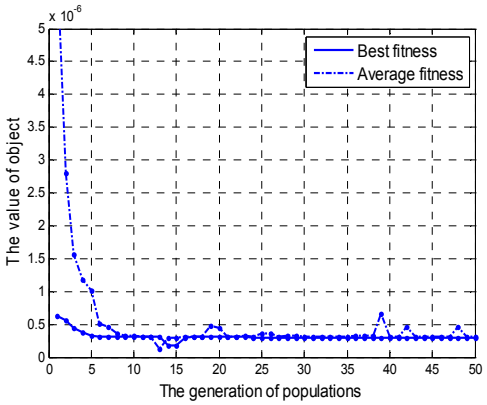


(b) The displacement error

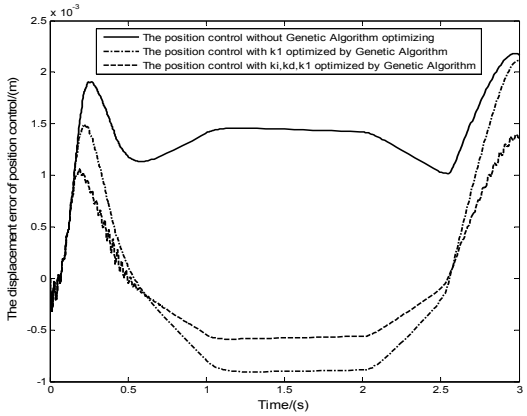


(c) The duty ratio

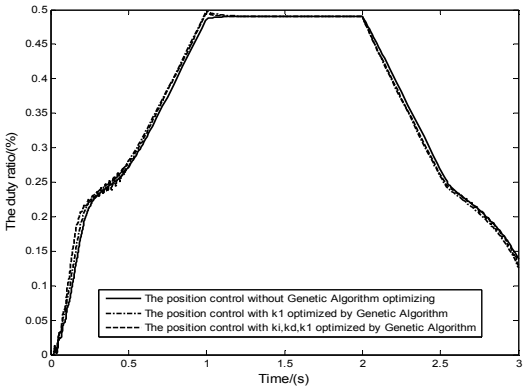
Fig. 8. The performance of the position control with k_1 optimized by GA.



(a) Computational optimized curve of GA

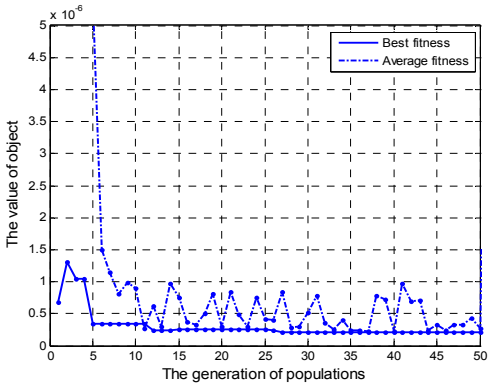


(b) The displacement error

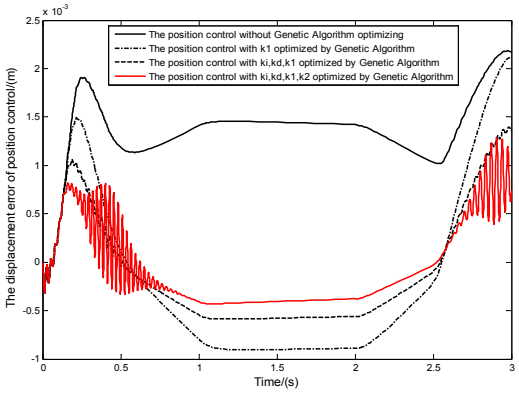


(c) The duty ratio

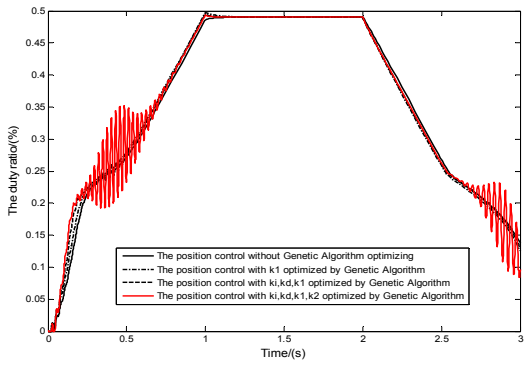
Fig. 9. The performance of the position control with K_p, K_i and k_1 optimized by GA.



