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반복 제어기를 이용한 광디스크 포커스 제어
Repetitive control design for an ODD focusing servo system

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ABSTRACT

As the disk in the ODD rotates, disturbances acting on the ODD servo system generally have periodic components. Such disturbances can make the system unstable and make the controller hard to work. The repetitive controller can be the solution of the periodic disturbances by making the periodic control signals. In this paper repetitive controller is proposed that make the control signal follow the periodic disturbances. A low pass filter, which can make the system stable, is proposed by the simple stability conditions. We will show the performance of the repetitive controller in actual commercial system. Simulation and experimental results will be given as the evidences.

1. Introduction

As the technology has developed, the amount of data, we need to deal with, is growing. Nowadays in the view of the data capacity and the cost of the data storage, an ODD (Optical Disk Drive) is one of the best devices that we can easily use. In spite of the cheapness of its media, the ODD has some disadvantages such as slow data transfer rate. To make up for its weakness like this slowness of the data transfer rate, almost all of the developers want to rotate the media faster. It is natural that the faster the disk rotates the more disturbance occurs.

In the field of control, the disturbance can make the stability of the system decline. Also, it can make the signal processing very hard. As a result, the rejection of the disturbance has been a great topic in the researcher's thesis. There are many ways of rejecting disturbance. Shock-proof memory and disturbance observer can be typical examples.

The repetitive controller can be a candidate for rejecting the disturbance. It has many advantages. It is very easy to be interpreted and to be implemented. Above all, the repetitive controller has great performance when the system has periodic disturbance. Because the disturbance in ODD happens from the high rotational speed of spindle motor, it is known that the disturbance has the periodic characteristics.

The repetitive controller and the modified repetitive controller have been proposed for many years. The main topics in the repetitive control are the stability and performance. As they are in the relations of trade-off, many methods to analyze the system stability of the repetitive control and to make better performances have been studied by many people in the both continuous time domain and discrete time domain.

In this paper, we propose a repetitive controller in the discrete time domain for the focus-following servo system of an optical disk drive with uncertain plant coefficient. By using dynamic signal analyzer, we can get the lead-lag compensator of the selected ODD (Samsung 52X). By using LDV (Laser Doppler Vibrometer), we can have the plant's transfer function. These results give us the uncertain model of the real plant and from these we can design a repetitive controller in the discrete time domain.

2. System description

2.1 Focusing control in ODD

The main goal of the focusing servo control for the optical disk drive is to keep the distance between lens and the disk fixed at some ranges by the control of the vertical directional movement of the actuator. This means that the laser beam is focused on disk properly.

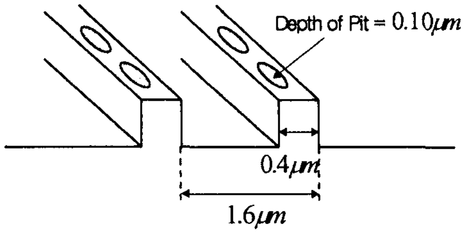

Fig. 1. Structure on tracks on ODD

In the case of CD-ROM (1x) drive, focusing control is needed because the vertical vibration of disk is a range

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within $\pm 500\mu m$.

In order to obtain the properly reflected signal in the presence of disk deviation, the accuracy for focusing control has to be less than approximately $\pm 1\mu m$.

2.2 The mathematical modeling of an actuator

The actuators of the CD-ROM can be classified into two systems. One is mechanical system and the other is electro-magnetic system.

Figure 2 illustrates the schematic diagram of the general actuator used for focusing.

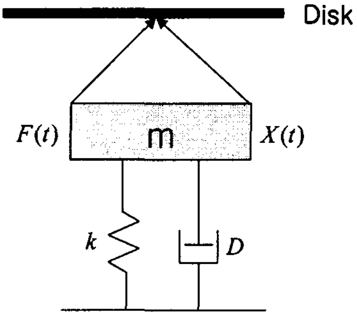

Fig. 2. Mechanism system of focusing actuator

In Fig. 2, m, k and D represent the mass of the focusing actuator, the spring coefficient, and viscous friction coefficient, respectively. $X(t)$ is the position of the focusing actuator and $F(t)$ is the force applied to the focusing actuator. The following equation can be obtained from the dynamics

$$F(t) = m\ddot{X}(t) + D\dot{X}(t) + kX(t) \qquad (1)$$

By applying the Laplace transformation to this equation, we can obtain the following equation.

