A Robust Fine Seek Controller Design Method Based on the Estimation of Velocity Disturbance

Moon-Noh Lee, Jin-Ho Shin, Seong-Woo Kim, Jong Min Lee, and Kyoung Bog Jin

Abstract: This paper presents a systematic method of estimating a velocity disturbance occurring in the fine seek control system of an optical disk drive. A fine seek loop gain adjustment algorithm is introduced to accurately estimate the velocity disturbance in spite of the uncertainties of the fine actuator. The velocity disturbance can be estimated from a measurable velocity, a fine seek controller output, and a compensated fine actuator model. A robust fine seek controller can be designed by considering a minimum fine seek open-loop gain, calculated by the estimated velocity disturbance. The proposed controller design method is applied to the fine seek control system of a DVD rewritable drive and is evaluated through the experimental results.

Keywords: Fine seek loop gain adjustment, minimum fine seek open-loop gain, optical disk drive, velocity disturbance, weighting function.

1. INTRODUCTION

Owing to deficiencies in track geometry and eccentric rotation of the disk, a velocity disturbance acting on the fine seek control system is generated in an optical disk drive. In optical disk drive systems, the improvement of the data transfer rate has been achieved mainly by the increase of the disk rotational speed, which leads to the increase of the velocity disturbance. Because such velocity disturbance makes it more difficult to design the fine seek control system, it should be attenuated effectively at the high rotational speed.

The fine seek control system of an optical disk drive is designed to quickly move an optical pick-up into a target track. To this end, it should introduce a velocity control scheme and effectively reject the effect of velocity disturbance. Generally, as the effect of velocity disturbance is increasing gradually, according to the disk rotational speed, it is difficult to accomplish an accurate velocity control during the fine seek action. Accordingly, the optical pick-up comes to pass by the target track and thus cannot resume, with stability, a continuous track-following control. To decrease the access time, the fine seek control system should achieve a stable velocity control against the velocity disturbance [1,3-5].

Until now, most fine seek controllers have been designed without the accurate consideration of velocity disturbance. As a result, velocity disturbance cannot be controlled precisely at the high rotational speed, and it is difficult to design the fine seek control system while maintaining a satisfactory performance. To design a stable fine seek control system, the controller design method, based on the estimation of velocity disturbance, is required. Off-line measurement methods using experimental instruments repeatedly tried to measure the velocity disturbance of the fine seek control system. However, those methods could not consider fine actuator uncertainties, such as actuator gain uncertainties and so on.

In this paper, we propose a schematic method to effectively estimate the velocity disturbance to construct the robust fine seek control system. The proposed method estimates the velocity disturbance using a measurable velocity and a fine seek controller output. A fine seek loop gain algorithm is introduced to estimate accurately the velocity disturbance in spite of the actuator uncertainties. A minimum fine seek open-loop gain is calculated by the estimated velocity disturbance and a tolerable limit of velocity error. A robust fine seek controller is designed by considering a robust H_∞ control problem with a weighting

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function of a slightly larger gain than the minimum fine seek open-loop gain. The proposed controller design method is applied to the fine seek control system of a DVD rewritable drive and is evaluated through an experiment at high disk rotational speed.

The remainder of the paper is organized as follows. In Section 2, the fine seek control system of an optical disk drive is briefly described and the fine seek controller design method, based on the estimation of velocity disturbance, is given in Section 3. The experimental results, applied to a DVD rewritable drive, are presented in Section 4 and concluding remarks are given in Section 5.

2. THE FINE SEEK CONTROL SYSTEM OF OPTICAL DISK DRIVES

In most optical disk drives, the tracking actuator is a compound actuator, composed of a high bandwidth fine actuator mounted on the top of a large coarse actuator. The fine actuator with a much smaller structure and a limited range is capable of following high-frequency commands. In contrast, the coarse actuator provides a large operating range at the sacrifice of its bandwidth. Thus, the track seek requires the adequate compromise of both actuators, which move the beam spot in the radial direction of the disk [7,8]. In most cases, a voice-coil motor and a stepping motor are utilized as the fine actuator and coarse actuator, respectively. Fig. 1 shows a schematic view of an optical disk drive mechanism.

