Robust Tracking Servo System Considering Force Disturbance for the Optical Disk Recording System

Kiyoshi Ohishi, *Member, IEEE*, Toshimasa Miyazaki, *Member, IEEE*, Koichi Inomata, Hitoshi Yanagisawa, Daiichi Koide, and Haruki Tokumaru

***Abstract*—This paper proposes a new robust tracking servo system for the optical disk recording system with feedforward controller based on the prediction of the tracking error. In optical recording systems, the feedback servo system must suppress the influence of force disturbance and parameter variation. To overcome this problem, this paper designs the robust feedback control system by using coprime factorization and disturbance observer. The detecting signal of the optical disk recording system is only a tracking error. Hence, the feedforward controller of the proposed tracking control system is constructed based on both the "zero-phase-error tracking" control theory and the prediction of the tracking error. The experimental results point out that the proposed tracking servo system has a quick and precise tracking response and keeps the residual tracking error below its tolerance.**

***Index Terms*—Disturbance rejection, optical disk recording system, prediction of the tracking error, robust control, zero-phase-error tracking control.**

I. Introduction

RECENTLY, the optical disk recording system has been used for storing information including audio and visual data. Optical disk recording systems, such as compact disk-recordable (CD-R) and digital versatile disk (DVD), have a radial runout (maximum amplitude is 100 μm peak-to-peak), which is caused by the track eccentricity of the optical disk. The tracking actuator must follow its reference track to keep the residual tracking error below its tolerance. The tracking control system must suppress the tracking error within 0.1 μm against the maximum value of track eccentricity. In the next-generation optical disk recording system, the tracking error should be less than 0.03 μm. Moreover, the optical disk recording system sometimes has the influence of force disturbance. Hence, the tracking control system of the optical disk recording system should keep the robust performance against force disturbance.

Generally, the tracking servo system for optical disk recorders is accomplished by the feedback control designed for robust performance and wide frequency band. Recently, several tracking control systems have been realized by proportional–integral–differential (PID) control system, repetitive control, and H^∞ control theory. The PID control system has a very simple structure. However, its feedback control system sometimes cannot realize the desired disturbance suppression response [1], [2]. The repetitive control has been applied to the tracking control of the optical disk recording system. It has carried out the precise tracking control [3], [4]. However, it is difficult to keep the robust performance on parameter variation and the desired disturbance suppression response. The robust control system based on H^∞ control theory can keep a robust stable condition for parameter variation and can have a desired frequency characteristics by its loop shaping [5]. However, it is difficult for a feedback system using H^∞ controller to suppress its tracking error below the next-generation tolerance.

The tracking control system of a hard disk drive (HDD) has been constructed by using the two-degrees-of-freedom control system [6], [7]. The tracking control system of the HDD detects the actual position signal. However, the tracking control system of the optical disk recording system detects only the tracking error signal. Moreover, the position reference, which is synchronized with disk rotation speed, is generated by the track eccentricity of the optical disk [3], [4]. Therefore, it is very difficult to obtain the amplitude and the phase of position reference in advance. As a result, it is difficult to realize the two-degrees-of-freedom control system for the optical disk recording system because the input signal is only a tracking error signal. However, the tracking control system for the next-generation optical disk recording system should be a two-degrees-of-freedom control system that can be designed by considering the force disturbance, the robust stability of parameter variation, and the reference input response.

For this purpose, this paper proposes the new two-degrees-of-freedom control system by using only the tracking error signal. The proposed robust feedforward tracking servo system is constructed by both the "zero-phase-error tracking" (ZPET) control and the robust feedback control, which use disturbance observer and coprime factorization.

The robust feedback control system is a dual-loop control system based on coprime factorization and disturbance observer. Disturbance observer has a simple structure, and it is valid for disturbance rejection and suppression of mechanical parameter variation [8]–[10]. The proposed robust feedback control system has been performed for the speed control of the servo motor system [8], [9]. This paper applies the robust feedback control system to the tracking actuator. Its control system should realize the more precise and quicker motion

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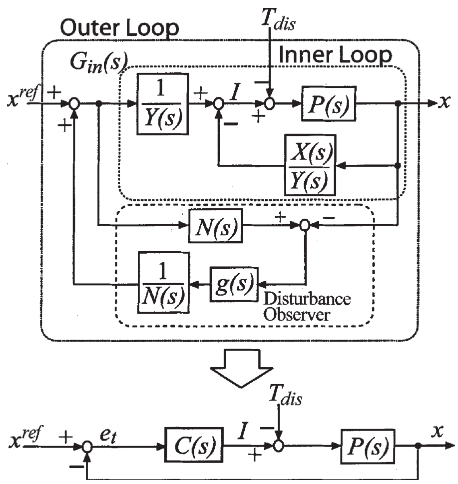

Fig. 1. Robust feedback controller based on disturbance observer and coprime factorization.

control than that of the servo motor. The frequency bandwidth of the control system is wider than 5000 rd/s. Because ZPET control is a feedforward controller [11], [12], it requests the optical disk recording system to obtain the position reference signal in advance. However, its detecting signal is only a tracking error. Therefore, this paper proposes a new ZPET control system based on the prediction of the tracking error for the optical disk recording system. The proposed tracking servo system realizes the desired tracking control performance using only the tracking error. It is reported experimentally that the proposed feedforward control system reduces the tracking error in comparison with repetitive control [13]. Moreover, the influence of both parameter variation and sudden disturbance is suppressed by the proposed tracking control system.

