ROBUST FOLLOWING CONTROL OF OPTICAL DISK RECORDING SYSTEM BASED ON ZPET CONTROL AND SUDDEN DISTURBANCE OBSERVER

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Abstract: In optical recording system, the tracking control system must follow the track of optical disk against the influence on the track eccentricity and the force disturbance. This paper proposes a new robust following control system with the proposed feedforward controller and the proposed sudden disturbance observer. The proposed feedforward controller is based on "Zero Phase Error Tracking" (ZPET) control using only the tracking error. The experimental results point out that the proposed robust following control system suppresses the influence on both periodic disturbance and sudden disturbance. Hence, the proposed robust following control system realizes the desired precise tracking control performance against both disturbances using only tracking error.

Keywords: Optical disks, Tracking systems, Robust control, Coprime factorization, Feedforward control, Disturbance rejection

1. INTRODUCTION

Recently, optical disk recording system is used for storage of audio, visual and so on. Optical disks, such as CD and DVD, have a radial run-out (maximum amplitude is 100[μm] peak-to-peak), which is caused by the track eccentricity of optical disk. Tracking control system must suppress the tracking error against the track eccentricity. Moreover, optical disk recording system sometimes has the influence on sudden disturbance such as force disturbance. Hence, the tracking control system of optical disk recording system should keep the robust performance against sudden disturbance.

Generally, tracking control system for optical disk recording system is accomplished by the feedback control having robust performance and wide frequency band. Recently, the several tracking control system has been realized by PID control system, repetitive control, H^∞ control theory and so on(Ohishi *et al.* 200)(Ohishi *et al.* 2001)(Katayama *et al.* 1995)(Yamaguchi *et al.* 1998). However, it is often difficult for only feedback system to suppress its tracking error blow the target tolerance.

This paper proposes a new two degrees of freedom tracking control system. The proposed system is a robust following control system, which is constructed by the ZPET control, the sudden disturbance observer and the robust feedback control which uses disturbance observer and coprime factorization. The proposed sudden disturbance observer uses the current tracking error signal and the memorized tracking error signal.

The robust feedback control system is a dual loop control system based on coprime factorization and ordinary disturbance observer(Miyazaki and Ohishi 2002). Since ZPET control is a feedforward controller(Tomizuka 1996) (Tomizuka 1987). This paper proposes a new ZPET control system based on prediction of tracking error for optical disk recording system, because the detecting signal of the following control system is only a tracking error. The proposed feed-forward control system suppresses the tracking error caused by periodic disturbance, in comparison with the conventional repetitive control(Koide *et al.* 2003*b*). Moreover, for purpose of suppressing the sudden disturbance, this paper constructs a new disturbance observer, which estimates only sudden disturbance without the periodic disturbance. The proposed total following control system realizes the desired following control performance against both disturbances using only tracking error.

2. ROBUST FEEDBACK CONTROL SYSTEM

In order to realize the high performance following control of optical disk recording system, this paper proposes the new digital robust feedback control system based on coprime factorization. The proposed feedback control system has a dual loop system as shown in Fig.1(Miyazaki and Ohishi 2002).

The inner loop system is equivalent to the closed loop system based on state feedback and state observer. The outer loop system is equivalent to the closed loop system based on disturbance observer. The proposed robust feedback controller $C(z^{-1})$ is determined by the coprime factorization $N(z^{-1})$, $D(z^{-1})$, $X(z^{-1})$, $Y(z^{-1})$, and the free parameter $g(z^{-1})$ as shown in (2)(Miyazaki and Ohishi 2002). $g(z^{-1})$ is equivalent to a low pass filter of disturbance observer. A gain of $g(z^{-1})$ is unity in steady state.

$$P(z^{-1}) = \frac{N(z^{-1})}{D(z^{-1})},$$
$$N(z^{-1})X(z^{-1}) + Y(z^{-1})D(z^{-1}) = 1 \quad (1)$$
$$C(z^{-1}) = \frac{X(z^{-1})}{Y(z^{-1})} + \frac{1}{Y(z^{-1})}\frac{g(z^{-1})}{1-g(z^{-1})}\frac{1}{N(z^{-1})} \quad (2)$$