The seek control system of an optical disk drive divides into the fine seek control system and the coarse seek control system according to the number of tracks that the optical pick-up has to move. The fine seek control system is to move a small distance of hundreds of tracks, and the coarse seek control system is to move a relatively larger distance. For this reason, the fine seek control system has a velocity control loop to the fine actuator and the coarse seek control system has a velocity control loop to the coarse
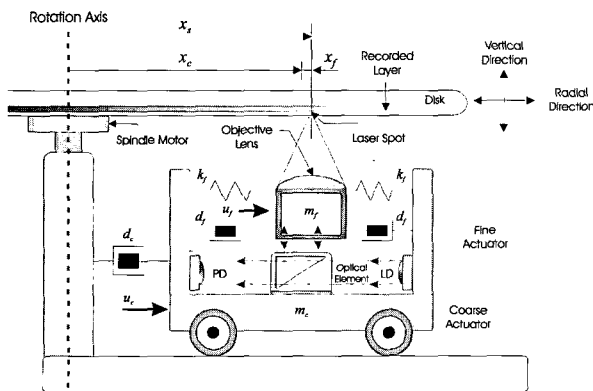
actuator. Most seek actions execute several fine seek actions to accurately reach the target track, regardless of the moving distance of the optical pick-up. To minimize access time, the repeated number of fine seek actions should be minimized by optimizing the performance of the fine seek control system [10]. As the stability of the fine seek control system becomes higher, the repeated number of fine seek actions is smaller, and thus the access time is minimized.

In the case of using a stepping motor as a coarse actuator, the coarse seek control system is composed so that the stepping motor is controlled by an open-loop pulse input determined by a velocity profile. Then, the fine actuator is controlled to quickly compensate the large shift of the optical lens from an optical axis caused by the movement of the stepping motor. The velocity profile should be determined by the properties of the stepping motor, and is composed by a unit of macro steps. On the other hand, the fine seek control system is composed so that the fine actuator is controlled to follow a reference velocity, and the stepping motor is controlled to properly compensate the small shift of the optical lens caused by the movement of the fine actuator. In this case, the stepping motor moves by a unit of micro steps to increase the stability of the fine seek control system. In the coarse seek control system, because the stepping motor is moved by an open-loop velocity input, it cannot be controlled to reject the effect of the velocity disturbance. However, because the fine seek control system measures the velocity of the optical pick-up for the accurate velocity control, a fine seek controller can be designed to effectively reject the effect of the velocity disturbance.

Fig. 2 represents a block diagram of a fine seek control system. In this figure, $P_f(s)$ is the fine actuator, $P_c(s)$ is the coarse actuator, $C_f(s)$ is the fine seek controller, $V_f(s)$ is the driver of the fine actuator, and $V_c(s)$ is the driver of the coarse actuator. The v_r, v_f, v_c, v_m, v_d are the reference velocity, the velocity of the fine actuator, the velocity of the coarse actuator, the measurable velocity, and the velocity disturbance, respectively. The measurable velocity v_m is the beam spot velocity relative to the velocity disturbance. That means that the velocity v_f is not available as a signal, and thus it cannot be measurable. Only the measurable velocity v_m can be measurable in the fine seek control system. The nonlinear function $f(x_m)$ represents a stepping motor moving algorithm that moves the
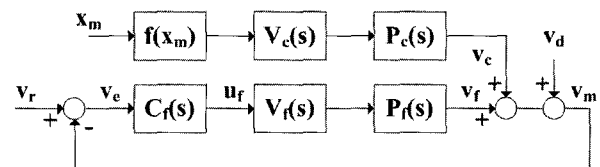

Fig. 1. Schematic view of an optical disk drive mechanism.

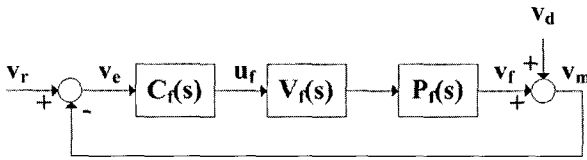Fig. 2. Block diagram of a fine seek control system.

