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유전자 알고리즘을 사용한 2관성 모터 시스템의 자동 극배치 제어기 설계

(Autonomous Pole Placement Controller Design of Two-Inertia Motor System Based on Genetic Algorithms)

徐 글 로 리 아 *, 朴 楨 日 **

(Gloria Suh and Jung Il Park)

요 약

2관성 시스템을 제어할 때 자주 발생하는 진동은 빠른 속도 응답을 얻거나 외란 제거를 어렵게 한다. 본 논문은 2관성 모터시스템에 대해서 유전자 알고리즘을 사용하여 세 가지 속도 제어기(I-P, I-PD, 상태 피드백)의 자동 극배치 제어기를 설계하는 방법을 제시한다. 오버슈트와 세틀링 시간을 줄이는 관점에서 유전자 알고리즘을 사용하여 최적의 파라미터를 선정한 다음 이들을 각 제어기의 이득을 계산 할 때 사용한다. 몇 가지의 시뮬레이션을 통해서 제안한 제어기의 성능을 보인다. 제안한 제어기는 유연한 샤프트를 갖는 2관성 모터 시스템의 제어기의 자동 설계법이 될 수 있다.

Abstract

The vibration, which often occurred in a two inertia motor system, makes it difficult to achieve a quick response of speed and disturbance rejection. This paper provides an autonomous pole assignment technique for three kinds of speed controllers (I-P, I-PD, and State feedback) using GAs(Genetic Algorithms) for a two-inertia motor system. Firstly, the optimal parameters are chosen using GAs in view of reducing overshoot and settling time, then those are used in computing the gains of each controller. Some simulation results verify the effectiveness of the proposed design. The proposed controller is expected to be the autonomous design way for controlling a two-inertia motor system with flexible shaft.

Keyword : Two-inertia system, Pole placement controller, Autonomous controller design, Genetic algorithms.

I. Introduction

A two-inertia motor system, such as an industrial rolling machine with a flexible shaft, has very low natural resonant frequency because of the long shaft and low stiffness between the motor and load. This makes it difficult to achieve the precise speed control due to torsional vibration. Hence, many engineers and scientists have focused attention on the reducing oscillation and the settling time in a two-inertia motor system. For example, a speed control using an

* 正會員, 英陽女子高等學校
(YoungYang Girls' High school)
** 正會員, 嶺南大學校 電子情報工學部
(School of Electrical Engineering and Computer Science, Yeungnam University)
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I-P or I-PD controller without an observer to estimate load torque was developed[1]. That paper dealt with systematic analysis and design guidelines for two-inertia system. The techniques of pole assignment are compared only for I-P, and I-PD controller. The Kalman filter and LQ-based speed controller for torsional vibration suppression was also developed[2]. The controller considered in that paper is only the LQ controller using a Kalman filter in the state space. However, there is a difficult problem in that the weighting matrix Q and R should be reselected whenever the system's characteristic is changed. The pole placement technique using the weighted ITAE index proposed in this paper can resolve this problem. Vibration suppression for 2-mass and 3-mass system, which used feedback from the imperfect derivative of the estimated torsion torque, was also studied[3]. The controller used in that paper is a 2-DOF(degree of freedom) PI controller with conventional disturbance observer. By adjusting 2-DOF PI gains, the damping factor of system can be controlled so that the vibration can be effectively suppressed. The auto-tuning of controller and observer parameters of a 2-DOF control system using genetic algorithms was developed[4]. That paper searches five parameters, that is, a filter time constant, a proportional gain, and three filter coefficients. Parameters to find using GAs in [4] are completely different from those to find in this paper. Our paper searches parameters of damping ratios and natural frequencies, which are used in design of the pole placement controller.

In the authors' previous work[5], the systematic analysis and speed controller design technique for a two-inertia motor system was described. A description of how to assign closed-loop poles was also included for three controllers (I-P, I-PD and State feedback) by using the new weighted ITAE(Integral of Time multiplied by the Absolute Error) performance index put a weight on overshoot, considering the fact that the overshoot easily causes vibration in a two-inertia motor system. However, numerous trials were necessary in order to choose the optimal parameters of a pole assignment controller. In order to overcome this problem, the auto-tuning technique of controller gains using genetic algorithms is presented in this paper. Both methods proposed in this paper and author's previous work[5] search the optimal parameters offline. But the ITAE values in the previous work are calculated at regular intervals for damping ratios and natural frequencies, which result in lots of calculations. The parameters with minimum ITAE value out of lots of them will be optimal parameters. This paper's method gives us to these optimal parameters by using GAs autonomously so that the calculation burden can be reduced. Some simulation results verify the effectiveness of the proposed design.

