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Variable Gain Type PID Control Using PSO for Ultrasonic Motor

Faridah A. Rahman*, Yusuke Murata*, Kanya Tanaka*, Yuki Nishimura*,
Shigeru Uchikado**, Yasuhiro Osa***
* Yamaguchi University,2-16-1 Tokiwadai, Ube Yamaguchi, Japan, ktanaka@yamaguchi-u.ac.jp
** Tokyo Denki University, Saitama, Japan, uchikado@j.dendai.ac.jp
*** Kobe City College of Technology, Kobe, Japan, osa@kobe-kosen.ac.jp

Abstract —**Ultrasonic motor exhibits non-linearity that relates the input (Phase difference) and output (Velocity). It also causes serious characteristic changes during operation. PID control has been widely used as the design scheme for USM. However, it is difficult for the conventional PID control to compensate such characteristic changes of the plant and non-linearity. To overcome this problem, we propose a variable gain type PID control in which PID gains are optimized using a particle swarm optimization (PSO).**

1. INTRODUCTION

Ultrasonic motor (USM) employs vibration generated in impressed voltage to a piezoelectric element as a drive source. USM has excellent features, such as small-size, light-weight, no running sound, high torque even at the low speed, and high retention torque in the stop condition. In addition, since USM does not produce electromagnetic noise in principle or is not influenced by the electromagnetic field, USM is excellent in terms of electromagnetic compatibility (EMC) [1], [2]. Therefore, USM is expected as an actuator of medical and welfare equipments. Since USM is driven by the frictional power in principle, it is difficult to derive a plant model of USM based on physical analysis. Though some plant models for USM were proposed, they were too complicated for the control [3], [4]. Therefore it is difficult to apply an advanced control theory to USM because it usually starts from the expression model of the plant. Since PID control can be constructed even if there is no plant model, PID control has been widely used as the design scheme for USM[5]-[7]. However, there are limitations of the control performance using the conventional fixed-gain type PID control because USM causes serious characteristic changes during operation and contains non-linearity. In that case, it is difficult for the conventional one to compensate such characteristic changes of the plant and non-linearity.

As a way to overcome those problems, the research on dynamically adjusts for each gain in PID control using neural network and genetic algorithm are proceeding. Nevertheless, there are still possibilities for PID gains to converge in a local solution and speed convergence to optimum value, which are among the points much need to be improved.

Meanwhile, stochastic optimization method which refers to Particle Swarm Optimization (PSO) has been actively researched. In comparison with back-propagation method in neural network, PSO performs the optimization only by using the numerical value of the evaluation function. Thus, the continuity of the objective function and differentiability are not needed to solve the complex nonlinear optimization problem. Moreover, despite the simple algorithm in PSO compare to genetic algorithm, PSO is able to solve the nonlinear optimization problem efficiently.

In this paper, we propose a variable gain type PID control by optimizing each gain in PID control using a particle swarm optimization (PSO) [8]. The effectiveness of the proposed control method is confirmed by experiments.

2. PID CONTROL FOR USM

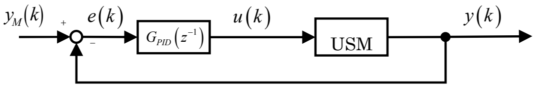


Fig.1. Block diagram of PID control.

At first, we explain the conventional fixed-gain type PID control shown in Fig.1 for USM. In Fig.1, $y_M(k)$ is the object input, $u(k)$ is the control input towards the plant, while $y(k)$ represents the output from the plant. The error between the object input and the output is considered as $e(k)=y_M(k)-y(k)$. The control input $u(k)$ is defined as

$$\begin{aligned}u(k)&=(K_P+K_I+K_D)e(k)\\&\quad-(K_P+K_D)e(k-1)+K_De(k-2)\end{aligned}\tag{1}$$

where K_P, K_I, K_D are proportional gain, integral gain, and derivative gain, respectively.

As mentioned before, it is difficult to compensate non-linearity and characteristic changes of USM using the conventional fixed-gain type PID control. Therefore, we propose a variable gain type PID control in which PID gains are optimized using PSO. Fig.2 shows the construction of the proposed control method.

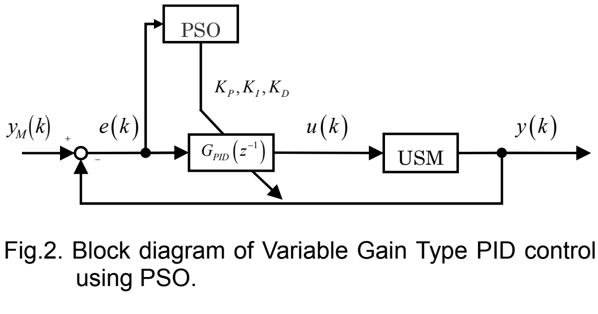


Fig.2. Block diagram of Variable Gain Type PID control using PSO.