II. Robust Feedback Control for the Optical Disk Recording System

A. Robust Feedback Control System

For realizing the high-performance tracking control of the optical disk recording system, this paper proposes the robust feedback control system based on coprime factorization. The proposed feedback control system has a dual-loop system as shown in Fig. 1 [8], [9]. 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 $C(s)$ is determined by the coprime factorization $N(s)$, $D(s)$, $X(s)$, and $Y(s)$ and by the free parameter $g(s)$ as shown in (3) [8]. $g(s)$ is equivalent to a low-pass filter of disturbance observer. A gain of $g(s)$ is unity in steady state, as shown in (3), i.e.,

$$P(s) = \frac{N(s)}{D(s)}, \qquad N(s)X(s) + Y(s)D(s) = 1 \tag{1}$$

$$C(s) = \frac{X(s) + Q(s)D(s)}{Y(s) - Q(s)N(s)} \tag{2}$$

$$Q(s) = \frac{Y(s)}{N(s)} g(s), \qquad g(0) = 1. \tag{3}$$

TABLE I
Specifications of DDU1000

Optical Disk	Type	CD-ROM
	Disk Size	ϕ120[mm]
	Track Pitch	1.6[μm]
	Rotation Speed	200 - 3600[rpm]
Optical Pick-up	Type	SANYO SF-P151EX
	Semiconductor laser	Wavelength 785[mm]
	Detection Method	3-spot method
Tracking Actuator	Type	Voice Coil Motor
	Sensitivity	1.30[μm/V]
	First Resonance Frequency	85[Hz]
	Second Resonance Frequency	30[kHz]

The image of the robust feedback controller $C(s)$ is illustrated in Fig. 1. $g(s)$ defines the complementary sensitivity function $T(s)$ of the outer-loop system. The sensitivity function $S(s)$ and the disturbance rejection response $G_{\mathrm{dy}}(s)$ of the robust feedback controller $C(s)$ are obtained using (4) and (5), i.e.,

$$S(s) = (1 - g(s))\, Y(s)D(s) \tag{4}$$

$$G_{\mathrm{dy}}(s) = (1 - g(s))\, Y(s)N(s) \tag{5}$$

$$C_1(s) = \frac{X(s)}{Y(s)} + \frac{1}{Y(s)} \frac{g(s)}{1 - g(s)} \frac{1}{N(s)}. \tag{6}$$

In the robust feedback controller shown in (6), this paper proposes the new design method considering the robust stability condition and the disturbance rejection condition.

B. Robust Stability Condition

At first, this paper determines the robust stability condition to the uncertainty of plant system. This paper carries out the tracking control by using the tested optical disk recording system DDU1000, whose maximum disk rotation speed is 3600 r/min. DDU1000 is the standard examination system of the optical disk recording system for developers. The specifications of DDU1000 are shown in Table I. These parameters are determined from the curve-fitting model of the frequency characteristics of voice coil motor. The frequency characteristics of voice coil motor are identified by using the swept sine analysis, whose frequency is in the range of 1–50 kHz. This paper obtains its transfer function, which is the fifth-order system shown in (7). The plant system is the current-driven voice coil motor that has the characteristics of the fifth-order system given by (see Fig. 2 and Table II)

$$\begin{aligned} P_5(s) &= \frac{x(s)}{I(s)} \\ &= \frac{\frac{K_a}{M}}{s^2 + \frac{D}{M}s + \frac{K_s}{M}} \frac{s + b_2}{s + a_2} \frac{b_0}{s^2 + a_1 s + a_0}. \end{aligned} \tag{7}$$

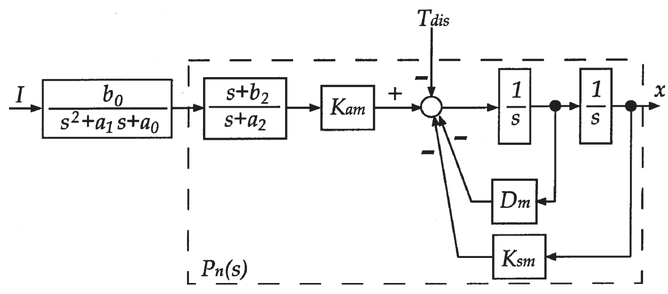

Fig. 2. Block diagram of the tracking system.

TABLE II
PARAMETERS OF THE TESTED PLANT SYSTEM

K_s/M	2.82×10^5	a_1	6238	a_2	9759
D/M	40.73	a_0	3.10×10^{10}		
K_a/M	4.75×10^7	b_0	3.42×10^9	b_2	8.459×10^4

where K_a, M, D, and K_s are the force constant, the mass of the moving parts of the actuator, the viscosity coefficient, and the spring constant, respectively.

The tested robust control system is constructed by the software algorithm of a digital signal processor (DSP) (TMSC320 C6701), whose sampling time is 33 μs. In (7), 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 of 15 kHz of the tested software servo system. Hence, the plant system of a digital control system becomes the third-order system given by

$$P_n(s) = \frac{\frac{K_a}{M}}{s^2 + \frac{D}{M}s + \frac{K_s}{M}} \frac{s+b_2}{s+a_2}. \tag{8}$$

This paper denotes $P(s)$ as $P_n(s)$ when these parameters are nominal. The frequency characteristics of the plant system are shown in Fig. 3. In Fig. 3, $P_n(s)$ traces the actual plant system within the limits of the Nyquist frequency.

For the purpose of considering the robust stable condition, this paper defines the multiplicative perturbation $E(s)$ in (9). In (10), $E_{\rm in}(s)$ is the multiplicative perturbation of the inner-loop system in Fig. 1. $\hat{G}_{\rm in}(s)$ is the nominal dynamics of $G_{\rm in}(s)$, and it is $N(s)$. That is,

$$E(s) = \frac{P(s)}{P_n(s)} - 1 \tag{9}$$

$$\begin{aligned} G_{\rm in}(s) &= \hat{G}_{\rm in}(s)\{1 + E_{\rm in}(s)\} \\ &= \hat{G}_{\rm in}(s)\left\{1 + \frac{Y(s)D(s)E(s)}{1 + N(s)X(s)E(s)}\right\} \end{aligned} \tag{10}$$

$$\|E_{\rm in}(s)g(s)\|_\infty < 1 \text{ and } |E_{\rm in}(j\omega)|^{-1} \geq |g(j\omega)|^\forall \omega \tag{11}$$