Ⅱ. Two-inertia motor system and three controllers

Before entering the main section, let us review the authors' previous work[5]. In the authors' previous work, a model of a two-inertia motor system and the derivation of optimal controller gains by utilising a pole assigning technique was described for three kinds of controllers.

A motor and load coupled by a shaft with a finite stiffness is shown in Fig. 1, in which

J_M motor inertia; ω_M motor speed;

T_M motor torque; T_L load torque;

K_{sh} torsion stiffness of the drive shaft;

J_L load inertia; ω_L load speed;

T_{sh} shaft torque; θ_M motor angle; θ_L load angle

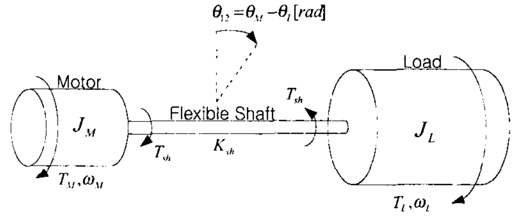


그림 1. 유연한 샤프트를 갖는 2관성 모터 시스템
Fig. 1. Two-inertia motor system model coupled by flexible shaft.

Figure 2 is a simple block diagram representation of a two-inertia motor system.

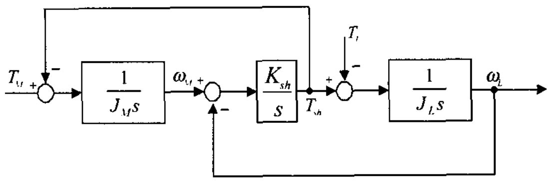


그림 2. 2관성 시스템의 블록도
Fig. 2. Block diagram of a two-inertia system.

The state equation of a mechanical plant for a two-inertia system is given by

$$\dot{X}(t) = AX(t) + BT_M(t) + ET_L(t) \qquad (1)$$
$$Y(t) = CX(t)$$

where output vector $Y = \omega_M$, state vector $X = [\omega_M \ \ \omega_L \ \ \theta_{12}]^T$ and $\theta_{12} = \theta_M - \theta_L$.

$$A = \begin{bmatrix} 0 & 0 & -\frac{K_{sh}}{J_M} \\ 0 & 0 & \frac{K_{sh}}{J_L} \\ 1 & -1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{J_M} \\ 0 \\ 0 \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ -\frac{1}{J_L} \\ 0 \end{bmatrix}, \quad C = [1 \ \ 0 \ \ 0].$$

The transfer function from T_M to ω_M in Fig. 2 can be calculated as follows:

$$T(s) = \frac{s^2 + \omega_a^2}{J_M s(s^2 + \omega_0^2)} \qquad (2)$$

where ω_a and ω_0 represent the anti-resonant frequency and the resonant frequency, respectively. The inertia ratio of load to motor, K, and the resonance ratio, R, are defined as follows:

$$\omega_0 = \omega_a\sqrt{1+K}, \quad K = \frac{J_L}{J_M}, \quad \omega_a = \sqrt{\frac{K_{sh}}{J_L}}, \quad R = \frac{\omega_0}{\omega_a} = \sqrt{1+K} \qquad (3)$$

Figures 3 through 5 represent the structure of each speed control system using I-P, I-PD, and state feedback controllers, respectively. The closed-loop transfer function for I-P controller of Fig. 3 is given by

$$\frac{\omega_L}{\omega_r} = \frac{K_I\omega_a^2}{J_M s^2(s^2 + \frac{K_P}{J_M}s + \omega_0^2) + K_P\omega_a^2 s + K_I(s^2 + \omega_a^2)} \qquad (4)$$