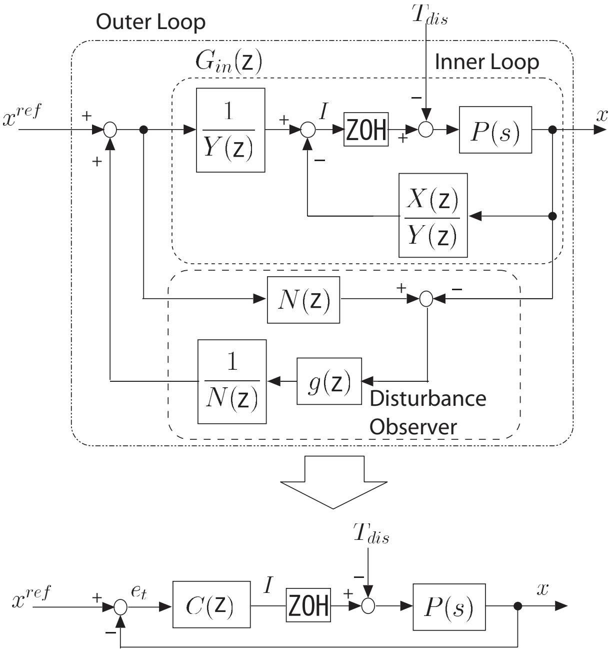


Fig. 1. Robust feedback controller based on disturbance observer and coprime factorization

This paper carries out the following control by using the tested optical disk recording system DDU1000, whose maximum disk rotation speed is

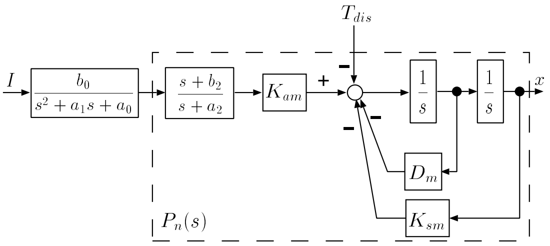


Fig. 2. Block diagram of tracking system

3600[rpm]. The plant system is the current-driven voice-coil motor, which has the characteristics of five-orders system as shown in (3), Fig. 2 and Table 1, where K_a , M , D and K_s are a force constant, a mass of the moving parts of actuator, a viscosity coefficient and a spring constant, respectively.

$$P_5(s) = \frac{x(s)}{I(s)} = \frac{\frac{K_a}{M}}{s^2+\frac{D}{M}s+\frac{K_s}{M}}\frac{s+b_2}{s+a_2}\frac{b_0}{s^2+a_1s+a_0} \quad (3)$$

Table 1. Parameters of tested plant system

K_s/M	2.82×10^5	a_1	6238	a_2	9759
D/M	40.73	a_0	$.10\times10^{10}$		
K_a/M	4.75×10^7	b_0	3.42×10^9	b_2	8.459×10^4

The tested robust control system is constructed by the software algorithm of DSP (TMSC320 C6701), whose sampling time is 33[μsec]. In (3), the tested plant system has the first resonant frequency at 85[Hz], the secondary resonant frequency at 30[kHz] and the phase-lead-lag element at 6[kHz]. The first resonant frequency is dominant for the frequency characteristics of tracking actuator. The secondary resonant frequency is higher than the Nyquist frequency 15[kHz] of tested software control system. Hence, the plant system of digital control system becomes the three-orders system as shown in (4). This paper designs the digital feedback controller based on (4). $P_n(z)$ has an unstable zero z_u.

$$P_n(z^{-1}) = \frac{d_2z^{-1}+d_1z^{-2}+d_0z^{-3}}{1+c_2z^{-1}+c_1z^{-2}+c_0z^{-3}} \quad (4)$$