3. VARIABLE GAIN TYPE PID CONTROL USING PSO FOR USM

3.1 Principle of PSO

PSO is a stochastic optimization method modeled by the behavior of birds flock to find food known as one of the potential method. The outline for PSO is marked as follows. Let consider the optimization problem of maximizing the evaluation function $f : M \to M' \subset R$ for variable $x \in M \subset R^n$. Let there be N particles (mass point) on M dimensional space, where the position vector and velocity vector of $i(=1,2,3,....,N)$ th particle for m searching number are x_i^m and v_i^m. The best position for each particle in the evaluation function $f(x)$ of $x_i^1, x_i^2, ...x_i^m$ searching point is represented as P_i (Pbest), while the best position of $f(x)$ in the searching point for the whole particle is represented as P_g (Gbest). The particles are manipulated according to the following recurrence equations:

$$v_i^{m+1} = wv_i^m + c_1 r_1 \left\{ P_i - x_i^m \right\} + c_2 r_2 \left\{ P_g - x_i^m \right\} \qquad (2)$$

$$x_i^{m+1} = x_i^m + v_i^{m+1} \qquad (3)$$

w represented the inertia weight, c_1 and c_2 are two positive constant, where r_1, r_2 are uniform random numbers of [0,1].

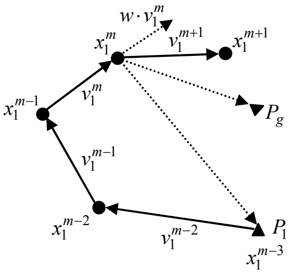


Fig.3 Search example of PSO

The example for optimized solution search using PSO is shown in Fig.3. Now, x_1^{m-3} searching point is Pbest, and Pbest for the individual number g is assumed to be the Gbest. The velocity vector of v_1^{m+1} is formed based on three vectors as shown in (2). The first one is inertia vector, which is the vector from weighting factor w and the velocity vector v_1^k. The remaining two are vectors for each P_i and P_g, which formed from weighting factors c_1 as well as c_2, and also [0, 1] of uniform random numbers r. From those interactions, velocity vector v_1^{m+1} acts so that the particle comes closer to optimum value.

In addition, the method to level up the searching ability of PSO called "Inertia Weight Approach" is used in this paper. Weighting factor w in (2) is replaced with the equation below:

$$w^m = w_s - \frac{(w_s - w_e) \times m}{m_{\max}} \qquad (4)$$

$m_{\max}$ represents the maximum searching number, where initial value w_s and final value w_e of w are designed to satisfy $w_s > w_e$. From (4), each time the searching number proceeds, the velocity vector v_1^{m+1} of (2) will go down due to the decrease in w^m value.

3.2 Variable gain type PID control

Consider the object input $y_M(k)$ is the output of the following reference model.

$$y_M(k) = \frac{z^{-1} b_{M0}}{1 + a_{M1} z^{-1} + a_{M2} z^{-2}} r(k) \qquad (5)$$

We need to think that each gain, K_P, K_I and K_D as the axis in $M_{PID} \subset R^3$ space. Then, let consider the particles in M_{PID} as $x_i^m = \left(K_{Pi}{}^m, K_{Ii}{}^m, K_{Di}{}^m \right)$. We evaluate these particles using the following evaluation function.

$$Fitness = \frac{1}{1 + \sum_{i=T_s}^{T/2} e(i)^2} \qquad (6)$$

where, $T/2$ is half cycle of the object input, and T_s is start-time of the evaluation. $Fitness$ shows the follows-up of evaluation function for the object input. The purpose is to decrease the steady-state error by maximizing the function. Optimization process of PID gains by PSO is shown in Fig.4. The USM control for right rotation and the left rotation use the different PSO in tracking the object input of (5). Since the characteristics of USM is different depends on the rotation direction, we evaluate both rotation separately.