The closed-loop transfer function for the system shown in Fig. 4 using an I-PD controlleris obtained as follows:

$$\frac{\omega_L}{\omega_r} = \frac{K_I\omega_a^2}{\tilde{J}_M s^2(s^2 + \frac{K_P}{\tilde{J}_M}s + \tilde{\omega}_0^2) + K_P\omega_a^2 s + K_I(s^2 + \omega_a^2)} \qquad (5)$$

$$\text{where} \quad \tilde{J}_M = J_M + K_D, \quad \tilde{\omega}_0 = \omega_a\sqrt{1+\tilde{K}}, \quad \tilde{K} = \frac{J_L}{\tilde{J}_M} \qquad (6)$$

The closed loop transfer function for a state feedback controller as shown in Fig. 5 is given by

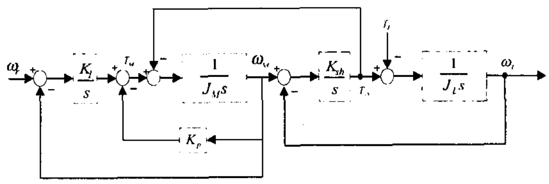


그림 3. I-P 제어기를 사용한 속도 제어 시스템
Fig. 3. Speed control system with I-P controller.

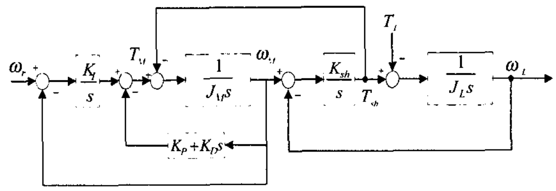


그림 4. I-PD 제어기를 사용한 속도제어 시스템
Fig. 4. Speed control system with I-PD controller.

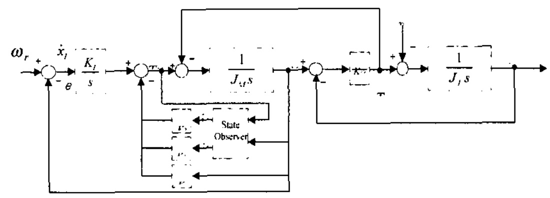


그림 5. 상태 피드백 제어기를 사용한 속도제어 시스템
Fig. 5. Speed controll system with state feedback controller.

$$\frac{\omega_L}{\omega_r}=\frac{K_I\omega_a^2}{J_M s^2(s^2+\frac{K_1}{J_M}s+\hat{\omega}_0^2)+(K_1+K_2)\omega_a^2 s+K_I(s^2+\omega_a^2)} \quad (7)$$

where $\hat{\omega}_0=\sqrt{\omega_0^2+\frac{K_3}{J_M}}$ (8)

The weighted ITAE performance index, which is used in this paper, is given by

$$I(k+1)=I(k)+ke(k),\ if\ e(k)>0$$
$$I(k)+k\left|e(k)\right|^{\gamma},\ otherwise \quad (9)$$

where $e(k)=\omega_r(k)-CX(k)$, $0\prec\gamma\leq 1$.

In the authors' previous work[5], it was shown that a controller designed by using this weighted ITAE index reduces the overshoot or oscillation because the closed-loop system has a large damping property by weighting for overshoot. This technique assists us in selecting optimal location of poles without oscillation. Also, the minimum values of this ITAE index can easily be derived compared to those of the conventional ITAE index, which does not have γ in an exponent[5].

The closed loop transfer function can be arranged as follows:

$$\frac{\omega_L}{\omega_r}=\frac{\omega_1^2\omega_2^2}{(s^2+2\varsigma_1\omega_1 s+\omega_1^2)(s^2+2\varsigma_2\omega_2 s+\omega_2^2)} \quad (10)$$

where ω_i and ς_i (for i=1,2) are the natural frequency and the damping ratio, respectively. Comparing (10) and each closed-loop transfer function, the gains of each controller and relation equation are obtained as follows:

(i) I-P speed controller

$$K_P=2(\varsigma_1\omega_1+\varsigma_2\omega_2)J_M \quad (11)$$

$$K_I=\frac{\omega_1^2\omega_2^2}{\omega_a^2}J_M \quad (12)$$

$$\omega_a^2(\omega_1^2+\omega_2^2+4\varsigma_1\varsigma_2\omega_1\omega_2)-\omega_1^2\omega_2^2=\omega_a^4(K+1)=\omega_a^2\omega_0^2 \quad (13)$$

$$\omega_1\varsigma_1(\omega_2^2-\omega_a^2)=\omega_2\varsigma_2(\omega_a^2-\omega_1^2) \quad (14)$$