(a) Computational optimized curve of GA



(b) The displacement error



(c) The duty ratio

Fig. 10. The performance of the position control with K_p K_i k_1 and k_2 optimized by GA.

The optimization results of the three optimization processes are shown in Table 5.

Table 5. The optimization results.

The position control algorithm	k_1	K_p	K_i	k_2
The position control without being optimized by GA	4	60	2	1
The position control with k_1 optimized by GA	5.45	60	2	1
The position control with K_p, K_i and k_1 opt imized by GA	5.47	96.24	5.76	1
The position control with K_p, K_i, k_1 and k_2 optimized by GA	2.78	68.68	9.66	1.96

6. Experimental Studies

The position control experiment is done to verify the simulation result based on the FESTO platform. The hydraulic loop is set up in Fig. 1 and the system pressure is 6 MPa. The sample rate of the displacement signal is 1 kHz, and the rate of control algorithm is 100 Hz. The position control experiments are done with different speed forward-displacement feedback algorithm parameters to verify the effective of the optimization result optimized by GA.

The displacement error and the cycle ratio are shown respectively to verify the effective of the optimized control parameters.

Fig. 11 shows the position control performance without any parameter optimized by GA, it can be concluded that: 1) The experiment result is similar with the simulation result, which illustrates the veracity of the mathematics modeling; 2) The speed forward-displacement feedback control algorithm is effective to control the position error in 2.5 mm in the practical experiment.

Fig. 12 shows the position control performance with k_1 optimized by GA, it can be concluded that the speed forward-displacement feedback control algorithm with k_1 optimized by GA is effective to decrease the position error to 1.5 mm in the practical experiment.

Fig. 13 shows the position control performance with k_1 K_p and K_i optimized by GA, it can be concluded that the speed forward-displacement feedback control algorithm with k_1 K_p and K_i optimized by GA is effective to decrease the position error to 0.9 mm in the practical experiment.

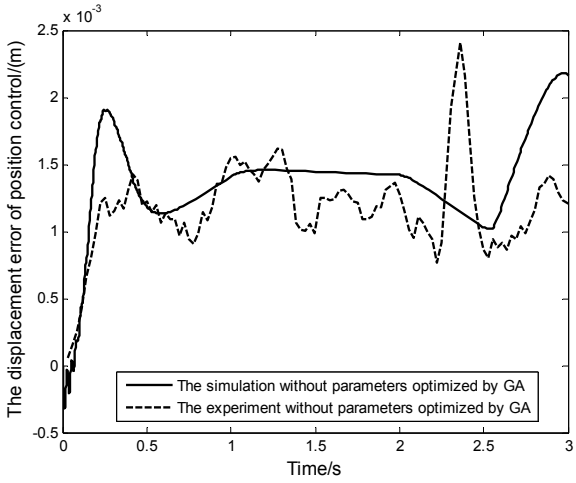


Fig. 11 (a). The position control without parameters optimized.

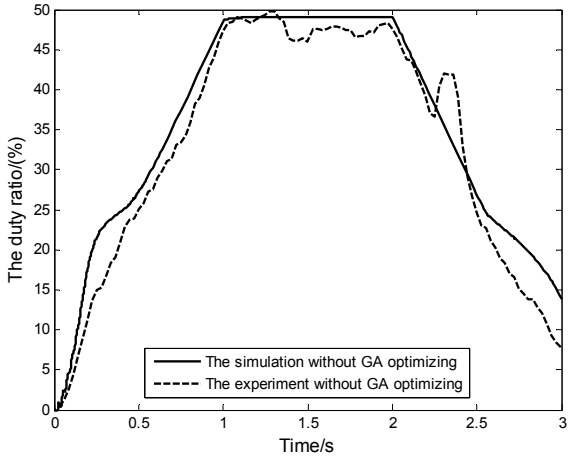


Fig. 11 (b). The position control without parameters optimized.

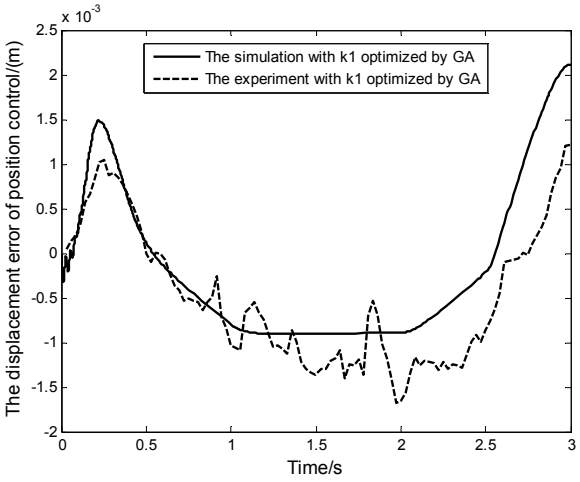


Fig. 12 (a). The position control with k_1 optimized by GA.