$$X(s) = \frac{1}{ms^2 + Ds + k}F(s) \qquad (2)$$

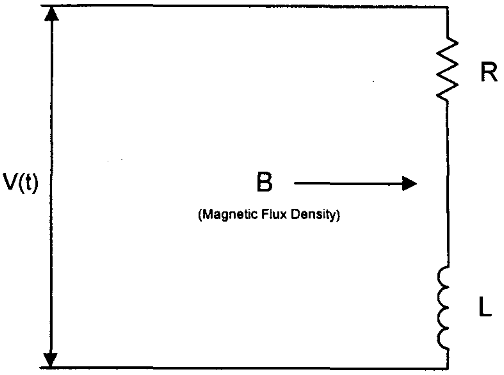

Fig. 3. Electro-magnetic system of focusing actuator

Electro-magnetic in Fig. 3 can be expressed by the following equation. The force F(s) is derived from the driving current.

$$F(s) = BlN \cdot I(s) \qquad (3)$$

where B is the magnetic density(tesla), l is the effective length of the coil, and N is the number of windings of the coil. The current is related to the input voltage by

$$I(s) = \frac{1}{R + sL}V(s) \qquad (4)$$

where R is the resistance and L is the inductance of the moving coil. From the given equations, the transfer function of the voltage-driven focusing actuator leads to

$$G(s) = \frac{X(s)}{V(s)} = \frac{BlN}{ms^2 + Ds + k} \cdot \frac{1}{R + sL} \qquad (5)$$

This equation can be converted to the next equation.

$$P_a(s) = \frac{Y(s)}{V(s)} = \frac{\frac{BlN}{k}}{\left(\frac{s}{\omega_n}\right)^2 + 2\varsigma\left(\frac{s}{\omega_n}\right) + 1} \cdot \frac{\frac{1}{R}}{\frac{s}{\omega_y} + 1} \qquad (6)$$

where $Q = \frac{1}{2\varsigma}$, $\omega_y = \frac{R}{L}$, ς is the damping ratio and ω_n is the natural frequency of the actuator.

This equation can be expressed by the following equation.

$$P_a(s) = \frac{Y(s)}{V(s)} = \frac{\frac{BlN}{k}}{\left(\frac{s}{\omega_n}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_n}\right) + 1} \cdot \frac{\frac{1}{R}}{\frac{s}{\omega_y} + 1} \tag{7}$$

3. Principle of Repetitive control

3.1 Internal model principle

Repetitive control has been researched based on the internal model principle. In order for the feedback control system in Fig.1 to achieve regulation ($\lim_{T\to\infty} e(t) = 0$) in the presence of disturbances with known modes, i.e. $R(s) = B_d(s)/A_d(s)$, it is necessary to include the dynamic compensator having a factor, $1/A_d(s)$, where it has been assumed that plant zeros do not cancel any disturbance modes, i.e. the characteristic roots of $A_d(s) = 0$.

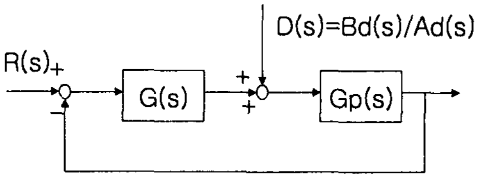

Fig. 4. Feedback control cystem

3.2 Repetitive control

Any periodic signal with period L can be generated by the free time-delay shown in Fig. 5 with an appropriate initial function. The system has many poles on the imaginary axis. It is therefore expected from the internal model principle that the asymptotic tracking property for exogenous periodic signals may be achieved by implementing the model exp(-Ls)/(1-exp(-Ls)) into the closed-loop system. A controller including this model is a repetitive control and a system with such a controller is called a repetitive control system.