(ii) I-PD speed controller

$$K_P=2(\varsigma_1\omega_1+\varsigma_2\omega_2)\tilde{J}_M \quad (15)$$

$$K_I=\frac{\omega_1^2\omega_2^2}{\omega_a^2}\tilde{J}_M \quad (16)$$

$$K_D=\frac{\omega_a^4 J_L}{\omega_a^2(\omega_1^2+\omega_2^2+4\varsigma_1\varsigma_2\omega_1\omega_2)-\omega_1^2\omega_2^2-\omega_a^4}-J_M \quad (17)$$

$$\omega_1\varsigma_1(\omega_2^2-\omega_a^2)=\omega_2\varsigma_2(\omega_a^2-\omega_1^2) \quad (18)$$

$$\tilde{\omega}_0^2=\omega_a^2(1+\tilde{K})=\omega_1^2+\omega_2^2+4\varsigma_1\varsigma_2\omega_1\omega_2-\frac{\omega_1^2\omega_2^2}{\omega_a^2} \quad (19)$$

(iii) State feedback speed controller with integral

$$K_1=2(\varsigma_1\omega_1+\varsigma_2\omega_2)J_M \quad (20)$$

$$K_I=\frac{\omega_1^2\omega_2^2}{\omega_a^2}J_M \quad (21)$$

$$K_2=\frac{2J_M}{\omega_a^2}(\omega_1\varsigma_1(\omega_2^2-\omega_a^2)-\omega_2\varsigma_2(\omega_a^2-\omega_1^2)) \quad (22)$$

$$K_3=J_M(\omega_1^2+\omega_2^2+4\varsigma_1\varsigma_2\omega_1\omega_2-\frac{\omega_1^2\omega_2^2}{\omega_a^2}-\omega_0^2) \quad (23)$$

$$\hat{\omega}_0^2=\omega_1^2+\omega_2^2+4\varsigma_1\varsigma_2\omega_1\omega_2-\frac{\omega_1^2\omega_2^2}{\omega_a^2} \quad (24)$$

If we choose K_2 as a positive constant and $\omega_2\rangle\omega_1$, $\varsigma_1\omega_1=\varsigma_2\omega_2$, then the relation between ω_1 and ω_2 in a closed-loop system is given by

$$\omega_2=\sqrt{2\omega_a^2\left(1+\frac{K_2}{K_1}\right)-\omega_1^2}>\sqrt{2\omega_a^2-\omega_1^2} \quad (25)$$

Ⅲ. Controller design using genetic algorithms

In order to find a minimum ITAE index value as described in the authors' previous work[5], the ITAE calculation for many cases must be done. To overcome this calculation burden, we are introducing an autonomous method, which can be used to find

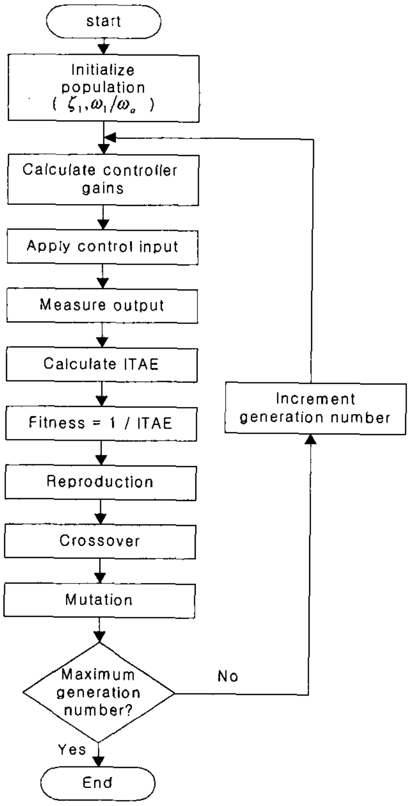


그림 6. 최적 파라미터를 선정하기 위한 스텝 시퀀스
Fig. 6. The sequence of steps needed to choose optimal parameters

optimal parameters of a controller using genetic algorithms.