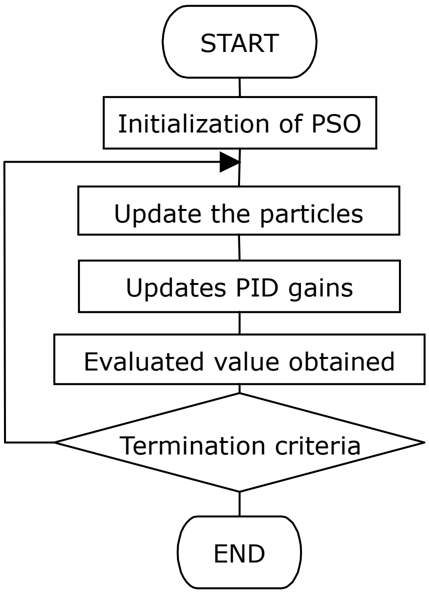


Fig.4. Flowchart of PSO

4. EXPERIMENTAL RESULTS

4.1 Conditions of experiments

To confirm the effectiveness of the proposed design method, we carried out the experiments using the existing USM servo system. Fig.5 presents the USM servo system used in the experiments. In Fig.5, USM, encoder, and magnetic brake are connected on the common axis. The position information from the encoder is input to the counter board set up in the personal computer. Information of the control input calculated from the output and the object input in the PC is transferred to the driving circuit via the I/O board. Table 1 shows the specifications of USM, encoder, and load. The driving circuit is shown in Fig.6 and Table 2 shows the specifications of the driving circuit. The phase difference control circuit is constructed using a digital circuit with a shift register. The voltage control and the voltage control circuit at the final stage are constructed using a digital potential meter, a digital operational amplifier, and a booster transistor. To make stable start, a driving frequency is fixed at 36.0 [kHz], i.e., 1.0 [kHz] higher than resonance frequency of USM. As for USM drive, the phase difference control method adopted. The phase difference is adjusted between -90 [deg.] and 90 [deg.] by 1.406 [deg.]. To confirm the effectiveness of the proposed method, we carried out an experiment using existing USM. In the experiment, we compared the proposed method with the conventional one. As the object input, a rectangular wave with 1 [sec.] cycle and with $\pi/20$ [deg.] amplitude is used. Parameters of the reference model are adopted as follows:

$$b_{M0}=0.0009,\ a_{M1}=-1.9400,\ a_{M2}=0.9409$$

4.2 PID control

The experiments on fixed-gain type PID control are carried out using the fixed value for each gain where $K_P=5.0, K_I=0.2$ and $K_D=0.2$. The object input $y_M(k)$ and the output response $y(k)$ for PID control are shown in Fig.7. We can see that the output $y(k)$ follows the object input $y_M(k)$ with stability. Fig.8 is a histogram of 50 times positioning errors $e(k)=y(k)-y_M(k)$, which is at 0.9[sec.] after changing the sign of the object input. In the right rotation, the positioning error has been distributed between –0.0288 and 0.0072. On the other hand, in the left rotation, the positioning error has been distributed between –0.0036 and 0.0072. Because the accuracy of the encoder is 0.0036 [deg.], the positioning accuracy is not necessarily good. From the above result, we know that it is difficult to get high positioning accuracy of USM which exhibits non-linearity and characteristic changing, only by applying the fixed gain type PID control.

Table 1. Specifications of USM, encoder and load.

USM	Rated rotational speed：100 rpm
	Rated torque：0.392 N･m
	Holding torque：0.392 N･m
Encoder	Resolution：0.0036 deg
Magnetic Brake	0～0.2 N･m

Table 2. Specifications of drive circuit.

Driving frequency	36.0 kHz
Driving voltage	150 V
Phase difference	-90～90 deg
Resolution of phase difference	1.406 deg
Sampling time	1.0 ms

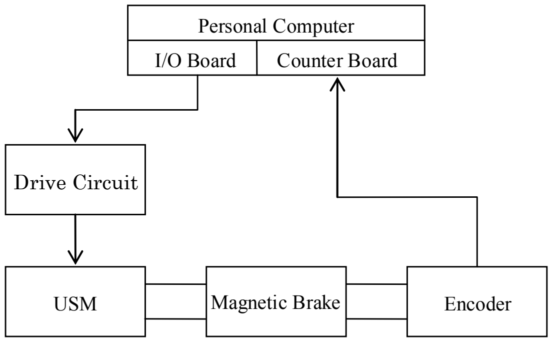


Fig.5. USM servo system.

