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최소 탐색시간을 위한 2단 구동기의 최적설계법

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권대갑

AN OPTIMUM DESIGN METHOD OF DUAL-STAGE ACTUATORS FOR MINIMUM SEEK TIMES

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ABSTRACT

In this paper, we propose a design method using Taguchi method and a neural network. Using this method, we can design a dual-stage actuator having the required tracking/focusing properties in real time. Also, as an application of this method, a proposed dual-stage *pick-up actuator having the required properties was designed. The seek time of this designed actuator is less than 13 msec by a time optimal technique. Simulation results show that this method can potentially be implemented in all the dual-stage actuators.

1. INTRODUCTION

In optical pick-up actuators, seek time is one of the most important performance factors. In order to shorten seek time, an actuator with a large drive force is required. For the above requirements, a lot of researches on pick-up actuators have been carried out.[1,2] Design method to satisfy the tracking and focusing properties[3]

Also, design parameter variations according to manufacturing errors and assembly errors of actuators affect the required seek times. In this paper, we propose a robust optimum design method using Taguchi method and to increase the acceleration of a 2-axis actuator were proposed.[4] Such design methods merely increase the maximum drive acceleration and force of the actuator. However, seek time cannot be minimized by the maximum drive acceleration and force, because friction force and back EMF exist; thus, a time optimal technique is needed to minimize seek time.

and a neural network. By this method, seek times, which is robust from parameter variations of pick-up actuators, are minimized.

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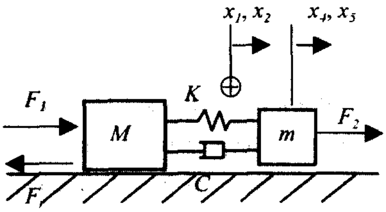
*김선모, 권대갑 : 한국과학기술원 기계공학과

2. TRACKING/FOCUSING PROPERTIES AND CHARACTERISTIC PARAMETERS OF A PICK-UP ACTUATOR

First, we determine the characteristic parameters and tracking/focusing properties of a pick-up actuator to use in the proposed optimum design. Figure 1 shows a dynamic model of a dual-stage pick-up actuator. x_1 and x_2 are the position and velocity of the mass center, respectively. x_4 and x_5 are the position and velocity of the bobbin, x_3 and x_6 are currents of the coarse tracking actuator coil and the fine tracking actuator coil, respectively. Also, F_1 represents the driving force for the coarse tracking actuator, and F_2 that of the fine tracking actuator. F_r is the friction force.



⊕ : Mass Center

Fig. 1 Coupled dual stage actuator model

Thus, the state equation of the actuator is

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -\frac{\beta}{M} & \frac{\phi_1}{M} & 0 & 0 & 0 \\ 0 & -\frac{\phi_1}{L_1} & -\frac{R_1}{L_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ \frac{K}{m} & \frac{C}{m} & 0 & -\frac{K}{m} & -\frac{C}{m} & \frac{\phi_2}{m} \\ 0 & 0 & 0 & 0 & -\frac{\phi_2}{L_2} & -\frac{R_2}{L_2} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{Bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} -\frac{\alpha}{M} \\ \frac{E_1}{L_1} \\ \frac{E_2}{L_2} \end{Bmatrix} \tag{1}$$

and

$$x_1(0) = -S_1, \quad x_2(0) = 0, \quad x_3(0) = \frac{\alpha}{\phi_1}, \quad |u_1| \le 1$$
$$x_4(0) = -S_2, \quad x_5(0) = 0, \quad x_6(0) = 0, \quad |u_2| \le 1$$

where M is the total mass, m is the fine actuator's mass, and α, β are coefficients corresponding to friction force. Further, K is the spring constant, C is the damping coefficient, and R, L, and ϕ are resistance, inductance and force constant of the actuator, respectively. S_1 denotes a 1/3 full stroke and S_2 denotes a fine motion stroke of a fine tracking actuator. The subscripts expressed as 1 and 2(excepting state variables) refer to the coarse tracking actuator and fine tracking actuator, respectively. Finally, u_1 is E_1/L_1 and u_2 is E_2/L_2. Thus, minimum seek time, which is one of the tracking properties of the actuator, can be calculated from Eqn (1).

Table 1 represents the tracking and focusing properties. These properties-except for seek time and coarse actuator power-are closely related to 2-axis actuator performances.