Fig. 3. Block diagram of the simplified fine seek control system.
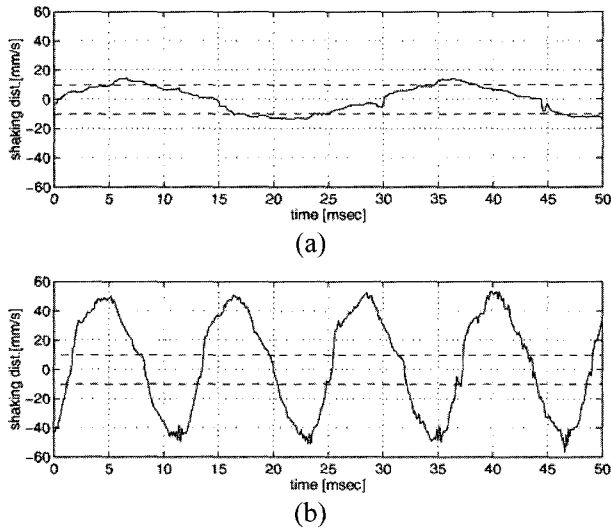

(a)

(b)

Fig. 4. Velocity disturbance when the CD disk is rotated at (a) 2000rpm and (b) 5000rpm.

stepping motor by a micro step whenever the moved distance of the fine actuator is larger than a micro step distance. The stepping motor does not move in the fine seek action under ten tracks, but it moves to diminish the lens shift in the fine seek action larger than a micro step distance. Finally, the stepping motor compensates only the lens shift of the fine actuator, and does not consider the effect of the velocity disturbance. Therefore, the fine seek control system can be represented by the simplified velocity control system (Fig. 3), except the stepping motor control loop regardless of the velocity disturbance.

In this control scheme, the fine seek controller should be designed to follow the reference velocity, in spite of the velocity disturbance. If the fine seek control system effectively controls the velocity disturbance during the fine seek action, the remaining velocity of the optical pick-up is minimized, and a continuous track-following control, after the fine seek action, can be started on the target track.

Fig. 4 shows the velocity disturbance when the CD disk rotates at 2000rpm and 5000rpm under the condition that both fine and coarse actuators are stopped [2,4]. It represents that the effect of the velocity disturbance increases according to the disk rotational speed. Usually, if the remaining velocity at the target track is greater than 10 mm/s, the track-following control cannot be started stably. However,

as the disk rotational speed approaches 2000rpm, the velocity disturbance is greater than the allowable limit of 10 mm/s. For the stable fine seek control, the remaining velocity of the fine actuator is controlled to hold, within the allowable limit. Therefore, the fine seek control system should be designed to reject the effect of the velocity disturbance. Because the track-pitch of a DVD disk is less than that of a CD disk, an allowable limit is also smaller than that of a CD disk. The same quantity of velocity disturbance has more influence on DVD drives than CD drives.

3. A ROBUST FINE SEEK CONTROLLER DESIGN BY THE ESTIMATION OF VELOCITY DISTURBANCE

This chapter describes a velocity disturbance estimation method applicable to the fine seek control system of an optical disk drive. The estimation method includes a loop gain adjustment algorithm to consider the effect of the fine actuator, modeling uncertainties. The estimated velocity disturbance can be utilized in the design procedure of a fine seek controller.

3.1. A velocity disturbance estimation method

In general, the behavior of the fine actuator can be described by a second-order linear system. Although a mathematical model might adequately describe the behavior of the fine actuator to some extent, unavoidable modeling errors always exist. In this paper, it is assumed that each actuator parameter is known to the extent that it lies in some interval, that is, the uncertain parameter varies over a known range of a nominal value. Suppose that, in consideration of the uncertainties, the fine actuator is described as

$$P_f(s) = \frac{k_f s}{s^2 + \alpha_f s + \beta_f}[(m/s)/A], \tag{1}$$

$$k_f = k_{fn} + \delta k_f, \quad |\delta k_f| \le m_k,$$

$$\alpha_f = \alpha_{fn} + \delta \alpha_f, \quad |\delta \alpha_f| \le m_\alpha, \tag{2}$$

$$\beta_f = \beta_{fn} + \delta \beta_f, \quad |\delta \beta_f| \le m_\beta.$$

The k_{fn}, α_{fn}, and β_{fn} are nominal values of the fine actuator coefficients, and δk_f, $\delta \alpha_f$, and $\delta \beta_f$ represent the coefficient uncertainties. The m_k, m_α, and m_β are the maximum values of the uncertainties. According to the data sheet, we assume that the coefficient values of the fine actuator vary within 10% of their nominal values. From the relation among the velocity disturbance v_d, the measurable velocity v_m, and the velocity v_f, the velocity disturbance can be described as follows:

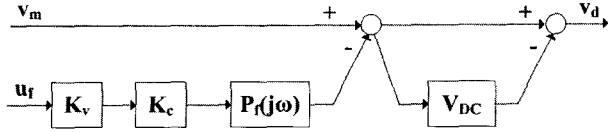$$V_d(j\omega) = V_m(j\omega) - V_f(j\omega)P_f(j\omega)U_f(j\omega). \tag{3}$$

Fig. 5. Block diagram for the velocity disturbance estimation.