$$|g(s)| < \left|E_{\rm in}^{-1}(s)\right|. \tag{12}$$

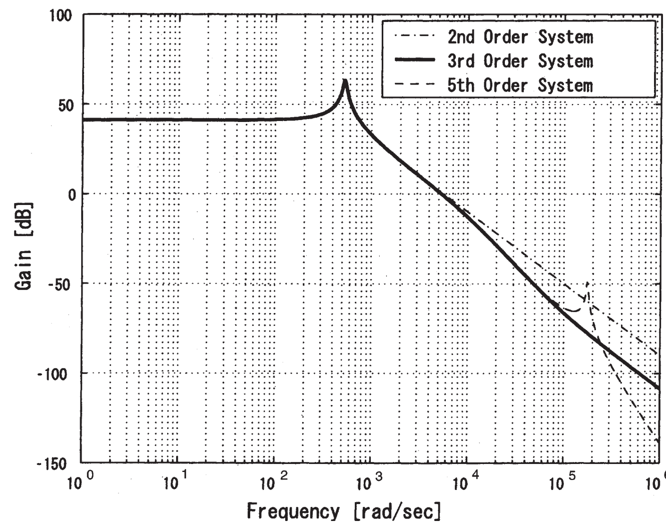

Fig. 3. Frequency characteristics of the tested system.

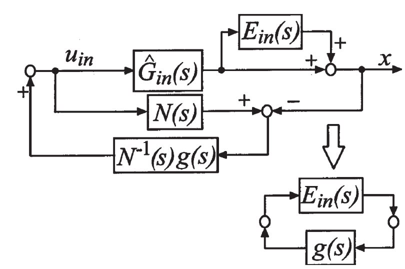

Fig. 4. Robust stability condition.

To keep the robust stable condition by using the Small Gain Theorem [5], $E_{\rm in}(s)$ should be a stable function in all frequency bands, and the gain of $g(s)$ should be smaller than that of $E_{\rm in}^{-1}(s)$ in all frequency bands. The image of robust stability condition of $C(s)$ is illustrated in Fig. 4.

C. Disturbance Rejection Response

When a human walks and runs with a handy optical disk recording system, the tracing actuator is influenced by force disturbance. Such force disturbance is not usually periodic disturbance like a radial runout. Fig. 5(a) shows the measured force disturbance waveform $T_{\rm dis}(t)$. This is the time response of force disturbance. Fig. 5(b) shows the frequency response of force disturbance, which is calculated from the time response by using fast Fourier transform (FFT) analysis. The dynamical model $T_{\rm dis}(s)$ of force disturbance is determined by fitting the frequency response, as shown in (13). The disturbance model is of the fourth order, as shown by

$$T_{\rm dis}(s) = \frac{0.002(s^4 + 250^4)}{s^4 + 80^4}. \tag{13}$$

Moreover, using Fig. 6, the position disturbance $T_{\rm pd}(s)$ caused by $T_{\rm dis}(s)$ is defined in (14), which is the dotted line in Fig. 7. Hence, the disturbance suppression response $G_{\rm dy}(s)$ of the tested servo system is determined by (15). From these

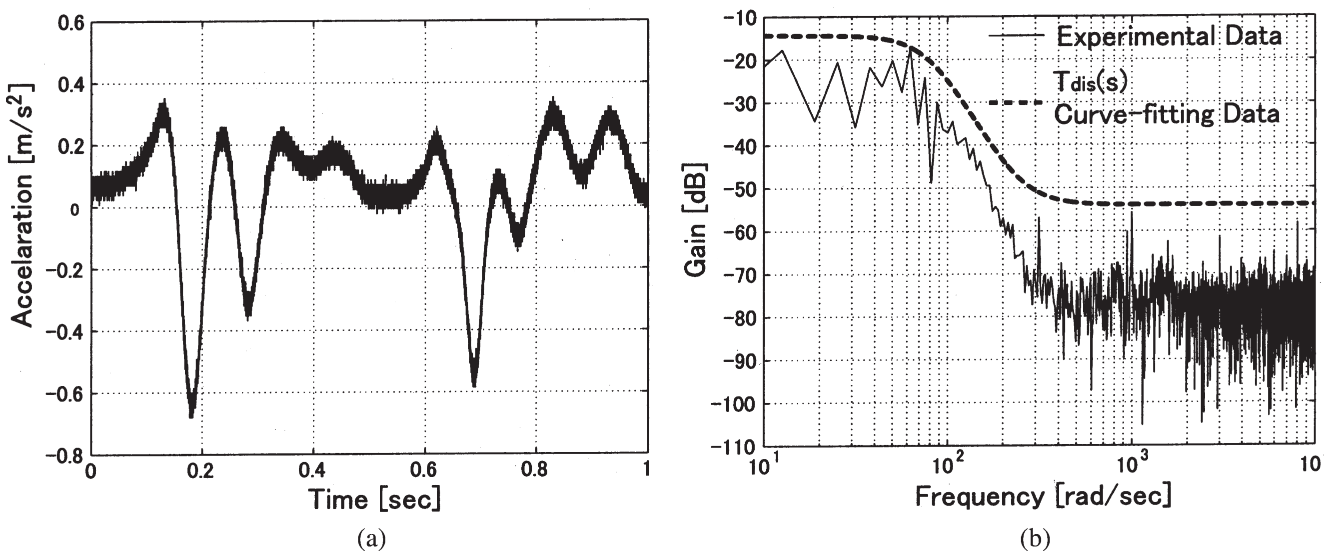

Fig. 5. Force disturbance of the optical recording system. (a) Disturbance waveform $T_{\mathrm{dis}}(t)$. (b) Frequency characteristics $T_{\mathrm{dis}}(s)$.

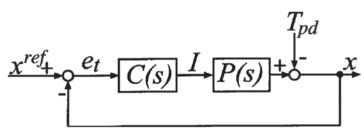

Fig. 6. Feedback control system for the optical disk.