In this paper, poles are assigned to have identical real part as shown in (26) that gives optimal performance in terms of the settling time of transient response[1]. The condition for these poles is given by

$$-\omega_1\varsigma_1 = -\omega_2\varsigma_2 \tag{26}$$

1. Outline of the controller design

Here, γ in (9) is set at 0.7. In the proposed autonomous design, two individuals, that is, ς_1 and ω_1/ω_a, are optimised by using genetic algorithms. These are selected at random at first, then vary with values between 0.6 and 1.0 according to the genetic operation. In the genetic operation, an inverse of the ITAE value is evaluated as the fitness value, where the higher fitness results in the better solution. The best solution at each generation is successively reflected in the controller gains.

The overall sequence of steps needed to choose optimal parameters using genetic algorithms is shown in Fig. 6.

The parameters of genetic algorithms used are shown in Table 1.

표 1. 유전자 알고리즘의 파라미터
Table 1. Parameters of genetic algorithms.

Item	Condition
Population size	8
Number of individuals	2
Crossover probability	0.9
Mutation probability	0.012
Maximum generation number	30

2. Choosing optimal parameters and their verification

The specifications of the two-inertia motor system used in this study are shown in Table 2.

표 2. 2 관성 모터 시스템의 기계 파라미터
Table 2. Mechanical parameters of a two-inertia motor system.

Item	Value
Motor inertia[Kgm^2]	7.455×10^{-5}
Torsion stiffness[Nm/rad]	0.05
Resonant frequency[rad/s]	39.69
Anti-resonant frequency[rad/s]	30
Inertia ratio (K)	0.75
Sampling time[ms]	2

In order to verify the performance of auto-tuning using GAs, we compare the responses before training with responses after training for each controller. And we also compare the optimal parameters obtained by numerous trials for many ς_1 and ω_1/ω_a with the optimal parameters obtained by using GAs.

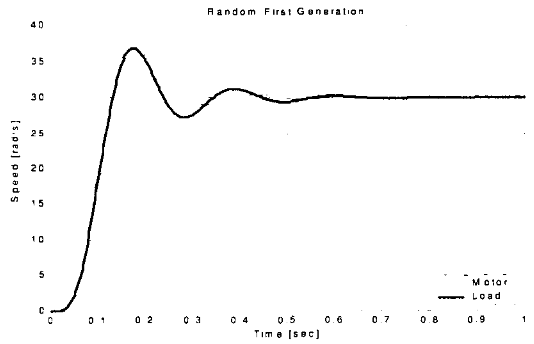
(i) I-P speed controller

Table 3 shows optimal parameters, ς_1 and ω_1/ω_a, obtained with GAs(values without parentheses) and those(values within parentheses) obtained by numerous trials for several ς_1 and ω_1/ω_a in an I-P control. Both cases have almost same values. We found the optimal parameters for several inertia ratios, respectively.

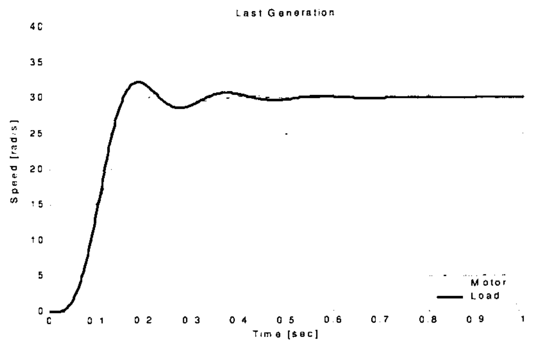
Using optimal parameters obtained by genetic operation, I/P gains are calculated using (11), (12).

표 3. I-P 제어시의 최적 파라미터
Table 3. Optimal parameters for I-P control.

Design conditions	K	0.5	0.75	1.0	1.5	2.0
	R	1.23	1.32	1.41	1.58	1.73
Selected para-Meters	ITAE	6.132	5.046	4.570	4.435	4.108
	Fitness	0.163	0.198	0.219	0.226	0.243
	ς_1	0.70 (0.73)	0.72 (0.75)	0.81 (0.79)	0.84 (0.84)	0.87 (0.84)
	ω_1/ω_a	0.60 (0.60)	0.61 (0.60)	0.66 (0.63)	0.68 (0.74)	0.84 (0.91)



(a) ς_1=0.62, ω_1/ω_a=0.79(using random parameters before training)



(b) ς_1=0.72, ω_1/ω_a=0.61(using optimal parameters after training).

그림 7. I-P 제어시의 속도 응답
Fig. 7. Speed responses for I-P controller.