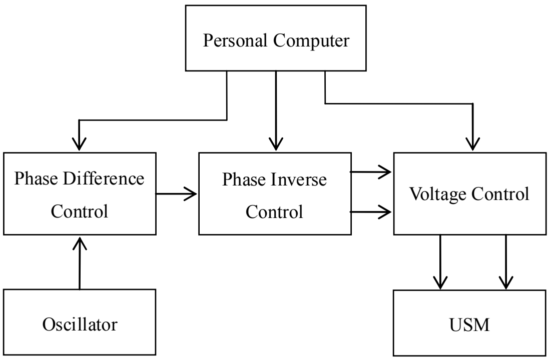


Fig.6 Drive circuit.

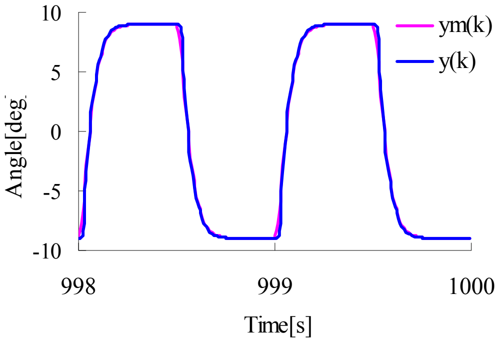
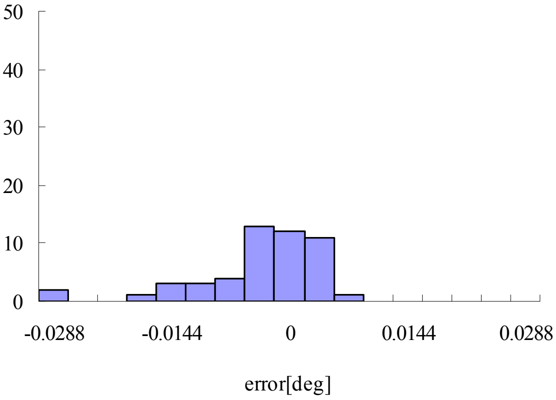
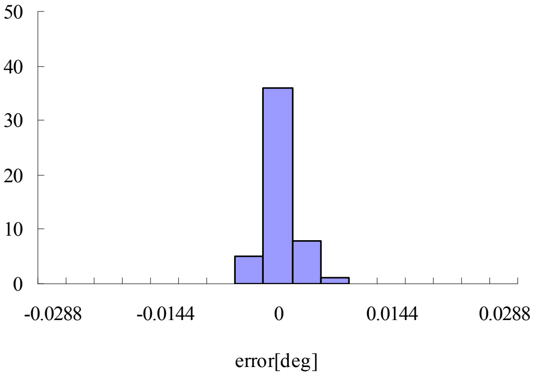


Fig.7 Responses of PID control.



(a) Right rotation



(b) Left rotation

Fig.8 Positioning accuracy of PID control.

4.3 Variable gain type PID control with no-load

In the proposed method, we carried out the experiments in the case of no-load. The parameters in PSO are $c_1 = 1.0$, $c_2 = 1.0$, $w_e = 0.4$, and $w_s = 0.9$. Initial values of the position and the velocity in each particle are chosen as the uniform random numbers in the following ranges:

$$\left\{ \begin{array}{l} x_i^0 = \{[6.0, 4.0], [0.1, 0.3], [0.1, 0.3]\} \\ v_i^0 = \{[1.0, -1.0], [0.1, -0.1], [0.1, -0.1]\} \end{array} \right.$$

Fig.9 shows the object input $y_M(k)$ and the output $y(k)$ for the proposed method. We can see that the output follows the

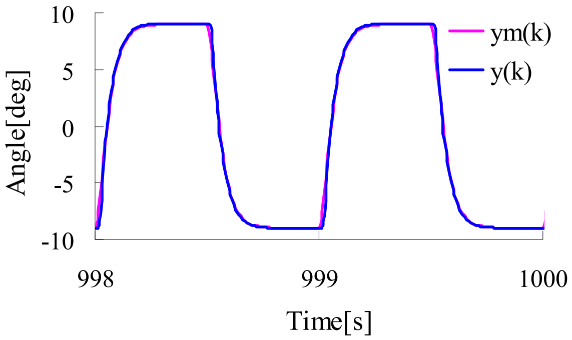
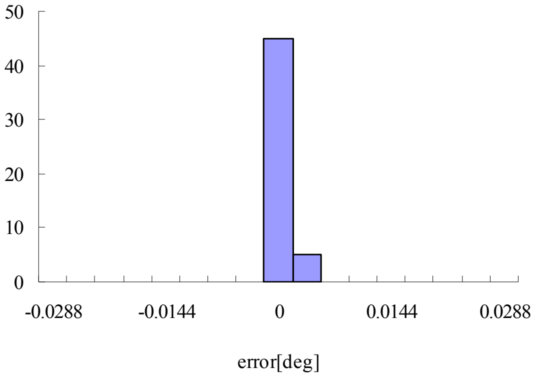
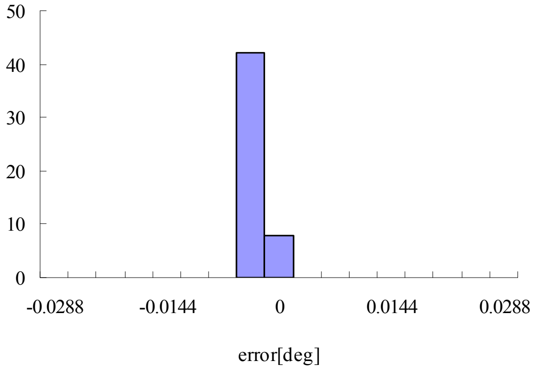