The all parameters $N(z^{-1})$, $D(z^{-1})$, $X(z^{-1})$, $Y(z^{-1})$ of coprime factorization is designed by using pole allocation method on z-plane. The free parameter $g(z^{-1})$ has the same unstable zeros of $P_n(z^{-1})$. The low pass filter $g(z^{-1})$ of outer loop system is shown in (5) and (6).

$$g(z^{-1}) = \frac{K(z^{-1}+z_uz^{-2})}{1+g_1z^{-1}+g_0z^{-2}} \quad (5)$$

$$K = \frac{1 + g_1 + g_0}{1 + z_u} \tag{6}$$

In the robust feedback controller as shown in (2), this paper determines the robust stability condition to the uncertainty of all plant parameters. For the purpose of considering the robust stable condition, this paper defines the multiplicative perturbation $E(s)$ in (7). In (8), $E_{in}(z^{-1})$ is the multiplicative perturbation of inner loop system of Fig.1. $\hat{G}_{in}(z^{-1})$ is the nominal dynamics of $G_{in}(z^{-1})$, and it becomes the same system as $N(z^{-1})$. $E(z^{-1})$ is the digital dynamics of multiplicative perturbation $E(s)$. In order to keep the robust stable condition by using Small Gain Theorem, $E_{in}(z^{-1})$ should be a stable function in all frequency band using the state feedback and the state observer. And the gain of $g(z^{-1})$ should be also smaller than that of $E_{in}^{-1}(z^{-1})$ in all frequency band, as shown in (9).

$$E(s) = \frac{P(s)}{P_n(s)} - 1 \tag{7}$$

$$G_{in}(z^{-1}) = \hat{G}_{in}(z^{-1})\left\{1 + E_{in}(z^{-1})\right\}$$

$$E_{in}(z^{-1}) = \frac{Y(z^{-1})D(z^{-1})E(z^{-1})}{1 + N(z^{-1})X(z^{-1})E(z^{-1})} \tag{8}$$

$$|E_{in}(z^{-1})^{-1}| < |g(z^{-1})| \tag{9}$$

In order to design the feedback control system considering the specification of Table 2, the poles of tested robust feedback controller $C(z^{-1})$ are determined as shown in Table 3. The frequency characteristics of $g(z^{-1})$ are shown in Fig.3.

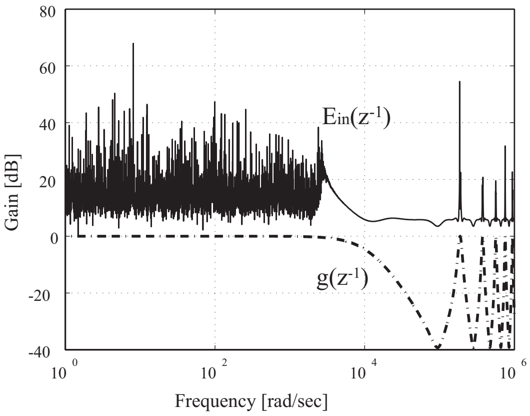


Fig. 3. Frequency characteristics of $g(z^{-1})$

Table 2. Specification of robust following control system

Parameter variation	from 80% to 120% of nominal K_{sn}
Disturbance Rejection	Maximum value becomes less than -40[dB]
Sensitivity function	-60[dB] around 100[rad/sec]

Table 3. Poles of tested robust feedback controller $C(z^{-1})$

Sampling Time	33.3 [μsec]
Poles of state feedback	0.939±j0.033, 0.944
Poles of state observer	0.781±j0.200, 0.851
Poles of $g(z^{-1})$	0.851, 0.851

3. SUDDEN DISTURBANCE OBSERVER

When a human walks and runs with the handy optical disk recording system, the tracking actuator has the influence on force disturbance. It is a sudden disturbance. Fig.4 shows the images of disturbance on optical disk recoding system. However, it is difficult to estimate only sudden disturbance without the periodic disturbance. Then, this paper realizes the sudden disturbance observer by using the memorized periodic disturbance as shown in Fig.5.