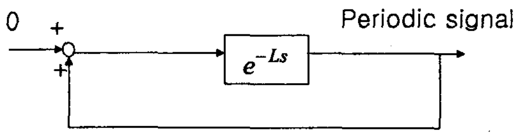

Fig. 5. Generator of periodic signal

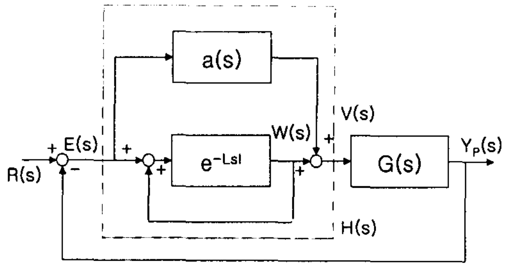

Fig. 6. Repetitive control system

Figure 6 shows the typical simple repetitive control system designed by the periodic signal generator. The system consists of a reference command R(s), controlled output $Y_P(s)$, error signal E(s), transfer matrix for the compensated plant G(s), appropriate proper stable rational function a(s), response for initial condition of G(s). Then the following relations can be retrieved as it is noted in [4].

$$\begin{aligned} &E(s) = R(s) - Y_p(s), \\ &Y_p = G(s)V(s) + \bar{Y}(s), \\ &V(s) = a(s)E(s) + W(s), \\ &W(s) = \exp(-Ls)[W(s) + E(s)] + \bar{W}(s) \end{aligned} \tag{8}$$

where, $\bar{Y}(s)$ and $\bar{W}(s)$ are the Laplace transforms of the responses for initial conditions of G(s) and exp(-Ls), respectively.

4. Repetitive controller design

Though the various control structure in repetitive control is available, a simple structure is selected and this schematic diagram is depicted in Fig. 7. Where C(s) is a feedback compensator, K_{PD} denotes a sensor gain and P(s) and q(s) are a focusing actuator plant and a low pass filter respectively.

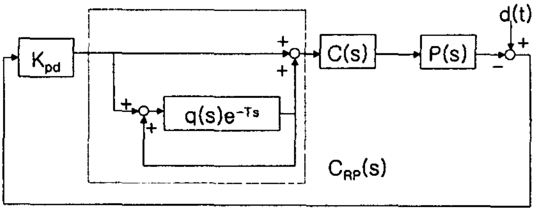

Fig. 7. Repetitive focusing servo system

When the above control structure is used, the stability of the repetitive control system should be considered, the following considerations for stability are necessary (see reference [1]).

(1) $G(s)(1+G(s))^{-1}$ is stable

(2) $|q(j\omega)|<|1+G(j\omega)|, \forall \omega \geq 0$

Where $G(s) = KPDC(s)P(s)$

The selection of the low pass filter q(s) is an important work in this condition. The considerations for stability mean that if the closed loop system without repetitive controller is stable and the system meeting the condition (2) is available, and the system will be stable. In graphical representation, these stability considerations can be analyzed as follow: the Nyquist plot of G(s) in every frequency must be the outside of the stability circle shown in Fig. 8.

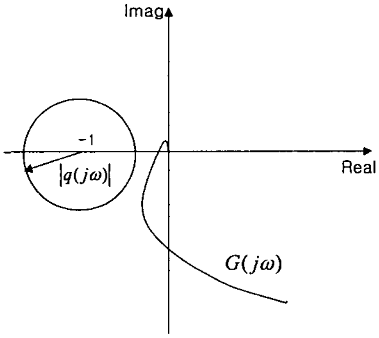

Fig. 8. Stability circle for the repetitive control system

Stability consideration with plant uncertainty:

$$|q(j\omega)| < \inf_{G \in G_E} |1+G(j\omega)|, \forall \omega \geq 0$$

Where $GE(s)= KPDC(s)PE(s)$ and $PE(s)$ are the external systems of the interval plant

This condition shows the general case of the former one and it comes from the consideration of the model uncertainty.

Design process can be summarized from [1].

Design process

1. Confirm the stability of the G(s).
2. Find the suitable cutoff frequency of the low pass filter q(s).
3. Choose the order of q(s) with the consideration of the sufficient roll-off.

5. Simulation and experimental results

5.1 Plant model

To design the controller of the actual system, we should find the transfer function of the actual plant. By using the Dynamic Signal Analyzer we can get the value of the transfer function of the pick-up separated form the commercial product (Samsung 52X CD-ROM model SC-152).