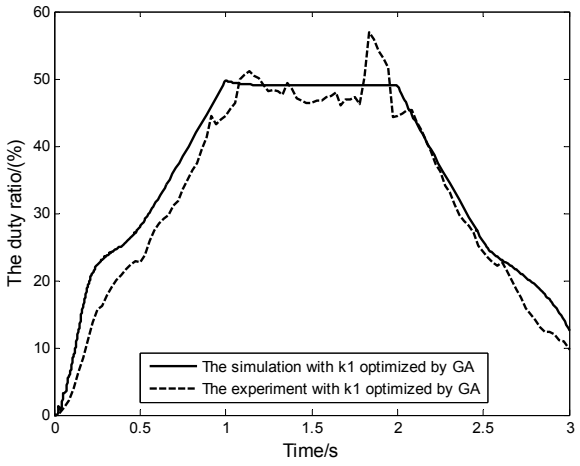
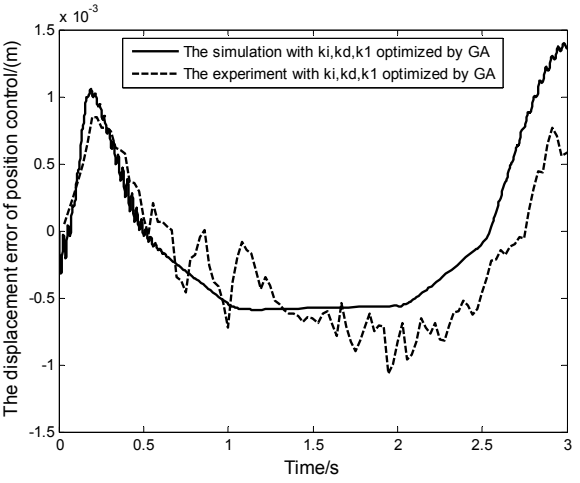
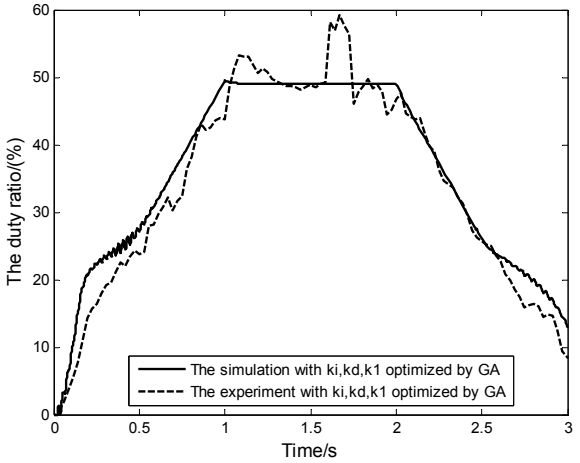


Fig. 12 (b). The position control with k_1 optimized by GA.



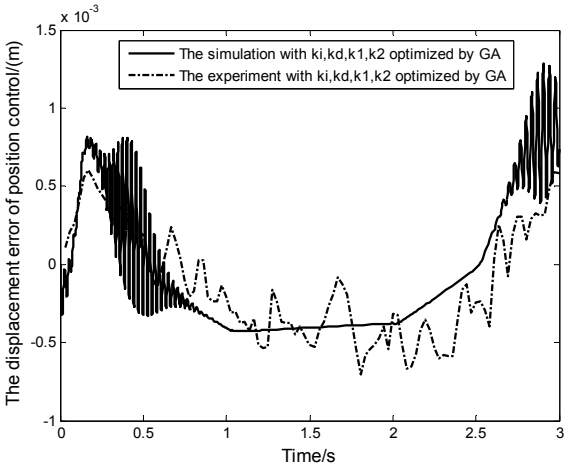
(a)