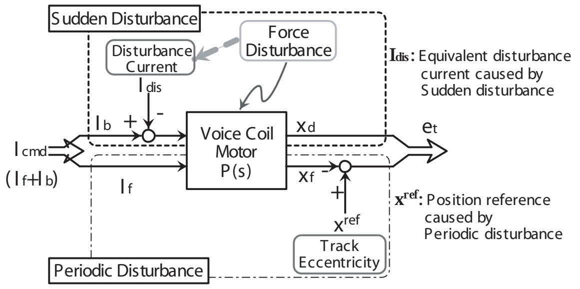


Fig. 4. Image of sudden disturbance and periodic disturbance

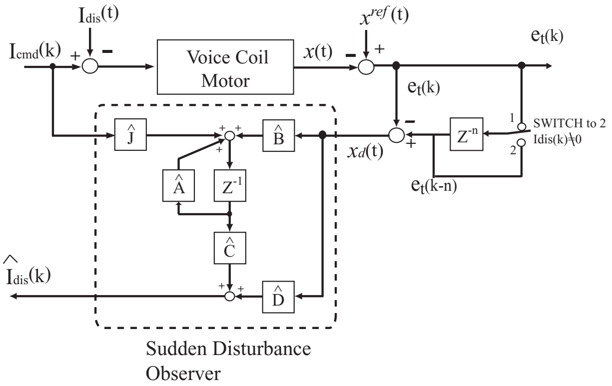


Fig. 5. Sudden disturbance observer

In following control of optical disk recording system, since the position of the beam spot is influenced on the periodic disturbance and the sudden disturbance as shown in Fig.4. $x_d(k)$ is treated as the output position caused by only sudden disturbance and $x_f(k)$ is treated as the output position caused by only periodic disturbance. The total output position is shown in (10). (11) shows the tracking error of optical disk recording system. The tracking error is obtained by the difference between the beam spot position $x(k)$ and the actual track position $x^{ref}(k)$. The following control system detects only the tracking error. The current command $I_{cmd}(k)$ of voice coil motor is shown in (12). In (12), $I_f(k)$ is the output variable of feedforward control system, and $I_b(k)$ is the output variable of feedback control system.

$$x(k) = x_d(k) + x_f(k) \tag{10}$$

$$e_t(k) = x^{ref}(k) - x(k) \tag{11}$$

$$I_{cmd}(k) = I_f(k) + I_b(k) \tag{12}$$

From (10) and (11), the actual tracking error $e_t(k)$ is shown in (13). Before the tracking actuator has the sudden disturbance, the tracking error becomes the periodic function caused by periodic disturbance as shown in (14). Here, n is determined by (15). T_s[sec] is a sampling time of feedforward controller, and N[rpm] is a revolution speed of optical disk recording system. Then, the tracking position $x_d(k)$ under the influence on sudden disturbance is shown in (16). As the results, the proposed sudden disturbance observer is constructed by using (16) as shown in Fig.5.

$$e_t(k) = x^{ref}(k) - x_f(k) - x_d(k) \tag{13}$$

$$e_t(k-n) = x^{ref}(k) - x_f(k) \tag{14}$$

$$n = \frac{60}{NT_s} \tag{15}$$

$$x_d(k) = e_t(k-n) - e_t(k) \tag{16}$$

The state equation of actual plant system is shown in (17). When the sudden disturbance $I_{dis}(k)$ is assumed as the sum of a step function and a lamp function, the expansion plant system for sudden disturbance observer is expressed in (18) and (19). The proposed feedback control system with sudden disturbance observer is shown in Fig.6.