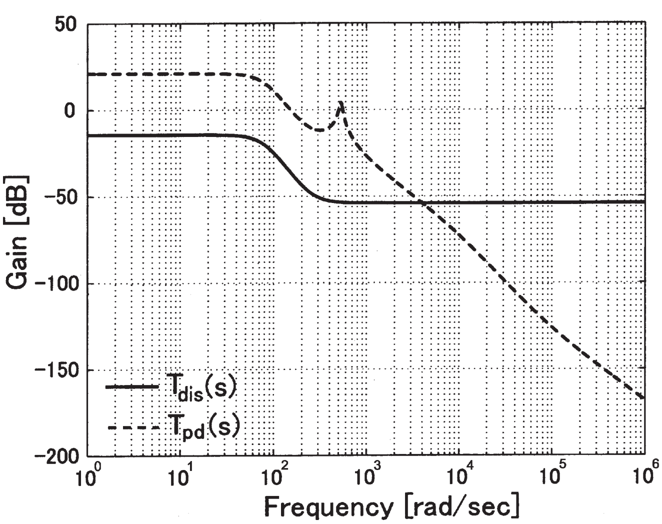

Fig. 7. Frequency characteristics of position disturbance $T_{\mathrm{pd}}(s)$.

equations, the condition for the desired disturbance suppression response is defined in (16). That is,

$$T_{\mathrm{pd}}(s) = \frac{\frac{K_a}{M}}{s^2 + \frac{D}{M}s + \frac{K_s}{M}} \frac{s+b_2}{s+a_2} T_{\mathrm{dis}}(s) \tag{14}$$

$$G_{\mathrm{dy}}(s) = \frac{x(s)}{T_{\mathrm{pd}}(s)} = Y(s)D(s)\left(1 - g(s)\right) \tag{15}$$

$$\begin{aligned} &\|T_{\mathrm{pd}}(s)S(s)\|_\infty < \varepsilon \\ &\quad \Rightarrow \|T_{\mathrm{pd}}(s)Y(s)D(s)\left(1-g(s)\right)\|_\infty < \varepsilon \\ &\quad \Rightarrow |1-g(s)| < \left|\varepsilon \left(Y(s)D(s)T_d(s)\right)^{-1}\right|. \end{aligned} \tag{16}$$

TABLE III
SPECIFICATIONS OF THE ROBUST TRACKING SERVO 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]

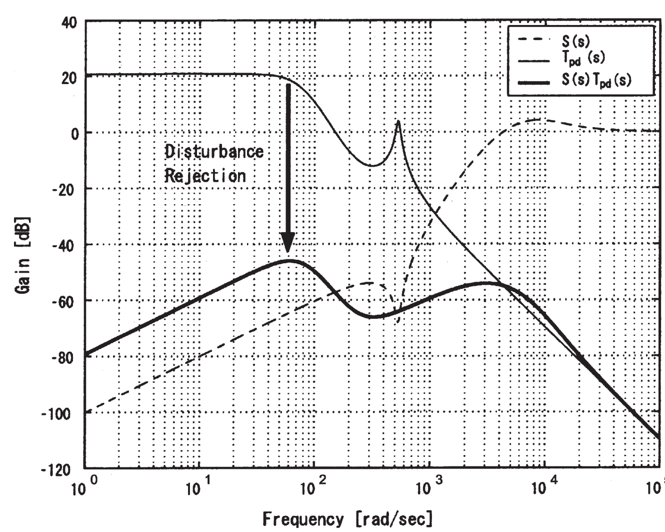

Fig. 8. Frequency characteristics of disturbance rejection response.

TABLE IV
POLES OF THE TESTED ROBUST FEEDBACK CONTROLLER $C(s)$

Poles of state feedback	-8000,-8000,-8000 [rad/sec]
Poles of state observer	-9000,-9000,-9000 [rad/sec]
Poles of $g(s)$	-12000,-12000 [rad/sec]

In (16), ε is the gain margin of the disturbance suppression response. When ε is small, the tested robust feedback controller $C(s)$ has a quick disturbance suppression response.

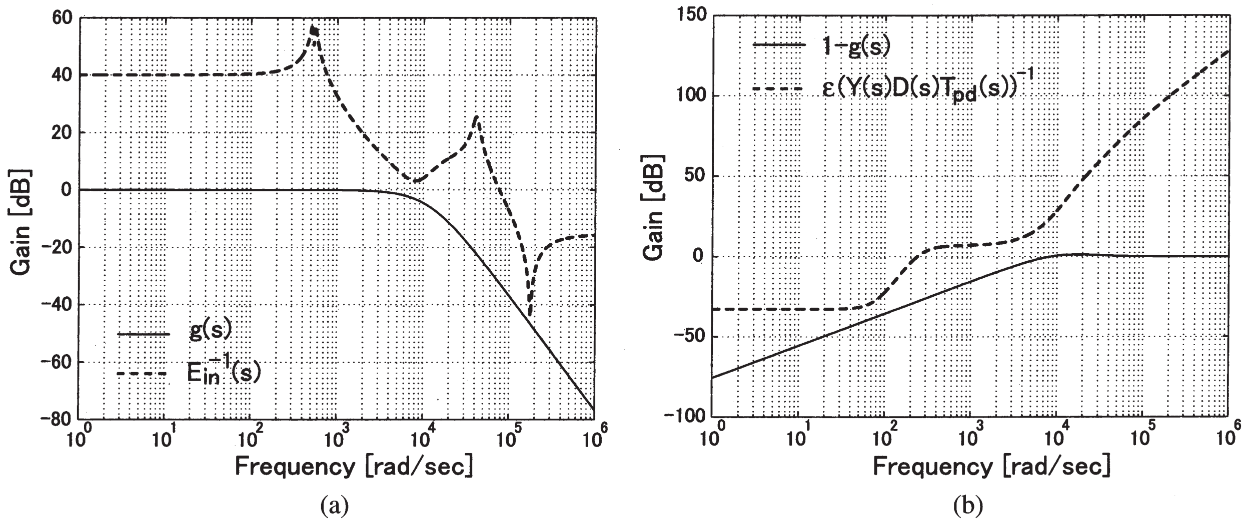

Fig. 9. Frequency characteristics of $g(s)$ considering the specification of the robust tracking servo system. (a) Robust stability condition. (b) Disturbance rejection condition.