Fig. 6. Block diagram for estimating the effect of the actuator uncertainties.

The driver $V_f(j\omega)$ is a voltage-current amplifier with the shape of a low pass filter, and the cutoff frequency of the driver is larger than the bandwidth of the fine seek control loop. Because the cutoff frequency is larger than the estimation range of the velocity disturbance, the driver $V_f(j\omega)$ can be approximated as the DC gain K_v of the driver.

Since the actuator uncertainties make the calculation of (3) impossible, the nominal actuator model $P_{fn}(j\omega)$ should be utilized to (3). Then, the estimated velocity disturbance has a non-insignificant difference due to the actuator uncertainties. Because the actuator uncertainties decrease the confidence of the estimated velocity disturbance, the velocity disturbance estimation method has to consider the effect of the actuator uncertainties. The velocity disturbance is estimated more accurately by using the nominal actuator model and a compensated gain K_c as

$$\hat{V}_d(j\omega) = V_m(j\omega) - K_c K_v P_{fn}(j\omega)U_f(j\omega). \qquad (4)$$

A block diagram for estimating the velocity disturbance can be described as Fig. 5.

This paper considers a loop gain adjustment algorithm to consider the actuator uncertainties. Because of an un-negligible DC value, due to the difference of bias voltages within circuits that can be included in the estimated velocity disturbance, it is necessary to subtract the DC bias value from the estimated velocity disturbance as in Fig. 5. In Fig. 3, the fine seek open-loop transfer function $L(s)$ is expressed by the product $C_f(s)V_f(s)P_f(s)$ of the fine seek controller, the driver, and the fine actuator. To consider the actuator uncertainties, we introduce a fine seek loop gain adjustment algorithm, that is, the gain of the fine seek controller is adjusted so that the fine seek open-loop $L(s)$ and the nominal fine seek open-loop $L_0(s)$ have the same phase margins, in spite of the actuator uncertainties. Based on the fine seek loop gain adjustment, the velocity disturbance estimation method is able to consider the effect of the actuator uncertainties by adjusting the DC gain of the fine actuator, according to the gain variation of the fine seek controller.

Fig. 6 represents a block diagram for estimating the effect of the fine actuator uncertainties. To estimate the effect of the fine actuator uncertainties, we input 0 to the reference velocity v_r and a sinusoidal input of a particular frequency is added to the velocity error, and
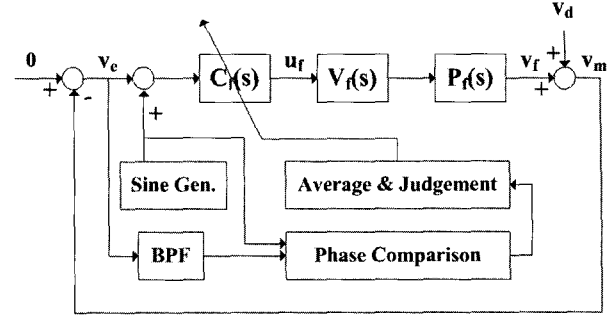
the added output is given to the fine seek controller. A neighborhood frequency of the fine seek loop bandwidth is selected as the frequency of the sinusoidal input. Because the reference velocity input is 0, the fine actuator executes the velocity control following the frequency of the sinusoidal input and the velocity of the fine actuator is measured by the measurable velocity v_m. To obtain only the frequency of the sinusoidal input, a band-pass filter is connected to the measurable velocity. At the frequency ω_0 of the sinusoidal input, the relation of the sinusoidal input $I(j\omega_0)$ and the band-pass filter output $x(j\omega_0)$ is described as follows:

$$\frac{x(j\omega_0)}{I(j\omega_0)} = \frac{L(j\omega_0)}{1 + L(j\omega_0)} = \left|\frac{L(j\omega_0)}{1 + L(j\omega_0)}\right| \angle \phi. \qquad (5)$$

The band-pass filter output is amplified by the gain of $|L(j\omega_0)/(1+L(j\omega_0))|$, and is delayed by ϕ as compared with the sinusoidal input. The phase difference ϕ can be obtained by calculating the difference between the phase of $L(j\omega_0)$ and the phase of $(1+L(j\omega_0))$. Without the actuator uncertainties, the phases of $L(j\omega_0)$ and $(1+L(j\omega_0))$ can be calculated, and the phase difference becomes the nominal phase difference ϕ_n. However, the phase difference comes to differ with the ϕ_n under the actuator uncertainties, that is, the difference between the phase of $L(j\omega_0)$ and the phase of $(1+L(j\omega_0))$ is different with the nominal phase difference. To make the phase difference and the nominal phase difference equal, the fine seek loop gain should be constantly maintained by adjusting, in reverse, the DC gain of the fine seek controller. This fine seek loop adjustment procedure is repeated until the difference, $(\phi-\phi_n)$, is attained within an allowable range.