$$\begin{aligned} x_p(k+1) &= Ax_p(k) + BI_{cmd}(k) \\ x_d(k) &= Cx_p(k) \end{aligned} \tag{17}$$

$$\begin{bmatrix} x_p(k+1) \\ I_{dis}(k+1) \\ \dot{I}_{dis}(k+1) \end{bmatrix} = \begin{bmatrix} A & -B & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_p(k) \\ I_{dis}(k) \\ \dot{I}_{dis}(k+1) \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} I_b(k) \tag{18}$$

$$x_d(k) = \begin{bmatrix} C & 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(k) \\ I_{dis}(k) \end{bmatrix} \tag{19}$$

$$\begin{aligned} z(k+1) = \hat{A}z(k) + \hat{B}\left\{e_t(k-n) - e_t(k)\right\} \\ +\hat{J}\left\{I_{cmd}(k) - I_f(k)\right\} \end{aligned} \tag{20}$$

$$\begin{bmatrix} \hat{I}_{dis}(k) \\ \hat{\dot{I}}_{dis}(k) \end{bmatrix} = \hat{C}z(k) + \hat{D}\left\{e_t(k-n) - e_t(k)\right\} \tag{21}$$

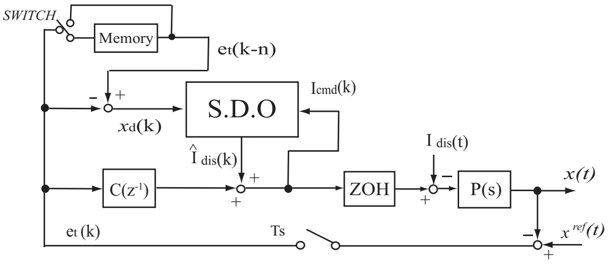


Fig. 6. Proposed feedback control system with sudden disturbance observer

4. FEEDFORWARD FOLLOWING CONTROL SYSTEM

For suppressing the tracking error, this paper proposes a new robust feedforward following control system, which is based on both ZPET control and the robust feedback control(Miyazaki *et al.* 2004).

In this paper, as the proposed feedback controller $C(z^{-1})$ always has an integral element, the precompensator $G_{ff}(z^{-1})$ has an integral element and the prediction function $G_{closed}(z^{-1})$ has a differential element. Then, the output current $I_f(k)$ of the ZPET controller are strongly affected by the observation noise and the quantization noise. In order to overcome this problem, this paper redefines $G_{ff}(z^{-1})$ and $G_{closed}(z^{-1})$. For this purpose, the plant system and the feedback controller, as shown in (22) and (23).

$$\begin{aligned} C(z^{-1}) &= \frac{C_n(z^{-1})}{C_d(z^{-1})} = C_1(z^{-1})C_2(z^{-1}) \\ &= \frac{C_{1n}(z^{-1})}{C_{1d}(z^{-1})} \frac{C_{2n}(z^{-1})}{(1-z^{-1})} \end{aligned} \tag{22}$$

$$P'(z^{-1}) = P(z^{-1})C_2(z^{-1}) \tag{23}$$

The controllers of feedforward control system are expressed in (24) and (25). However, ZPET controller has to use the two sampling forward tracking error $e_t(k+2)$. This paper proposes a new estimation method of the two sampling forward tracking error $e_t^{feedback}(k+2)$(Arai *et al.* 2000)(Yanagisawa *et al.* 2002)(Koide *et al.* 2003*a*). This paper treats a tracking error $e_t(k)$ as the periodic function such as (26). Using a memory of DSP, the proposed estimation method obtains the two sampling forward tracking error $e_t^{feedback}(k+2)$. The total structure of proposed robust following control system is illustrated as shown in Fig.7.

$$\begin{aligned} G'_{closed}(z^{-1}) &= \frac{P'(z^{-1})}{1 + C_1(z^{-1})P'(z^{-1})} \\ &= \frac{z^{-1}B'^{+}_{c}(z^{-1})B'^{-}_{c}(z^{-1})}{A'_c(z^{-1})} \end{aligned} \tag{24}$$

$$G'_{ff}(z^{-1}) = \frac{A'_c(z^{-1})B'^{-}_{c}(z)}{B'^{+}_{c}(z^{-1})[B'^{-}_{c}(1)]^2} \tag{25}$$