Figure 7 shows the responses before and after training with GAs, respectively. The overshoot and oscillation of the caseafter training when using GAs is less than that of the case before training. However, even though we selected optimal parameters for the proposed method, oscillation still occurred in the transient response in the I-P control.

(ii) I-PD speed controller

Table 4 shows optimal parameters obtained with GAs(values without parentheses) and those(values within parentheses) obtained by numerous trials for several ς_1 and ω_1/ω_a in an I-PD control. Using optimal parameters obtained by genetic operation, I/P/D gains are calculated using (15), (16), (17).

표 4. I-PD 제어시의 최적 파라미터
Table 4. Optimal parameters for I-PD control.

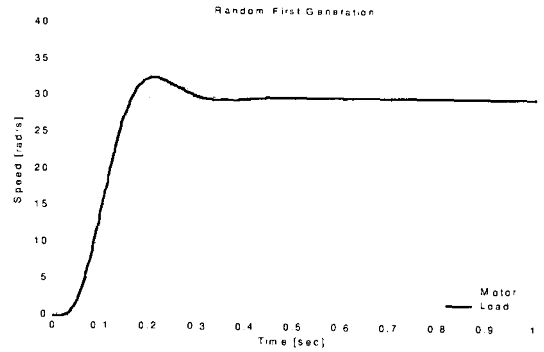
Design condi-tion	K	0.5	0.75	1.0	1.5	2.0
	R	1.23	1.32	1.41	1.58	1.73
Selected para-Meters	ITAE	4.573	4.539	4.397	4.387	4.391
	Fitness	0.220	0.227	0.228	0.228	0.243
	ς_1	0.926 (0.89)	0.903 (0.90)	0.892 (0.90)	0.906 (0.91)	0.912 (0.91)
	ω_1/ω_a	0.812 (0.70)	0.826 (0.72)	0.754 (0.73)	0.766 (0.75)	0.760 (0.76)

In the case of the I-PD controller, the optimal values appear at almost the same values of ς_1 and ω_1/ω_a irrespective of the inertia ratio[5]. For the inertia ratio of 0.75, ς_1 will be 0.903 and ω_1/ω_a will be 0.826. Then from (25) and (26), ω_2 will be 1.15 ω_a and ς_2 will be 0.65. The I/P/D gains are obtained as follows:

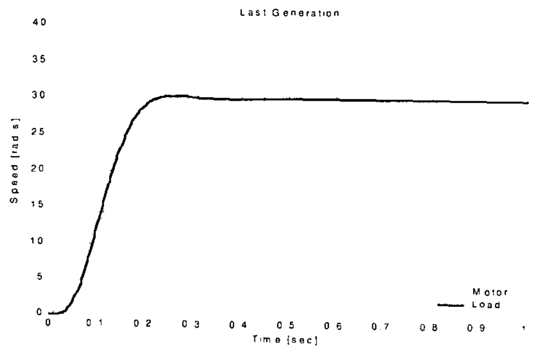
$$K_P = 1.2825\omega_a J_L, \quad K_I = 0.3845\omega_a^2 J_L,$$

$$K_D = 0.43 J_L - J_M$$

Similarly, both cases using the I-PD controller are plotted as shown in Fig. 8



(a) ς_1 =0.70, ω_1/ω_a =0.96(using random parameters before training)



(b) ς_1 =0.90, ω_1/ω_a =0.83(using optimal parameters after training)

그림 8. I-PD 제어시의 속도 응답

Fig. 8. Speed responses for I-PD controller.

(iii) State feedback speed controller with integral

In the state feedback controller, ω_2 is set as follows:

$$\omega_2 = \alpha\sqrt{2\omega_a^2 - \omega_1^2} \tag{27}$$

where a is the positive constant to meet inequality (25). The constant, a, is selected based on the torsion amount. If a is large, the torsion amount becomes large, and vice versa. Here, a is set at 1.5.

The optimal parameters are summarised in Table 5. The optimal parameters are almost the same, irrespective of the inertia ratio. This result coincides with the result of the authors' previous work[5]. This implies that the controller can be designed irrespective of inertia ratio. The optimal parameters are obtained as follows:

표 5. 상태 피드백 제어시의 최적 파라미터

Table 5. Optimal parameters for state feedback control.