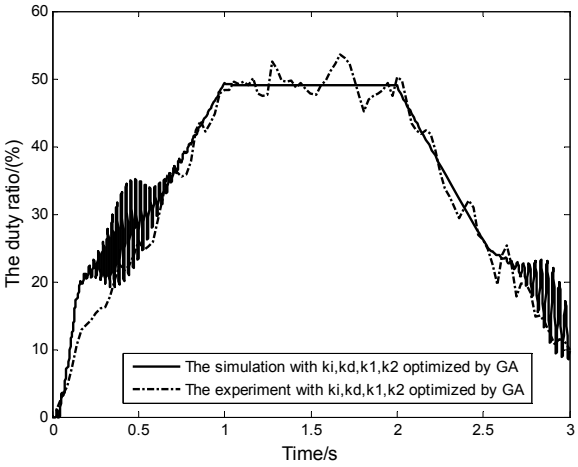
(b)

Fig. 13. The position control with k_1 K_p K_i optimized by GA.

Fig. 14 shows the position control performance with k_1 K_p K_i and k_2 optimized by GA, it can be concluded that the speed forward-displacement feedback control algorithm with k_1 K_p and K_i optimized by GA is effective to decrease the position error to 0.5 mm in the practical experiment.



(a)



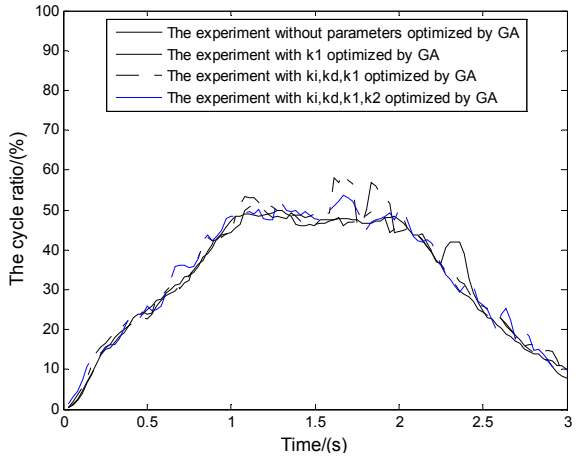
(b)

Fig. 14. The position control with k_1 K_p K_i k_2 optimized by GA

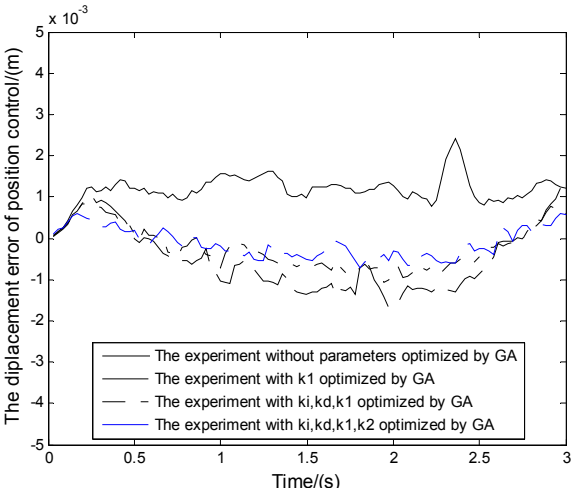
The displacement error of the start and end process is larger than the others which is shown in Fig. 11-14, which results from the dead zone of the past flow within the little duty ratio.

The performance o the position control with four optimization processes is compared to each other, on terms of the displacement error and the cycle ratio, which is shown in Fig. 15.

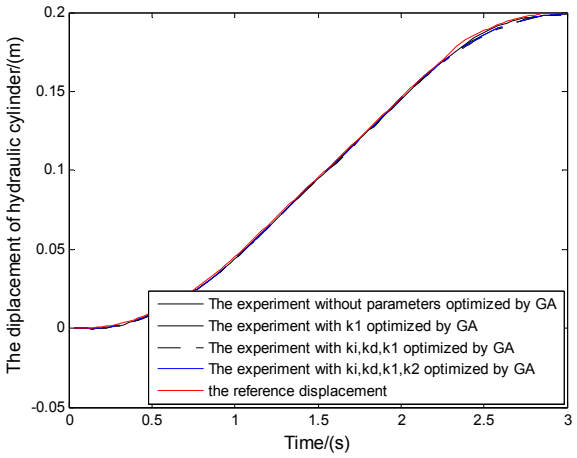
Fig. 15 shows that the performance of the position control with k_1 K_p K_i k_2 optimized by GA is better than the other three optimization method., and the position control with K_p, K_i, k_1 and k_2 optimized by GA has the better position control performance considered as little average standard deviation and object function, which illustrates the efficiency of GA.



(a) The duty ratio



(b) The displacement error



(c) The displacement

Fig. 15. The position control with different optimized control parameters.