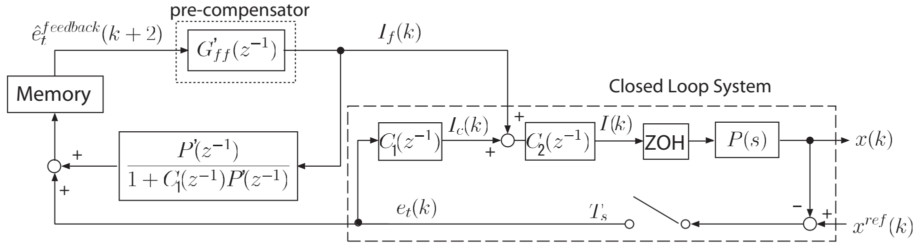


Fig. 7. Proposed feedforward following control system

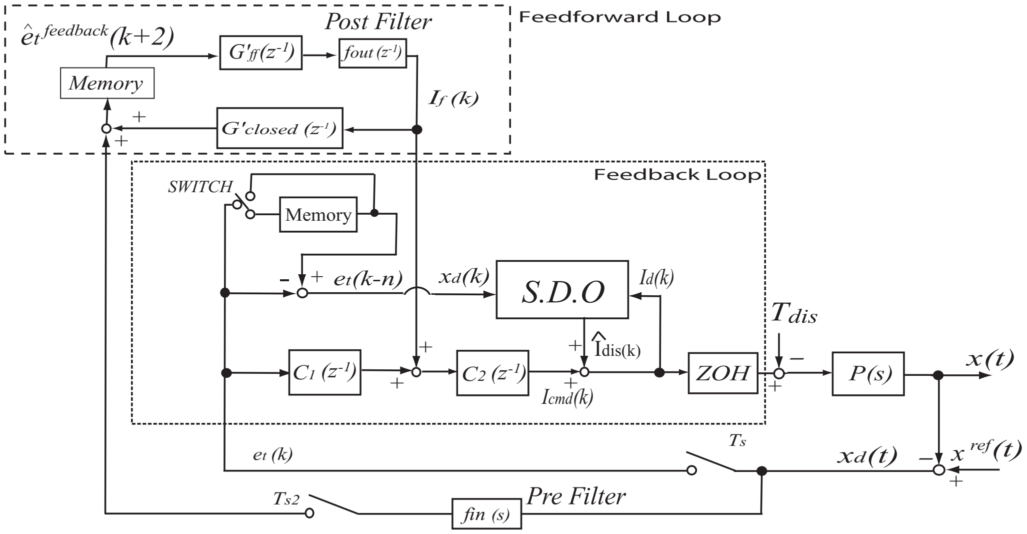


Fig. 8. Total structure of robust feedforward following control system with proposed sudden disturbance

$$e_t^{feedback}(k) = e_t^{feedback}(k+n) \tag{26}$$

The total structure of proposed following control system of optical disk recording system is constructed as shown in Fig.8. From these operations, the feedforward control system is little influenced by the sudden disturbance.

5. EXPERIMENTAL RESULTS

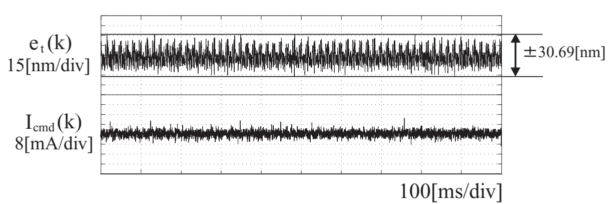
In order to confirm the validity of the proposed robust feedback control system, this paper shows the tested experimental results using the experimental system. The proposed control system is constructed by the software algorithm of DSP. The sampling time of feedback controller and new sudden disturbance observer is 33[μsec] and sampling time of feedforward controller is 66[μsec].