After executing the fine seek loop gain adjustment algorithm, if the DC gain of the fine seek controller is increased, as K_δ times of the nominal DC gain, the DC gain of the fine actuator should be decreased as $1/K_\delta$ times of the nominal DC gain, that is, $K_c=1/K_\delta$. Because the DC gain of the fine seek controller is

adjusted according to the effect of the actuator uncertainties, the estimated value of the actuator uncertainties should be reflected to the compensation gain K_c. Thus, the velocity disturbance estimation method comes to include the effect of the fine actuator uncertainties, and the velocity disturbance can be estimated more accurately.

After determining the gain parameters and the actuator model of Fig. 5, the velocity disturbance can be estimated by measuring the measurable velocity and the fine seek controller output. A low-order simple controller is only sufficient to stabilize the fine seek control system. The velocity disturbance estimation method can be applied to various disk rotational speeds and is able to estimate the variation of the velocity disturbance, according to the disk rotational speed. The estimated velocity disturbance can be utilized as fundamental data to design a robust fine seek controller.

3.2. A robust fine seek controller design

By applying the proposed velocity disturbance estimation method, the velocity disturbance can be estimated accurately. The disk rotational frequency and its multiple frequencies require a relatively high loop gain because the larger components of the velocity disturbance are generated in those frequencies. The fine seek controller should be optimally designed in consideration of this loop design specification. In Fig. 3, we obtain the velocity error $V_e(j\omega)$ as

$$V_e(j\omega) = \frac{1}{1 + L(j\omega)}(V_r(j\omega) - V_d(j\omega)) \qquad (6)$$

and a minimum fine seek open-loop gain $L_{min}(j\omega)$ can be described as

$$L_{min}(j\omega) = \left| \frac{V_r(j\omega) - \hat{V}_d(j\omega)}{v_{emx}} \right| \qquad (7)$$

by the application of the estimated velocity disturbance (4) and a tolerable limit v_{emx} of velocity error. Accordingly, if the velocity disturbance can be estimated, a minimum fine seek open-loop gain can be obtained by applying (7).

To design a robust fine seek controller, we deal with a robust $H\infty$ control problem with a reasonable weighting function. The weighting function is selected to have a slightly larger gain than the minimum fine seek open-loop gain. Most robust control algorithms often use unreasonable weighting functions by the intuition of the designers, and thus inapplicable controllers with high gain are obtained. If disturbances can be estimated, a minimum open-loop gain and loop bandwidth can be determined and the weighting functions can be selected optimally.

The uncompensated fine seek control system, $K_v P_f$ (s), can be represented by the state-state equations:

$$\dot{x}(t) = Ax(t) + H_1 p(t) + B_2(K_v u_f(t)),$$

$$v_e(t) = C_2 x(t) + H_2 p(t) + (v_d(t) - v_r(t)), \qquad (8)$$

$$q(t) = E_1 x(t), \; p(t) = \Delta q(t), \|\Delta\| \le 1,$$

where $x(t)$ is the state of fine actuator and $p(t)$ is the plant uncertainty input. The coefficient uncertainties are included in the uncertain matrices H_1, H_2, E_1. Besides, the fine seek controller can be modeled as

$$\dot{x}_c(t) = A_c x_c(t) + B_c v_e(t),$$

$$u_f(t) = C_c x_c(t), \qquad (9)$$

where $x_c(t)$ is the state of the controller. To consider the robust performance of the fine seek control system, a weighting function $W(s)$ is introduced as $Z(s) = W(s) V_e(s)$. Then, the controlled output $z(t)$ can be expressed as the state-state equations:

$$\dot{x}_w(t) = A_w x_w(t) + B_w v_e(t),$$

$$z(t) = C_w x_w(t), \qquad (10)$$

where $x_w(t)$ is the state of the weighting function.