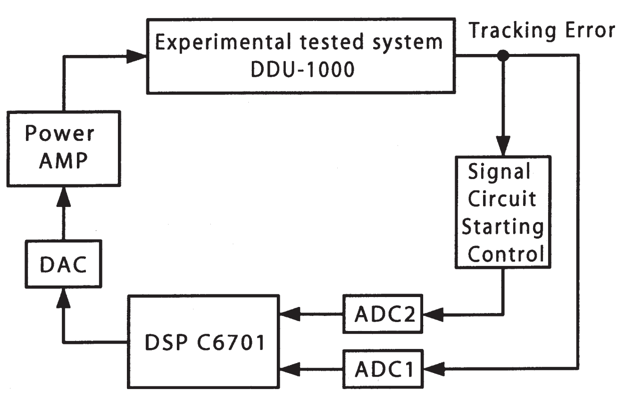

Fig. 10. Experimental system of the optical recording system.

To realize these robust control performances of $C(s)$, this paper satisfies both (12) and (16).

D. Experimental Results

In this paper, the robust feedback controller $C(s)$ needs to satisfy both the robust stability condition on $\pm 20\%$ multiplicative perturbation of the spring constant K_s and the disturbance rejection response $T_{\rm pd}(s)S(s)$, which is shown in Table III. In (12), the multiplicative perturbation $E_{\rm in}(s)$ of the inner-loop system is obtained by using its numerical analysis. In (16), the gain margin ε is set to 0.01 as shown in Fig. 8. To satisfy the desired disturbance rejection response, the sensitivity function $S(s)$ must become -60 dB at approximately 100 rd/s.

Therefore, the poles of the tested robust feedback controller $C(s)$ are determined as shown in Table IV. As a result, considering the specifications in Table III, the frequency characteristics of $g(s)$ and $1-g(s)$ are shown in Fig. 9(a) and (b).

To confirm the validity of the proposed robust feedback control system, this paper shows experimental results using the experimental system shown in Fig. 10. Fig. 11 shows the experimental results of the tracking response of the tested robust feedback controller $C(s)$. These experimental results point out that the tested robust feedback controller $C(s)$ follows the reference track to keep the residual tracking error e_t below 0.05 μm peak-to-peak. Moreover, when the optical disk recording system has the force disturbance $T_{\rm dis}(s)$, the tested robust feedback controller $C(s)$ keeps the residual tracking error e_t below 0.06 μm peak-to-peak, as shown in Fig. 11(b).

However, it is difficult for the robust feedback control system to keep the tracking error within 0.03 μm, which is the next-generation tracking servo system.

III. Feedforward Tracking Control System

A. ZPET Controller of the Tracking Control System

To suppress the tracking error below 0.03 μm, this paper proposes a new robust feedforward tracking control system, which is based on both ZPET control and the robust feedback control. ZPET control system is a feedforward controller [11], [12].

In the optical disk recording systems, its detecting signal is only a tracking error e_t. However, the precompensator of a feedforward controller should be connected to the feedback controller as shown in Fig. 12. $e_t^{\rm feedback}(k+d)$, which is the d times sampling forward tracking errors of the feedback controller in advance, is the input variable of the feedforward controller. The plant system for the feedforward controller is the discrete closed-loop transfer function from the output variable $I_f(k)$ of the feedforward controller to the output variable x of the optical disk recording system, which is obtained in (17). In (17), the precompensator of the ZPET control system is designed as shown in (18) [11], [12], i.e.,

$$G_{\rm closed}(z^{-1}) = \frac{P(z^{-1})}{1+C(z^{-1})P(z^{-1})} = \frac{z^{-1}B_c^{+}(z^{-1})B_c^{-}(z^{-1})}{A_c(z^{-1})} \tag{17}$$

$$\begin{aligned} I_f(k) &= \frac{A_c(z^{-1})B_c^{-}(z)}{B_c^{+}(z^{-1})\left[B_c^{-}(1)\right]^2} z e_t^{\rm feedback}(k) \\ &= \left(A'_{ff}z + \frac{A_{ff}(z^{-1})}{B_{ff}(z^{-1})}\right) z e_t^{\rm feedback}(k) \\ &= G_{ff}(z^{-1}) e_t^{\rm feedback}(k+2). \end{aligned} \tag{18}$$

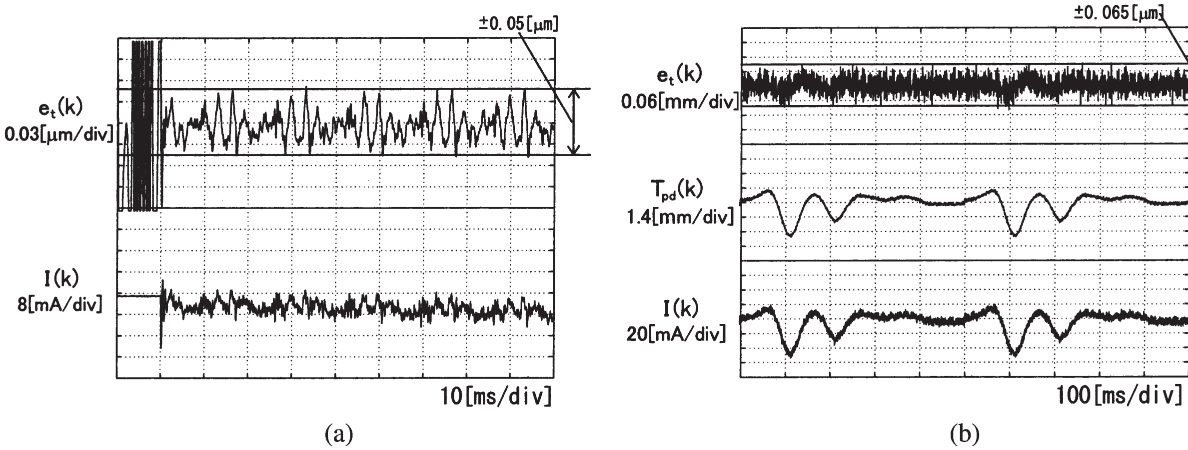

Fig. 11. Experimental results of the robust feedback control system. (a) Without disturbance. (b) With disturbance.