7. Conclusions

This paper proposes a compound algorithm of PI & speed feedforward- displacement feedback to apply for the position control. The speed feedforward-displacement feedback algorithm can solve the hysteresis resulting from the feedback control, and the PI control algorithm is designed and utilized to deal with the position error by adjusting to the duty ratio of HSV. GA is used to tune the control parameters, including speed forward coefficient, proportional and integral coefficient of displacement feedback, output coefficient to gain the optimization result, on terms of the performance of the position control system. The mathematics modeling is analyzed and simulated with Simulink using the finite chamber method, and the hydraulic loop is established to verify the simulation result with the optimized results on the FESTO platform.

The experiment and simulation result shows that: 1) HSV can be utilized to realize the precise position control by adjusting the PWM signal; 2) the compound algorithm of PI & speed feedforward-displacement feedback is put forward to decrease effectively the position error based on the analysis of the flow characteristic; 3) the Genetic Algorithm is used to tune the control parameters off-line and the optimization result of the variables optimized by GA has a better performance which is considered as the little position error than others and the position error is controlled within $-0.6mm \sim 0.6mm$.

Reference

[1]. Z. Xiang, G. L. Tao, J. W. Xie and H. Liu, Simulation and experimental investigation on pressure dynamics of pneumatic high-speed on/off valve, *Journal of Zhejiang University (Engineering Science)*, Vol. 42, No. 5, 2008, pp. 845-849.

[2]. Q. H. Gao, H. Z .Song, Z. H. Liu, Research on speed control in the starting and stopping processes of hydraulic cylinder with high speed on-off valve, *China Mechanical Engineering*, Vol. 24, Issue 1, 2013, pp. 47-51.

[3]. W. Wei, B. X. Yan, L. S. Yu, C. D. Xiao, Fuzzy-PID control strategy for an active suspension based on optimal control laws with genetic algorithm, *Journal of Vibration and Shock*, Vol. 31, Issue 22, 2012, pp. 157-162.

[4]. B. W. Li, L. Jun, F. Jian, Study on control method of brushless DC motors based on self-adoptive DRNN, *China Mechanical Engineering*, Vol. 22, Issue 19, 2011, pp. 2337-2340.

[5]. D. M. Hu, Study on the speed control of the variable-speed controlled closed-circuit hydraulic elevators, *Zhejiang University*, 2009.

[6]. L. Z. Bao, Optimal tracking control for vehicle active suspension systems, *Journal of System Simulation*, Vol. 21, Issue 2, 2009, pp. 551-553.

[7]. J. F. Cui, The improved coupling multi-motor synchronous control based on fuzzy controller, *Micromotors*, Vol. 44, Issue 3, 2011, pp. 75-77.

[8]. X. D. Chen, Study on the synchronization control strategy for hydraulic system based on Widrow-Hoff learning algorithm, *Manufacturing Technology & Machine Tool*, Issue 3, 2009, pp. 44-48.

[9]. Karam M. Elbayomy, Z. X. Jiao, H. Q. Zhang, PID controller optimization by GA and its performances

on the electro-hydraulic servo control system, *Chinese Journal of Aeronautics*, Vol. 21, Issue 4, 2008, pp. 378-384.
[10]. Mostafa Taghizadeh, Ali Ghaffari, Farid Najafi, Improving dynamic performances of PWM-driven servo-pneumatic systems via a novel pneumatic circuit, *ISA Transactions*, Vol. 48, Issue 4, 2009, pp. 512-518.
[11]. M. Taghizadeh, A. Ghaffari, F. Najafi, Modeling and identification of a solenoid valve for PWM control applications, *Computes Rendus Mecanique*, Vol. 337, Issue 3, 2009, pp. 131-140.
[12]. B. J. Chen, S. X. Yang and F. Cao, The character analysis of high speed on-off valve, *Journal of Beijing Institute of Technology*, Vol. 13, No. 3, 1993, p. 354.
[13]. Cheng Ruzhen, Yao Pingxi, Research on non-impact starting and stopping process of hydraulic cylinder, *Fluid Power Transmission & Control*, Issue 2, 2011, pp. 28-30.
[14]. Wei-Der Chang, A multi-crossover genetic approach to multi-variable PID controllers tuning, *Expert Systems with Applications*, Vol. 33, Issue 3, 2007, pp. 620–626.

2013 Copyright ©, International Frequency Sensor Association (IFSA). All rights reserved.
(http://www.sensorsportal.com)