Table 1 Tracking and focusing properties of a pick-up actuator

Tracking/Focusing Properties	
Seek Time	T_s
5 Hz Sensitivity(T)	$\dfrac{\phi_2}{\sqrt{\left(KR_2-\left(mR_2+CL_2\right)\varpi^2\right)^2+\left(\left(\phi_2^2+KL_2\right)\varpi-mL_2\varpi^3\right)^2}}$

200 Hz Sensitivity(T)	$\frac{\phi_2}{\sqrt{\left(KR_2-(mR_2+CL_2)\varpi^2\right)^2+\left((\phi_2^2+KL_2)\varpi-mL_2\varpi^3\right)^2}}$
Q-value(T)	$20\log\left(\frac{\sqrt{mK}}{C}\right)$
Power(Coarse)	$\frac{E_1^2}{R_1}$
Power(Fine)	$\frac{E_2^2}{R_2}$
5 Hz Sensitivity(F)	$\frac{\phi_f}{\sqrt{\left(KR_f-(mR_f+CL_f)\varpi^2\right)^2+\left((\phi_f^2+KL_f)\varpi-mL_f\varpi^3\right)^2}}$
200 Hz Sensitivity(F)	$\frac{\phi_f}{\sqrt{\left(KR_f-(mR_f+CL_f)\varpi^2\right)^2+\left((\phi_f^2+KL_f)\varpi-mL_f\varpi^3\right)^2}}$
Q-value(F)	$20\log\left(\frac{\sqrt{mK}}{C}\right)$
Power(F)	$\frac{E_f^2}{R_f}$

Further, we must define the characteristic parameters used to calculate the tracking and focusing properties; these are shown in Table 2. Our purpose is to design an actuator with required tracking and focusing properties. These properties represent the ability to compensate for tracking and focusing errors in wide frequency ranges. Seek time, which is calculated from the time optimal technique, is the most significant property in the design of a pick-up actuator with a fast seek property. Thus, to satisfy the required tracking and focusing requirements, the characteristic parameters are used as the design parameters of the pick-up actuator. In the next section, we propose a method using Taguchi method to obtain the minimum seek time which is robust from the variations of the characteristic parameters according to the manufacturing errors of a pick-up actuator.

Table 2 Characteristic parameters of a pick-up actuator

Characteristic Parameters related to the Tracking/Focusing Properties
M, m
R_1, L_1, E_1, ϕ_1
R_2, L_2, E_2, ϕ_2
R_f, L_f, E_f, ϕ_f
K, C

3. DETERMINATION OF A OPTIMUM FORCE CONSTANT BY TAGUCHI METHOD

In this section, we determine the optimum force constants to yield minimum seek times which is robust from the variations of the characteristic parameters. A minimum seek time corresponding to a set of characteristic parameters is calculated from Eqn (1) in the previous section. In order to minimize seek time, the characteristic parameters excepting ϕ_1, ϕ_2, and K have the maximum or minimum values within the given design range. In the cases of ϕ_1, ϕ_2, and K, however, optimum values to minimize seek time may differ from the fixed maximum or minimum values To find the optimum values of these parameters, we, first, defined the design ranges of the characteristic parameters as in Table 3. Seek distances, S_1 and S_2, were also determined to be 11 mm and 1 mm, respectively.

Table 3 Design ranges of the Characteristic parameters

Characteristic Parameters	Ranges
M	1 ~ 10 [g]
R_1	1 ~ 10 [Ω]

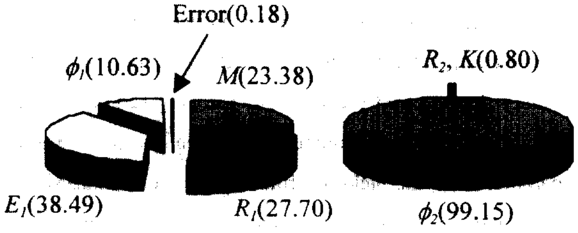
L_1	0.01 ~ 10	[mH]
E_1	1 ~ 5	[V]
ϕ_1	0.5 ~ 3.5	[N/A]
m	0.3 ~ 1.0	[g]
R_2	1 ~ 10	[Ω]
L_2	0.001 ~ 1	[mH]
E_2	1 ~ 5	[V]
ϕ_2	0.3 ~ 1.5	[N/A]
R_f	1 ~ 10	[Ω]
L_f	0.001 ~ 1	[mH]
E_f	1 ~ 5	[V]
ϕ_f	0.3 ~ 1.5	[N/A]
K	10 ~ 80	[N/m]
C	0.01 ~ 0.1	[Ns/m]