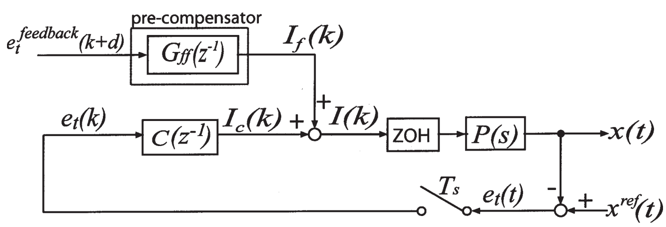

Fig. 12. Robust feedforward tracking servo system with a precompensator of the ZEPT control system.

Here, $A_c(z^{-1})$ and $B_c(z^{-1})$ are the polynomials of a closed-loop transfer function, and z^{-1} represents the delay of one sampling period. In (18), $B_c^-(z^{-1})$ includes the unstable zeros, and $B_c^+(z^{-1})$ includes the stable zeros. Replacing z^{-1} in $B_c^-(z^{-1})$ by z, this paper has $B_c^-(z)$, which has the complex conjugate frequency response of $B_c^-(z^{-1})$. $B_c^-(1)$ is calculated by substituting $z = 1$ into $B_c^-(z)$, and it is the steady-state value [11], [12]. Hence, the precompensator of the feedforward controller is obtained by (19), which is given by

$$G_{ff}(z^{-1}) = A'_{ff} + \frac{A_{ff}(z^{-1})}{B_{ff}(z^{-1})z}$$

$$A_{ff}(z^{-1}) = \sum_{i=0}^{8} A_{ffi} z^{-i}$$

$$B_{ff}(z^{-1}) = \sum_{i=0}^{6} B_{ffi} z^{-i}. \tag{19}$$

Its input variable is $e_t^{\text{feedback}}(k+2)$, which represents the two sampling forward tracking errors of the feedback controller. However, an ordinary optical disk recording system cannot obtain the two sampling tracking errors represented by $e_t^{\text{feedback}}(k+2)$.

B. Prediction of the Tracking Error

To overcome this problem, this paper proposes a new estimation method of the two sampling forward tracking errors, which is represented by $e_t^{\text{feedback}}(k+2)$ [14], [15]. Generally, as a tracking servo system regulates the target position in the very narrow space, this paper treats a tracking error $e_t(k)$ as the periodic function of the optical disk recording system. Hence, the tracking error $e_t^{\text{feedback}}(k)$ of only the feedback controller is estimated as shown in (20)–(22), i.e.,

$$e_t(k) = x^{ref}(k) - x(k) \tag{20}$$

$$x(k) = (e_t(k) + I_f(k))\, C(z^{-1})P(z^{-1}) \tag{21}$$

$$\frac{x^{ref}(k)}{1 + C(z^{-1})P(z^{-1})} = e_t(k) + \frac{P(z^{-1})}{1 + C(z^{-1})P(z^{-1})} I_f(k)$$

$$= e_t^{\text{feedback}}(k) \tag{22}$$

$$n = \frac{60}{NT_s}. \tag{23}$$

Using a memory of a DSP as shown in Fig. 13(a), the proposed estimation method obtains the two sampling forward tracking errors $e_t^{\text{feedback}}(k+2)$ of the feedback controller. n is determined by (23). T_s (in seconds) is a sampling time of the feedforward controller, and N r/min is a revolution speed of the optical disk recording system.

The total structure of the proposed robust feedforward tracking servo system is illustrated in Fig. 13(b). It becomes the robust feedforward tracking servo system based on the prediction of the tracking error.

C. Limitation Algorithm for the Feedforward Control System

For suppressing the windup phenomenon, Fig. 14 contains a new limitation algorithm of controller output [16], [17]. When the current reference $I_c(k)$ becomes larger than the limitation current I_{lim}, the current reference $I_c(k)$ is saturated as shown in (25), i.e.,

$$|I_c(k)| \le I_{\text{lim}} \Rightarrow I_c(k) \to I_c(k) \text{ and } e_t(k) \to e_t(k) \tag{24}$$

$$|I_c(k)| > I_{\text{lim}} \Rightarrow I_c(k) \to \text{sgn}\{I_c(k)\} I_{\text{lim}} = \tilde{I}_c(k)$$

$$\text{and } e_t(k) \to \tilde{e}_t(k). \tag{25}$$

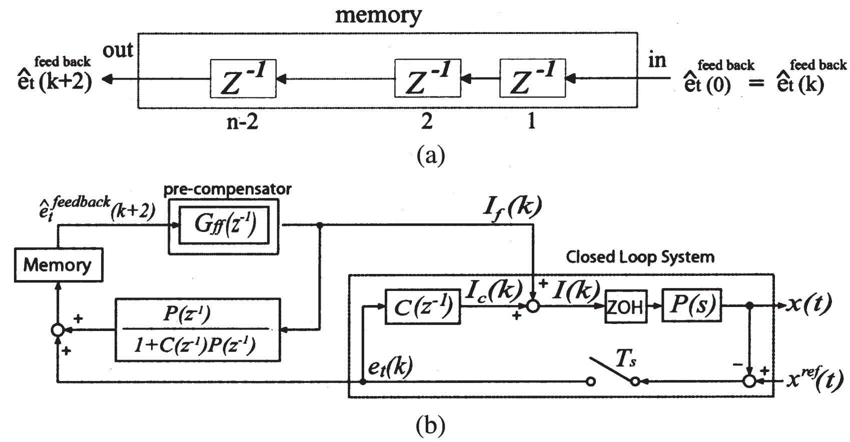

Fig. 13. Feedforward tracking servo system with prediction of the tracking error. (a) Estimation method of $e_t^{\text{feedback}}(k+2)$ using memory. (b) Block diagram for the prediction of the tracking error.