The plant modeling can be written as follows.

$$P = 4442.86 \times 0.7 \times \frac{1}{\left(\frac{s}{402.12}\right)^2 + \frac{1}{0.877}\left(\frac{s}{402.12}\right) + 1} \quad (9)$$

5.2 Controller design

The existing feedback compensator in the CD-ROM can be retrieved using the dynamic signal analyzer, HP35670A. From this measurement result, we can guess that the rough control loop and this is nearly the same as the transfer function from FES (Focus Error Signal) to FCIN (Focus Driver Input).

The transfer function of the controller in the actual system is shown as follows.

$$C(s) = 1.56 \times \frac{(s+2199.11+1796.99i)}{(s+289.03)} \cdot \frac{(s+2199.11-1796.99i)}{(s+43888.05)}$$

As we saw in the proceeding section the, main problem to design the repetitive controller is the selection of the cutoff frequency and the order of the q(s) filter. By using the data we can determine that the cutoff frequency should be around 600 Hz. Also we can get the conclusion that the first order filter is better than others.

The low pass filter q(s) is designed as shown below.

$$q(s) = \frac{1}{1 + s/1200\pi}$$

Then the total repetitive controller can be represented by the equation below.

$$C_{RP}(s) = \frac{1}{1 - q(s)e^{-(1/30)s}}$$

The $e^{-(1/30)s}$ term means that the period of the disturbance is 1/30, because the speed of spindle motor is 30 Hz.

5.3 Simulation results

The comparison the designed open loop is given as a Bode diagram in Fig. 9. Where the solid line open loop is designed by repetitive control and the dot line open loop is designed by lead-lag control. This result shows that the designed repetitive control is more effective than conventional lead-lag control in disturbance rejection. However, stability is guaranteed.

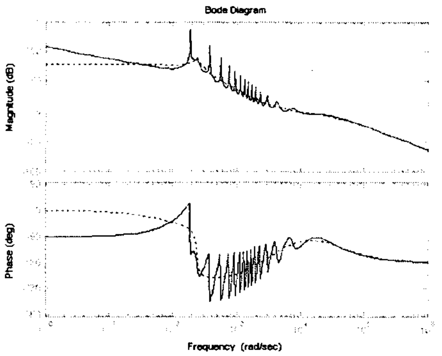

Fig. 9. Bode plots of G(s) with (solid) and without (dash) $C_{Rp}(s)$

To verify the effectiveness of designed repetitive control, we apply the equivalent disturbance to the system. Fig. 10 shows the disturbance signal, which is used in time domain simulation, and its frequency is a periodic harmonic component: 30, 60,90... Hz.

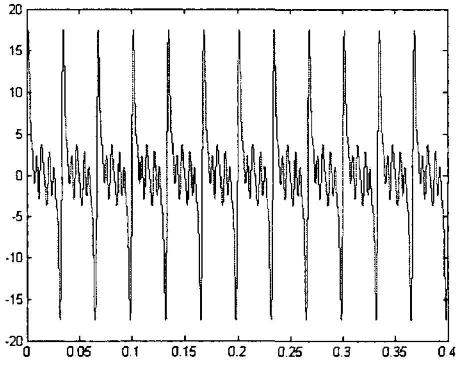

Fig. 10. Disturbance signal used in simulations

When the equivalent disturbance is applied to the system, following error signals, Fig, 12 and Fig. 13, are acquired. Fig.11 is error signal when the servo controller is designed by lead-lag control, and Fig.13 shows the error signal when the servo controller is designed by lead-lag control. From these simulations, we can find that the repetitive controller is more effective than lead-lag control in disturbance rejection. However, stability is guaranteed and this result can be find in simulation result.