We carried out a lot of simulations within the above ranges, and found that the optimum values of ϕ_2 and K were the maximum values within the above ranges. Therefore, ϕ_1, except for ϕ_2 and K, had to be optimized within the given design range. However, the characteristic parameters have the undesirable parameter variations due to manufacturing errors, assembly errors, and variations in the physical properties. Thus, in order to find the optimum value of ϕ_1 which is robust from these parameter variations, we used Taguchi method in this study. Because each noise factor which means the parameter variation was divided into three levels, the orthogonal array table of $L_{27}(3^{11})$ was used. Next, random values of the characteristic parameters except for ϕ_1 were chosen within the given ranges. The first, second, and third levels of $L_{27}(3^{11})$ correspond to +10, 0, and -10 % deviation from the random values, respectively. Next, 27 simulations were excuted to find an S/N ratio, η, as follows:

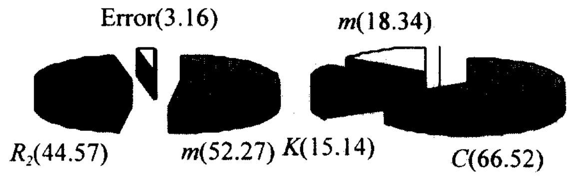
$$\eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right], \quad i = 1, 2, \cdots, 27$$

where y_i is the seek time calculated from Eqn (1) in the i^{th} noise factor condition, and n is the total number of simulations. Our purpose was to find the maximum value of η as ϕ_1 changes within the design range. When η is the maximum value, the force constant, ϕ_1, takes the optimum value. To maximize η means that seek time is minimized under the influences of undesirable parameter variations. Thus, a robust optimum design was achieved for a dual stage actuator. Also, the tracking properties, except for the seek time, were calculated from Table 1 by using the given random parameters. Focusing properties were calculated using m, K, C, and another set of random parameters related to the focusing properties. We prepared two hundred items of random simulation data for a neural network learning in the following section.

On the other hand, the parameter's contributions to seek time, 5 Hz sensitivity, 200 Hz sensitivity and Q-value are shown in Fig. 2. We can see that the significant parameters for each property. In figure (a), coarse actuator parameters are main parameters which affect seek time property. Also, in (b), (c) and (d), significant parameters for each property are different. That is, the influences of the significant parameters for a property are independent of other properties. Thus, two hundred items of data which consisting of the characteristic parameters and the tracking/focusing properties were used in the neural network learning that followed.



(a) Seek time (b) 5 Hz sensitivity



(c) 200 Hz sensitivity (d) Q-value

Fig. 2 Pi plots for the contributions of the significant effects

4. A DESIGN METHOD OF A DUAL-STAGE ACTUATOR USING A NEURAL NETWORK

4.1 LEARNING OF CHARACTERISTIC PARAMETERS AND TRACKING/FOCUSING PROPERTIES

We introduce a robust optimum design method using a neural network for the real time calculation the characteristic parameters of a dual-stage actuator having the required properties. First, we chose a back propagation structure as a neural network, the input and output nodes consist of the required tracking/focusing properties and the characteristic parameters, respectively.

In addition, through a lot of simulations, it was shown that each structure required two hidden layers for better learning effects. Table 4 shows the numbers of the hidden layers and nodes which used in the simulations. Figure 3 shows the mean values of the final errors at output nodes after 50,000 iterations.

Tabel 4 Numbers of layers and nodes under various simulation conditions

Simulation No.	Number of Hidden Layers	Number of Nodes	
1	1	20	
2	1	25	
3	2	15	15
4	2	20	15
5	2	25	15
6	2	15	20
7	2	15	25
8	2	20	25
9	2	25	25
10	2	30	25

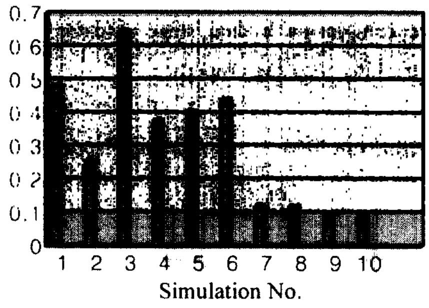


Fig. 3 Mean values of the final errors at output nodes after 50,000 iterations

From this figure, it is confirmed that simulation no. 9 had the minimum mean value. Thus, we chose the structure with two hidden layers and 25 nodes per layer.

In this structure, a learning rate of 0.05 and a momentum parameter of 0.3 were used to optimize learning results. From this neural network, we can obtain the characteristic parameters of a dual-stage actuator which has the required tracking/focusing properties in real time.