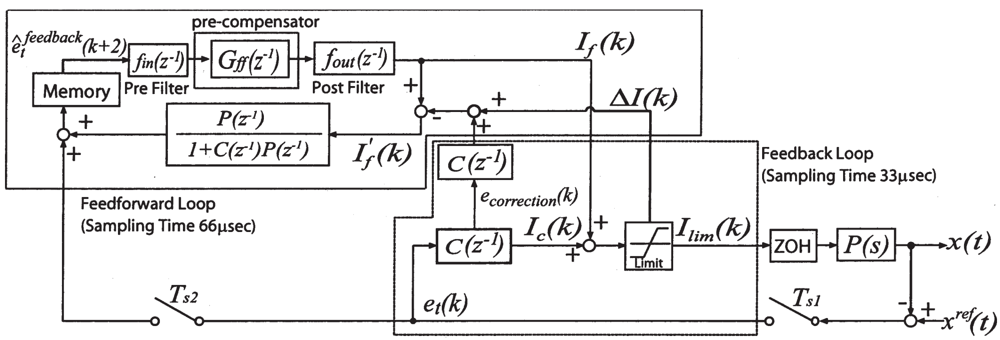

Fig. 14. Total structure of the proposed robust feedforward tracking servo system with the new limitation algorithm.

Initially, the robust feedback controller considers the saturation of the current reference $I_c(k)$ by using (26)–(31), which are defined as follows:

$$\boldsymbol{x}_c(k+1) = \mathbf{A}_c x_c(k) + \mathbf{B}_c e_c(k) \tag{26}$$

$$I_c(k) = \mathbf{C}_c x_c(k) + d e_c(k) \tag{27}$$

$$\tilde{e}_c(k) = e_c(k) - \frac{I_c(k) - I_{\lim}}{d} \tag{28}$$

$$\tilde{\mathbf{x}}_c(k+1) = \mathbf{A}_c x_c(k) + \mathbf{B}_c \tilde{e}_c(k) \tag{29}$$

$$\tilde{I}_c(k) = \mathbf{C}_c x_c(k) + d\tilde{e}_c(k) \tag{30}$$

$$e_{\text{correction}}(k) = \frac{I_c(k) - I_{\lim}}{d}. \tag{31}$$

The current reference $I_c(k)$ is computed using the state equation, as shown in (26), and the output equation of the robust feedback controller $C(z^{-1})$, as shown in (27). When the current reference is saturated, the current reference $I_c(k)$ is limited to $\tilde{I}_c = I_{\lim}$. As a result, the tracking error $e_t(k)$, which is the input signal of the robust feedback controller, must also be corrected to $\tilde{e}_t(k)$, as shown in (28). In (29) and (30), the state equation of $C(z^{-1})$ is recalculated and updated by using the corrected tracking error $\tilde{e}_t(k)$ at the same sampling time. The saturation influence of state variables in $C(z^{-1})$ is erased completely [18], [19].

Next, using $e_{\text{correction}}(k)$ in (31), the estimation system of $e_t^{\text{feedback}}(k+2)$ considers the saturation of the controller output of $C(z^{-1})$ by using (33) and (34). $\Delta I(k)$, which is caused by the saturation of the feedforward control system, is obtained using (32). From (32), the corrected current reference $I'_f(k)$ of the feedforward controller is determined in (33). Hence, the estimated tracking error $\hat{e}_t^{\text{feedback}}(k)$ by using $I'_f(k)$ is shown in (34). The saturation influence of the estimation system $e_t^{\text{feedback}}(k+2)$ is also considered completely. That is,

$$\begin{aligned}\Delta I(k) &\\ &= C(z^{-1})\tilde{e}_t(k) + I_f(k) - I_{\lim}\\ &= C\left(z^{-1}\right)\left(e_t(k) - e_{\text{correction}}(k)\right) + I_f(k) - I_{\lim}\end{aligned} \tag{32}$$

$$\begin{aligned}I_{\lim}(k) - C(z^{-1})e_t(k) &\\ &= I_f(k) - \Delta I(k) - C(z^{-1})e_{\text{correction}}(k)\\ &= I'_f(k)\end{aligned} \tag{33}$$

$$\begin{aligned}\hat{e}_t^{\text{feedback}}(k) &\\ &= e_t(k) + \frac{P(z^{-1})}{1 + C(z^{-1})P(z^{-1})} I'_f(k)\\ &= e_t(k) + \frac{P(z^{-1})}{1 + C(z^{-1})P(z^{-1})}\\ &\quad \times \left\{I_f(k) - \Delta I(k) - C(z^{-1})e_{\text{correction}}(k)\right\}.\end{aligned} \tag{34}$$