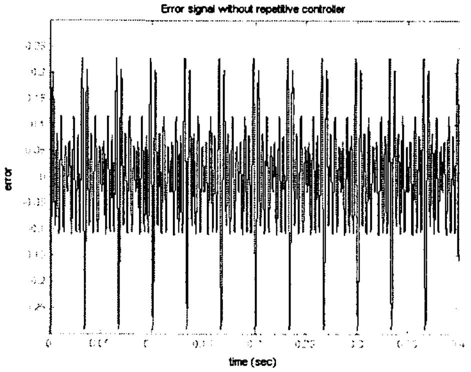

Fig. 11. Simulation results: focusing error without repetitive controller

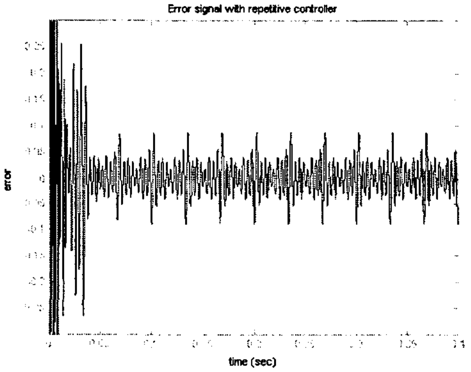

Fig. 12. Simulation results: focusing error with repetitive controller

5.4 Experimental results

The proposed repetitive control is realized using a DSP, DS1103, and the overall structure is given in Fig.13. The sampling frequency is $100kHz$ and 8bit AD, DA are used. The equivalent disturbance is generated by a function generated and its signal is applied to the servo loop. To find the amount of disturbance attenuation, digital oscilloscope and dynamic signal analyzer are used respectively.

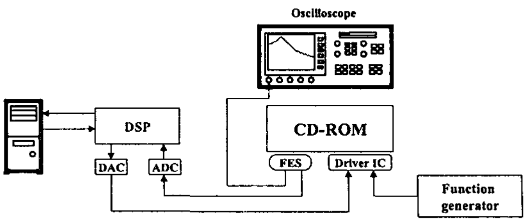

Fig.13. Schematic diagram of the experimental system

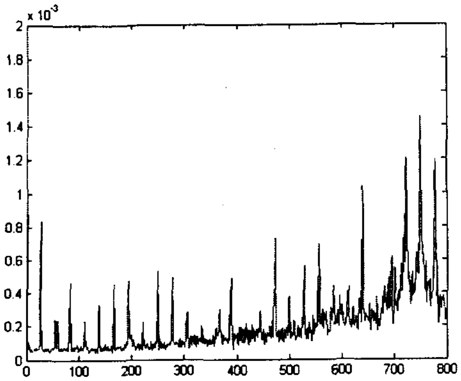

Fig. 14. Frequency spectrum of error signal without repetitive controller

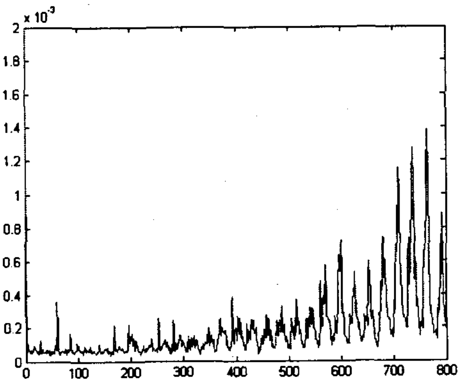

Fig. 15. Frequency spectrum of error signal with repetitive controller

Fig. 14 and 15 show the results of the experiment and as we are able to find that the harmonic components of the error signal were really decreased by using the repetitive controller. We can confirm that repetitive controller performs well in the focusing servo system.

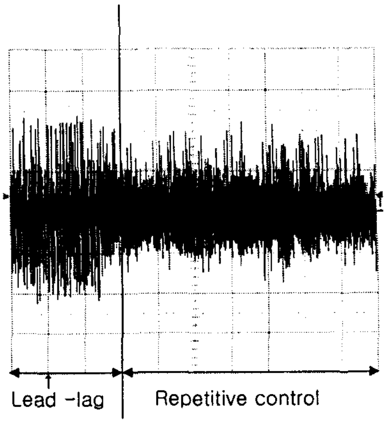

Fig. 16. Experimental result: error signal in time domain

6. Conclusion

The repetitive control design was studied and the simulation and realization of it is treated for a focusing servo in an ODD. First, the brief introduction of repetitive control was discussed, then, repetitive control theory was treated. Based on the focusing servo performance, the repetitive control was designed and was applied to the real system. To verify the effectiveness of repetitive control, the designed control was realized by DSP and it was applied to the commercial ODD. For periodic disturbance, simulation and experiments showed that the designed control is more effective than lead-lag control in disturbance rejection. However, the stability of system is guaranteed.

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