Fig.9 shows the experimental results of only robust feedback control system with sudden disturbance observer as shown in Fig.6. From Fig.9, the robust following control system realizes the stable response. However, it is difficult for only the robust feedback control system to suppress the influence on both the periodic disturbance and the sudden disturbance.

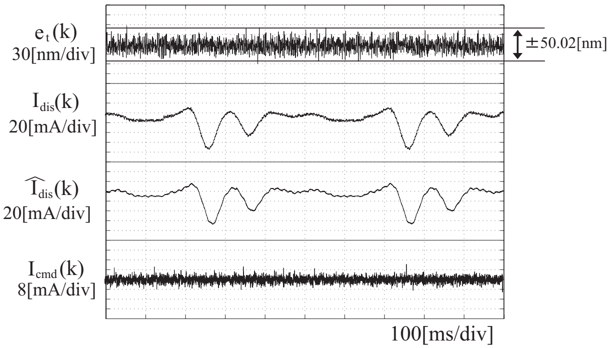
Fig.10 shows the experimental results of the feedforward control system with the proposed sudden disturbance observer. Fig.10(b) shows that the proposed sudden disturbance observer well compensates the tracking error caused by the sudden disturbance, in comparison with Fig.9(b). The residual tracking error becomes 39.12[nm]. The following control system keeps the small tracking error against the sudden disturbance input. Moreover, From Fig.10(a), the proposed control system keeps the smaller residual tracking error against the periodic disturbance in comparison with Fig.9(a). Therefore, the feedback loop of proposed sudden disturbance observer also suppresses the tracking error against the periodic disturbance. The actual tracking error $e_t(k)$ becomes a smaller value, and the actuator current command $I_{cmd}(k)$ is very smooth and stable as well as Fig.9(a).

6. CONCLUSION

This paper proposes a robust following control system with feedforward controller and new sudden disturbance observer for an optical disk recording system based on prediction of tracking error. The proposed robust feedback control system satisfies the robust stable condition. The feedforward control system is based on both ZPET control system and the prediction of tracking error. The proposed feedforward controller suppresses the influence on periodic disturbance caused by the track eccentricity. The sudden disturbance observer suppresses the influence on sud-

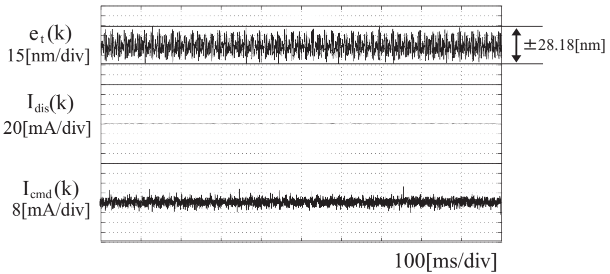


(a) With periodic disturbance

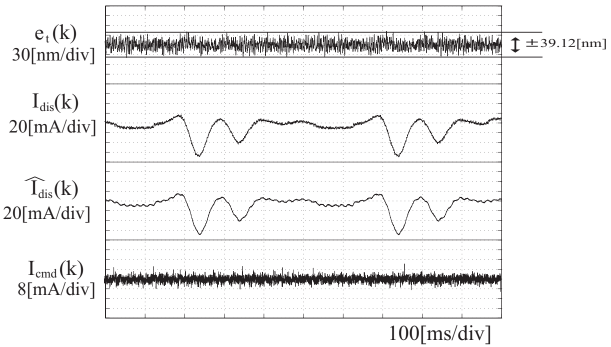


(b) With periodic disturbance and sudden disturbance

Fig. 9. Experimental results using only feedback following control system with sudden disturbance observer



(a) With periodic disturbance



(b) With periodic disturbance and sudden disturbance

Fig. 10. Experimental results using feedforward following control system sudden disturbance observer

den disturbance caused by the force disturbance when human walks and runs.

The experimental results in this paper confirms that the proposed robust feedforward following control system well suppresses the both residual tracking error and the influence on sudden disturbance on condition that revolution speed of optical disk is 3600[rpm].

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