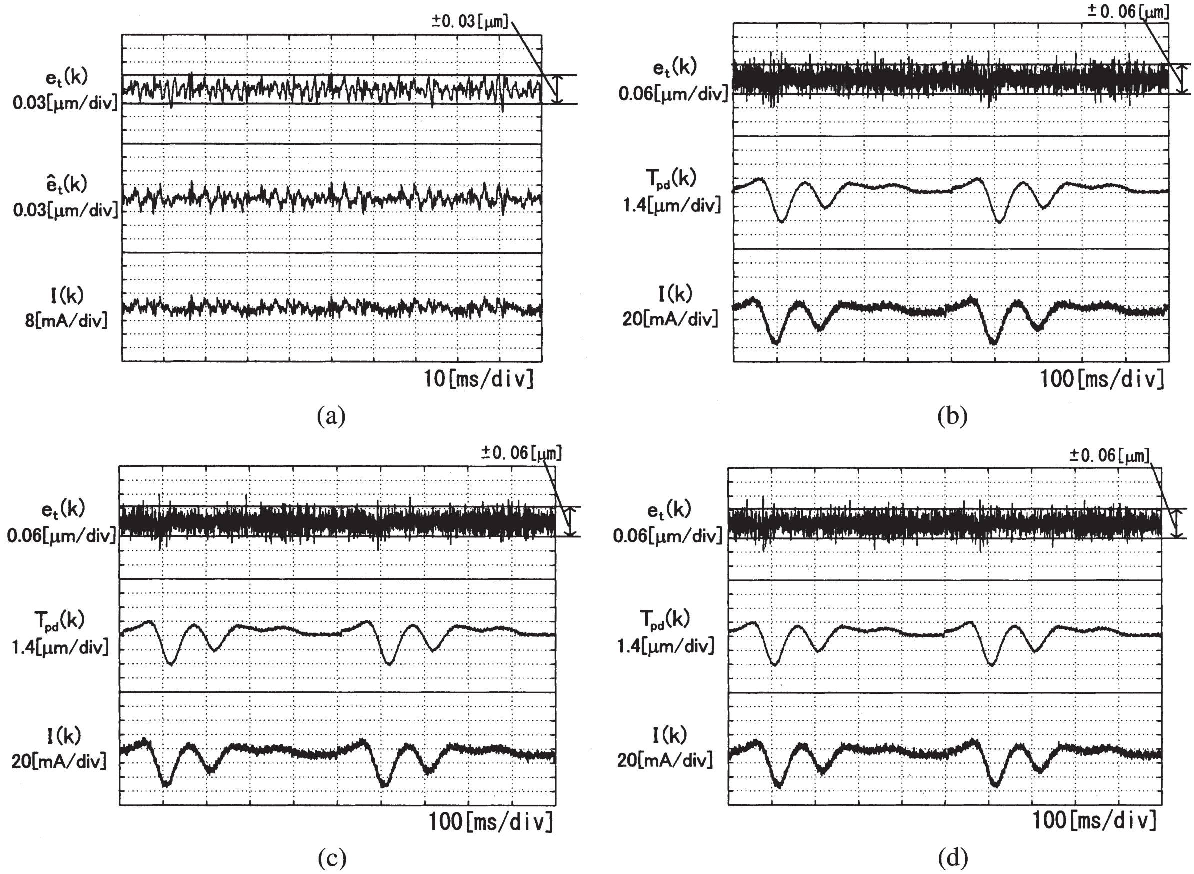

Fig. 15. Experimental results using the proposed robust tracking servo system. (a) Without disturbance nominal K_s. (b) With disturbance nominal K_s. (c) With disturbance, $K_s = 1.2K_{sn}$. (d) With disturbance, $K_s = 0.8K_{sn}$.

IV. Experimental Results

To confirm the validity of the proposed robust tracking control system, this paper shows the experimental results using DDU1000. The proposed feedforward control system is constructed by the software algorithm of DSP (TMSC320C6701), whose sampling time is 66 μs. Here, the sampling time of the feedback control system is 33 μs.

From the experimental tests, $G_{ff}(z^{-1})$ is affected by the various noises in Fig. 14. To eliminate these noises, this paper connects the two low-pass filters in series as shown in Fig. 14. This equipment $f_{\rm in}(z^{-1})$ removes the noise higher than the Nyquist frequency. Hence, the cutoff frequency of $f_{\rm in}(z^{-1})$ is 7.5 kHz. $f_{\rm out}(z^{-1})$ is aimed at removing the spike noise from $G_{ff}(z^{-1})$. Ideally, $f_{\rm out}(z^{-1})$ should be 1. Based on the experimental test, this paper determines the cutoff frequency of $f_{\rm out}(z^{-1})$, which is 600 Hz. Fig. 15 confirms that the proposed robust feedforward tracking servo system also has the precise and desired tracking control response. In Fig. 15(a), the proposed control system reduces the tracking error to 0.03 μs, which is approximately 60% in comparison with Fig. 11(a). From the experimental results in Figs. 11(a) and 15(a), the actual tracking error $e_t(k)$ is usually a small value, and the actuator current I is very smooth and stable. Fig. 15(b) shows the experimental results of the proposed tracking control system on the condition of force disturbance input. The proposed tracking control system keeps just the small tracking error value, in comparison with the tracking error value kept by the robust control system, as shown in Fig. 11(b).

Fig. 15(c) and (d) shows the experimental results of the proposed tracking control system when the spring constant K_s has a $\pm 20\%$ parameter variation. Given both parameter variation and force disturbance, the proposed robust tracking servo system keeps the fine tracking control response, in comparison with Fig. 15(b).

V. Conclusion

This paper proposes a new robust feedforward tracking servo system for an optical disk recording system based on the prediction of the tracking error. The proposed system mixed the feedforward controller, which is based on the ZPET control system, with the robust feedback controller, which is based on disturbance observer and coprime factorization.

The proposed robust feedback control system considers the influence of force disturbance and parameter variation and satisfies both the desired performance conditions of the disturbance rejection response and robust stability. The robust feedback control system well suppresses the force disturbance.

This paper proposes the feedforward control system based on the ZPET control system and the prediction of the tracking error. Moreover, because the proposed robust feedforward tracking servo system has a high gain, it has a windup phenomenon. To overcome the windup phenomenon, the proposed system has a new limitation algorithm of controller output.

The experimental results confirm that the proposed robust feedforward tracking servo system keeps the residual tracking error below the tolerance of 0.03 μm peak-to-peak, which is the next-generation tracking servo system, given that the revolution speed of the optical disk is 3600 r/min. Moreover, the proposed robust tracking control system suppresses the force disturbance effectively and keeps the tracking error less than 0.06 μm on the condition of parameter variation.

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