Applying the controller (9) and the weighting function (10) to the uncompensated system (8), the fine seek control system is described by the state-space equations:

$$\dot{x}_{cl}(t) = \bar{A} x_{cl}(t) + \bar{H}_1 p(t) + \bar{B}_1(v_d(t) - v_r(t)),$$

$$z(t) = \bar{C}_w x_{cl}(t), \qquad (11)$$

$$q(t) = \bar{E}_1 x_{cl}(t), \; p(t) = \Delta q(t), \|\Delta\| \le 1,$$

where $x_{cl}(t) = [x(t)^T \; x_c(t)^T \; x_w(t)^T]^T$ is the state of the fine seek control system, and the system matrices are expressed as follows:

$$\bar{A} = \begin{bmatrix} A & K_v B_2 C_c & 0 \\ B_c C_2 & A_c & 0 \\ B_w C_2 & 0 & A_w \end{bmatrix}, \; \bar{H}_1 = \begin{bmatrix} H_1 \\ B_c H_2 \\ B_w H_2 \end{bmatrix},$$

$$\bar{B}_1^T = \begin{bmatrix} 0 & B_c^T & B_w^T \end{bmatrix}, \; \bar{C}_w = \begin{bmatrix} 0 & 0 & C_w \end{bmatrix},$$

$$\bar{E}_1 = \begin{bmatrix} E_1 & 0 & 0 \end{bmatrix}.$$

To design a robust fine seek controller, we consider a robust $H\infty$ control problem so that the fine seek control system (11) is quadratically stable and satisfies $\|T_{(v_d - v_r)z}(j\omega)\|\infty < 1$ for velocity disturbance and all admissible uncertainties. If a fine seek controller satisfying the robust $H\infty$ control problem is obtained, we can derive

$$|V_e(j\omega)| = \frac{|T_{(v_d - v_r)z}(j\omega)||V_d(j\omega) - V_r(j\omega)|}{|W(j\omega)|} \qquad (12)$$

$$< \frac{|V_d(j\omega) - V_r(j\omega)|}{|W(j\omega)|} < \frac{|V_d(j\omega) - V_r(j\omega)|}{L_{min}(j\omega)} = v_{emx}$$

by applying the $||T_{(vd-vr)z}(j\omega)||_\infty < 1$, $W(j\omega) > L_{min}(j\omega)$, and (7). Therefore, the velocity error $V_e(j\omega)$ is less than the tolerable limit v_{emx} at all frequencies. The robust H_∞ control problem can be converted to an LMI problem finding the matrices A_c, B_c, C_c, $X>0$ and a constant $\lambda>0$ satisfying

$$\begin{bmatrix} \overline{A}X + X\overline{A}^T & \overline{B}_1 & \overline{H}_1 & X\overline{C}_w^T & \lambda X\overline{E}_1^T \\ \overline{B}_1^T & -I & 0 & 0 & 0 \\ \overline{H}_1^T & 0 & -\lambda I & 0 & 0 \\ \overline{C}_w X & 0 & 0 & -I & 0 \\ \lambda \overline{E}_1 X & 0 & 0 & 0 & -\lambda I \end{bmatrix} < 0 \quad (13)$$

from the Lemma 4 of [11]. Consequently, if a fine seek controller satisfying (13) is obtained, the fine seek control system is quadratically stable and the velocity error is less than the tolerable limit.

In general, since it is not known how much the velocity disturbance increases in accordance with the increasing speed factor, a minimum open-loop gain cannot be calculated as the disk rotational speed increases. Accordingly, most conventional controllers are repeatedly designed until target performance is satisfied, through experiments, using a trial and error method. However, the proposed controller design method, based on the estimation of velocity disturbance, can be applied reasonably to all disk rotational speeds.

4. EXPERIMENTAL RESULTS TO A DVD REWRITABLE DRIVE

To evaluate the validity of the proposed controller design method, we apply it to the fine seek control system of a DVD rewritable drive. The velocity disturbance estimation method can be implemented by an experimental digital board. We use 12-bit A/D converters, running at a sampling of 500 KHz, to obtain the measurable velocity and the velocity controller output. From the measured A/D data, a software program calculates an estimation quantity of the velocity disturbance.