Design conditions	K	0.5	0.75	1.0	1.5	2.0
	R	1.23	1.32	1.41	1.58	1.73
Selected parameters	ITAE	2.976	2.964	2.937	2.917	2.902
	Fitness	0.336	0.337	0.341	0.343	0.345
	ς_1	0.914 (0.90)	0.914 (0.90)	0.906 (0.90)	0.906 (0.90)	0.906 (0.90)
	ω_1/ω_a	0.958 (0.94)	0.958 (0.94)	0.948 (0.94)	0.948 (0.94)	0.948 (0.94)

$$\varsigma_1 = 0.914,\quad \omega_1 = 0.958\omega_a,$$

$$\omega_2 = 1.04\alpha\omega_a,\quad \varsigma_2 = 0.84/\alpha.$$

Then the gains of the state feedback controller from these values are obtained as follows:

$$K_1 = 3.502\omega_a J_M,$$

$$K_I = 0.993\alpha^2\omega_a^2 J_M,$$

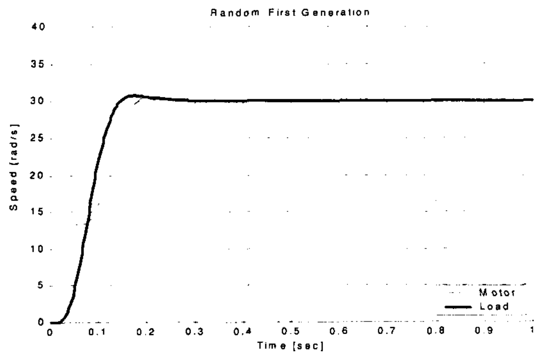
$$K_2 = 1.895(\alpha^2 - 1)\omega_a J_M,$$

$$K_3 = (2.985 + 0.089\alpha^2)\omega_a^2 J_M - K_{sh}$$

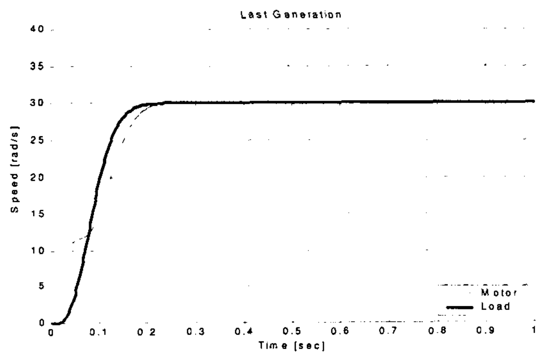
In the state feedback controller design, it is also required to properly select observer gain, which affects the system response. The responses are shown in Fig. 9.

From figures 7 through 9, the responses which derived by using optimal parameters obtained by using GAs indicate much better performance than the one derived using parameters at random. From tables 3 through 5, the optimal values obtained by using GAs nearly coincide with those of the authors' previous work[5]. This seems to indicate the effectiveness of GAs.

Figure 10 shows the fitness values in the genetic process when each controller is used. From Fig. 10, we can see that thefitness values increase in small increments according to an increasing generation. This means that the procedure of using GAs performs well. Comparing the three controllers, the fitness value of the state feedback control is larger than that of any other control. This means that the state feedback controller has the best performance.



(a) ζ_1=0.81, ω_1/ω_a=0.93(using random parameters before training)



(b) ζ_1=0.91, ω_1/ω_a=0.96(using optimal parameters after training)

그림 9. 상태 피드백 제어시의 속도 응답
Fig. 9. Speed responses for state feedback controller.

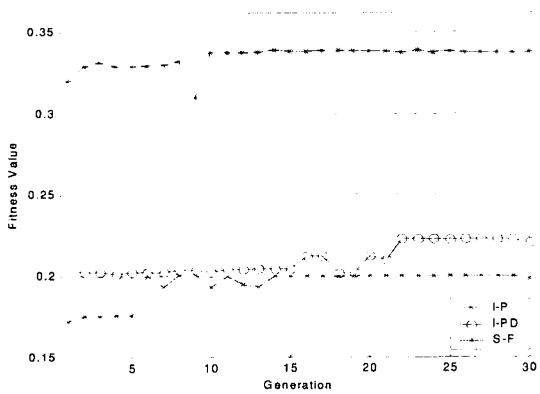
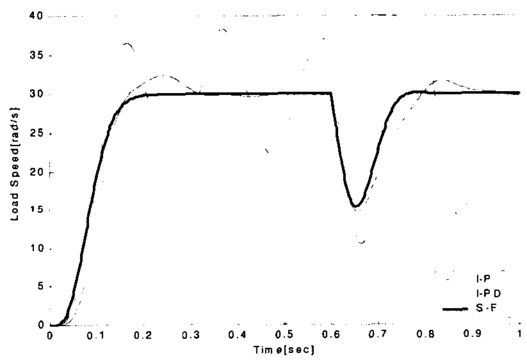