Fig.9 Responses of Proposed method.

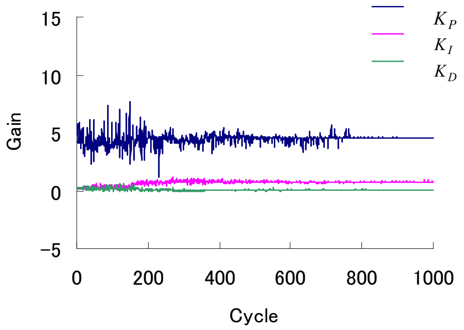


(a) Right rotation

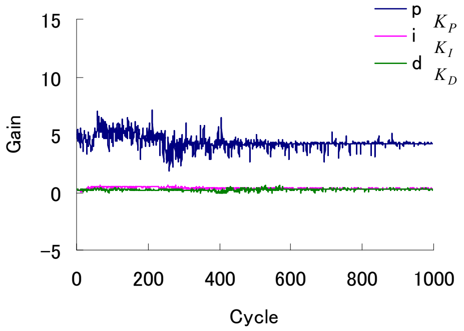


(b) Left rotation

Fig.10 Positioning accuracy of the proposed method with no-load



(a) Right rotation



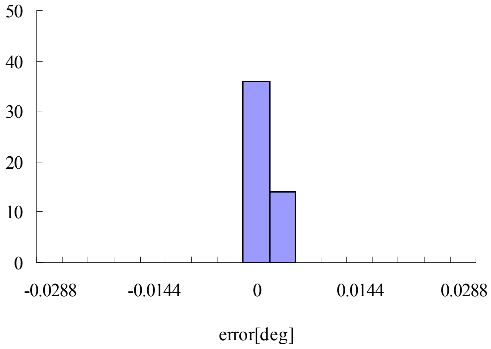
(a) Left rotation

Fig.11 Change situation of gains.

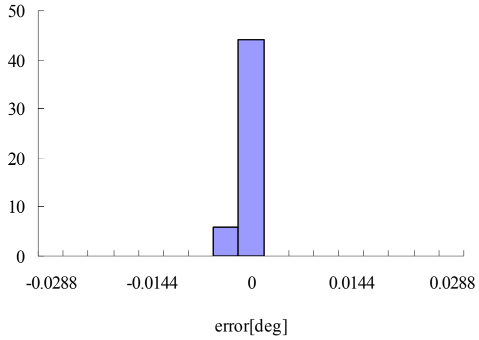
object input very well. Fig.10 shows the histogram of the positioning error between the output $y(k)$ and the object input $y_M(k)$. In the right rotation, the positioning error has been distributed within ±0.0036[deg.]. In the left rotation, the positioning error also has been distributed within ±0.0036[deg.]. Comparing with Fig.8, we can confirm the remarkable improvement in the positioning accuracy. Fig.11 shows the variation of the PID gains.

4.4 Variable gain type PID control with load

In the proposed method, we carried out the experiments in the case of adding the magnetic brake with 0.2[N･m] as the load. It is known that USM causes the characteristic changes in the case of adding the load. Fig.12 shows the histogram of the positioning error between the output $y(k)$ and the object input $y_M(k)$. In both rotations, the positioning error has been distributed within ±0.0036[deg.]. This means that the proposed method compensates the characteristic changes caused by the load to USM.



(a) Right rotation



(b) Left rotation

Fig.12 Positioning accuracy of the proposed method with the load.

5. CONCLUSION

In this paper, we proposed the variable gain type PID control using PSO to optimize the PID gains in order to compensate the nonlinearity and characteristic change of USM. The effectiveness of the proposed design method has been confirmed by experiments.

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