For an experiment, a DVD-ROM disk rotates at 3600rpm (DVD 6X) and 7200rpm (DVD 12X). The behavior of the fine actuator is well approximated by a second-order system, based on the frequency response measured by a dynamic structural analyzer. In consideration of the 1st resonance frequency, 1st resonance peak, and DC sensitivities, the nominal fine actuator is modeled as
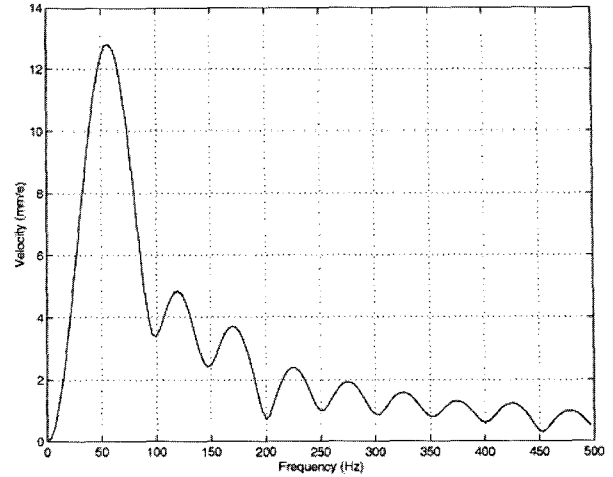

Fig. 7. The velocity disturbance estimated at DVD 6X.

$$P_{fn}(s) = \frac{574s}{s^2 + 420s + 179000}[(m/s)/A]. \quad (14)$$

According to the data sheet, the actuator coefficients vary within 10% on either side of their nominal values. Thus, it is assumed that $m_k=28.5$, $m_a=21$, and $m_\beta=8950$. The driver gain K_v is 2.5 and the cutoff frequency of the driver is 50 KHz beyond the estimation range of the velocity disturbance. Looking into the fine seek loop gain adjustment result, the DC gain of the fine seek controller becomes smaller, that is 1/1.6 times of the nominal DC gain. This means that the real gain of the fine actuator is 1.6 times as large as the nominal gain of (14). To accurately estimate the velocity disturbance, the adjusted result is reflected to the compensated gain, that is, $K_c=1.6$. By using the compensated gain, the nominal actuator model, and the driver gain, the velocity disturbance can be estimated by measuring the measurable velocity and the fine seek controller output.

Figs. 7 and 8 represent the velocity disturbances, estimated at the DVD 6X and 12X. These show that in the disk rotational frequency and its multiple frequencies, the relatively large components of velocity disturbance are generated. Besides, Figs. 7 and 8 show that the estimated quantity of velocity disturbance generated at each frequency is not to be more than twice, even if the disk rotational speed increases twice from 6X to 12X. Generally, though disks are the same kind, the velocity disturbances are generated differently in each, due to the differences in disk manufacturing. Therefore, this velocity disturbance estimation method should be applied repeatedly to various disks of the same kind, and the estimated quantities should be averaged.