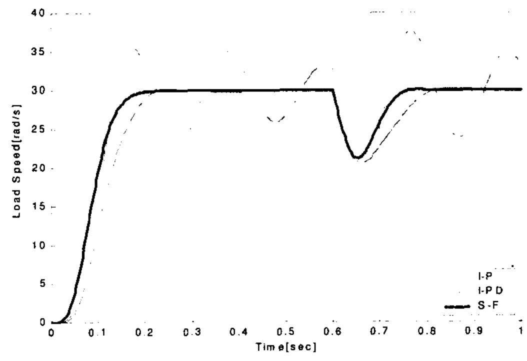
그림 10. 유전자 알고리즘의 적합도 함수의 변화
Fig. 10. Fitness values in the genetic process.

3. Comparison of three kinds of controllers

In this section, to evaluate the three controllers for a two-inertia motor system with a very low inertia ratio, which easily causes the oscillation, the following simulations are carried out for two different inertia ratios 0.15 and 0.25, respectively. The rejection behaviour of disturbance is also evaluated. The step disturbance, 0.005[N-m], is added to the control input in 0.6 second after starting. Each controller gains are obtained by using each gain equations from (11) through (23) for ζ_1=0.89, ω_1/ω_a=0.64, respectively. Other specifications used are the same as shown in Table 2 except for inertia ratio and torsion stiffness, which is changed according to the inertia ratio.



(a) Inertia ratio(K)=0.15, torsion stiffness = 0.01



(b) Inertia ratio(k)=0.25, torsion stiffness=0.017

그림 11. 관성비가 적을 때의 부하에 대한 속도 응답 (K=0.15,0.25)
Fig. 11. Load speed responses in the presence of disturbance when the inertia ratio is small. (K=0.15,0.25).

In Fig. 11, we can see that I-P controller causes oscillation and larger oscillation for disturbance particularly. However, the state feedback controller gives us a robust performance without the oscillation even though the inertia ratio is small. It also has a fast recovery compared to the I-P controller on disturbance. A state feedback controller designed in this way provides us with the best performance compared with the I-P controller and I-PD controller, and it can also be designed irrespective of inertia ratio.

Ⅳ. Conclusions

This paper described how to find the location of poles in order to reduce oscillation and settling time by using genetic algorithms for three speed controllers, namely, an I-P, an I-PD, and a state feedback controller in a two-inertia motor system. The controller that was designed based on the genetic algorithm allowed us to obtain the best system response which reduced oscillation and torsion. With the proposed auto-tuning of controller gains using genetic algorithms, we could resolve the problem of calculating an ITAE index value for many cases in order to select optimal parameters for the controllers

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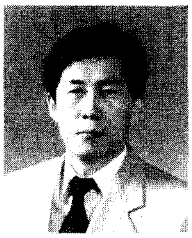
저 자 소 개

徐글로리아(正會員)

She received the B.S. degree in department of Mathematics Education in 1996 from Taegu University, and the M.S. degree and in Electronics Engineering in 2002 from Yeungnam University. She is currently a teacher in the YoungYang girls' high school, Kyungbuk province since 2003.



朴 楨 日(正會員)

He received the B.S. degree in Electronics Engineering in 1981 from Kyungbuk National University, and the M.S. degree and the Ph. D. in Electronics Engineering in 1983 and 1989, respectively, from Seoul National University. He is currently a professor in the School of electrical engineering and computer science, Yeungnam University since 1992. His current research interests include Neural-based intelligent control, Mechatronics, Servo/Linear motor control, High precision motion control, and Industrial application of control system. He can be reached at the School of electrical engineering and computer science, Yeungnam University, Daedong, Gyongsan Kyungbuk, 712-749, Korea, jipark@yu.ac.kr.