4.2 DETERMINATION OF DESIGN PARAMETERS FOR A PROPOSED DUAL-STAGE ACTUATOR

In order to design a real actuator, the design parameters related to the actuator's size, magnetic circuit dimensions, and coil dimensions were needed. The design parameters of an actuator can be variously determined according to the structure of the actuator. However, the design parameters of the proposed dual-stage actuator could have been calculated by various methods if the required characteristic parameters were given. Here, we used a SQP method to obtain the design parameters from characteristic parameters. Figure 4 shows this design structure, including the neural networks related to the tracking/focusing properties and the characteristic parameters. In this figure, N.N 1 and N.N 2 represent the back propagation structures of the previous section. Thus, we can design a dual stage actuator from the required tracking/focusing properties.

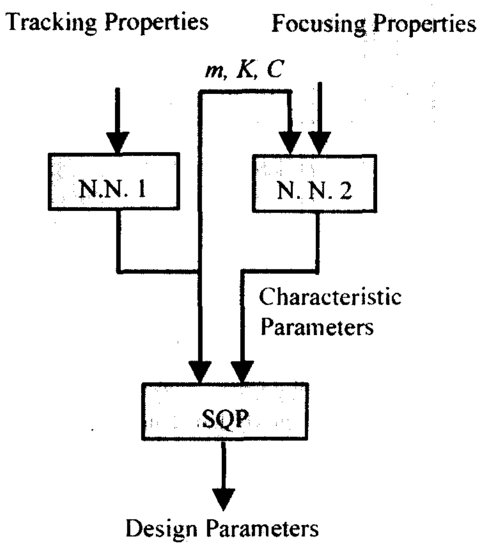


Fig. 4 Neural network structure for the design parameters

In this paper, we propose a dual-stage pick-up actuator of small size and mass, and high resonant frequencies for fast seek motion. Table 5 lists the required properties and the characteristic parameters for this actuator. The required properties represent the performances of the proposed actuator with fast seek motion and better dynamic characteristics.

Table 5 The required properties for the proposed Actuator

Tracking/Focusing Properties	
Seek Time : 12.5 msec	
Sensitivity(5Hz) : 6 mm/V(T), 7mm/V(F)	
Sensitivity(200Hz) : 250 μm/V(T), 270 μm/V(F)	
Q-value : 8 dB(T/F)	
Characteristic Parameters	
M : 7 [g]	ϕ_1 : 2.82 [N/A]
R_1 : 11 [Ω]	m : 0.7 [g]
L_f : 20 [μH]	ϕ_f : 0.752 [N/A]
E_1 : 5.45 [V]	L_1 : 5 [mH]
L_2 : 185 [μH]	ϕ_2 : 0.793 [N/A]
R_f : 2.533 [Ω]	E_2 : 2.67 [V]
E_f : 2.516 [V]	R_2 : 2.85 [Ω]
C : 0.0723 [Ns/m]	K : 44.64 [N/m]

Thus, the design parameters calculated from a SQP method using the characteristic parameters are shown in Table 6. The desired design parameters were directly calculated by SQP method. Because the differences between the properties of Table 5 and those of Table 6 are very small, we can obtain a proposed actuator with the required tracking/focusing properties. From this fact, we can say that our proposed design method using Taguchi method and a neural network structure is able to use a robust optimum design method of a dual-stage actuator.

Table 6 Design parameters for the proposed actuator

Desired design parameters
T_t : 0.2
T_f : 0.2

$W_t : 3$

$W_f : 1.4$

$D_s : 1.6$

$L_d : 3$

$h : 2$

$T_{mag} : 1.915$

$T_{yoke} : 1.84$

$H_{mag} : 5$

$T_c : 0.3$

$L_c : 7.1$

Tracking	Focusing
Seek Time : 12.88	
5Hz Sen. : 5.37	5Hz Sen. : 6
200Hz Sen. : 287	200Hz Sen. : 306
Q-value : 8.8	Q-value : 8.8

5. CONCLUSIONS

A seek time of a dual-stage actuator cannot be minimized by maximum drive acceleration and force, because a friction force and back EMF exist. Thus, a time-optimal technique was used for seek time minimization. In this study, we proposed a robust optimum design method using Taguchi method and a neural network. With this method, we were able to design a dual-stage actuator with the required tracking/focusing properties in real time. Also, as an application of this method, a proposed dual-stage pick-up actuator having the required properties was designed. The seek time of this designed actuator is less than 13 msec. Simulation results show that this method can be potentially implemented to all dual-stage actuators. In the future, we will experimentally investigate the performances and characteristics of our method.

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