Let us design a fine seek controller of DVD 12X, based on the estimated velocity disturbance. Fig. 9 represents a reference velocity v_r to execute a fine
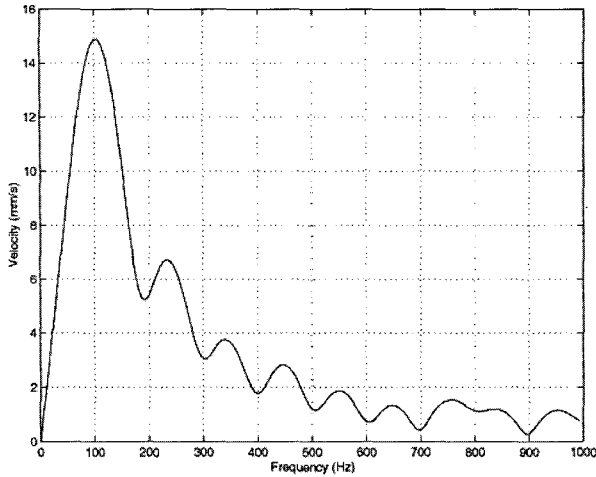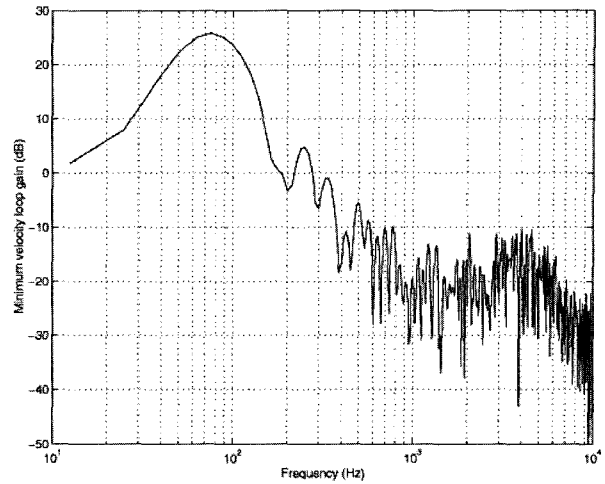
Fig. 8. The velocity disturbance estimated at DVD 12X.
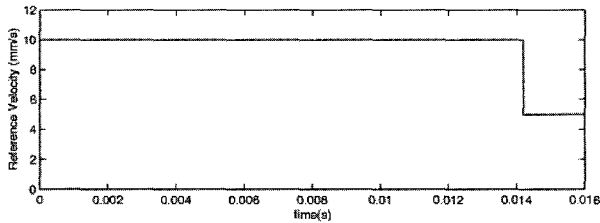
Fig. 9. The reference velocity for a fine seek action moving 200 tracks.
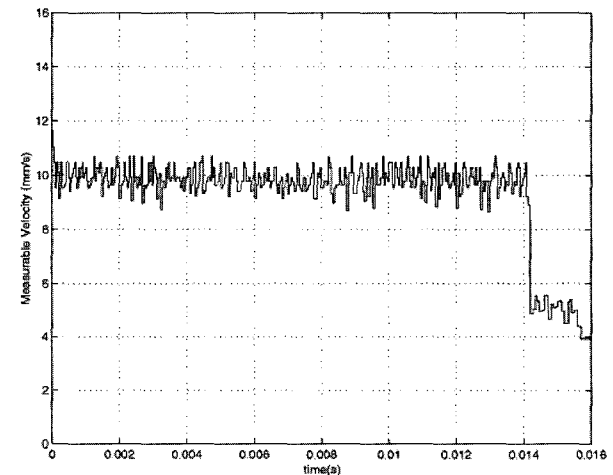
seek action moving 200 tracks. Because the velocity error results from errors occurring in the optical system, the mechanical system, and the servo system, the design limit of velocity error should be one-third of the tolerable limit of 1.0 mm/s. Fig. 10 shows a minimum fine seek open-loop gain of DVD 12X, calculated by the estimated velocity disturbance and reference velocity.

A weighting function is selected to have a slightly larger gain than the minimum fine seek open-loop gain as

$$W(s) = \frac{2.7 \times 10^3 s^2 + 4.24 \times 10^5 s + 1.07 \times 10^7}{s^3 + 942.5 s^2 + 2.84 \times 10^5 s + 2.68 \times 10^7}. \quad (15)$$

The fine seek controller design is accomplished by finding a controller $C_f(s)$ satisfying (13) with respect to (14) and (15). As a result, λ is 0.01 and the controller $C_f(s)$ is given by

$$\frac{1.9 \times 10^5 s^3 + 6.7 \times 10^9 s^2 + 2.3 \times 10^{13} s + 1.1 \times 10^{16}}{s^4 + 1.5 \times 10^5 s^3 + 3.3 \times 10^9 s^2 + 1.6 \times 10^{13} s + 5.6 \times 10^{15}}. \quad (16)$$

Fig. 11 presents the measurable velocity after applying the designed fine seek controller. It indicates that the velocity error is maintained within the tolerable limit of 1.0 mm/s, in spite of the velocity disturbance.

Fig. 10. A minimum fine seek open-loop gain of DVD 12X.

Fig. 11. The measurable velocity after applying the designed fine seek controller.

5. CONCLUSION

This paper proposed a robust fine seek controller design method, based on the estimated velocity disturbance. The fine seek loop adjustment algorithm is introduced to consider the effect of the actuator uncertainties. To estimate more accurately the velocity disturbance, the fine seek loop adjustment result is reflected to the nominal DC gain of the fine actuator. The proposed controller design method is applied to the fine seek control system of a DVD rewritable drive and is evaluated through an experiment.

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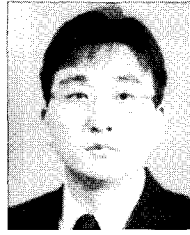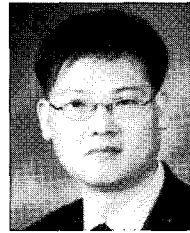
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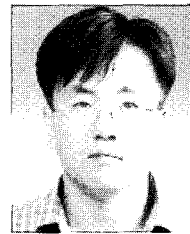
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