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Two-Stage Feedforward Tracking Control System with Error-Based Disturbance Observer for Optical Discs

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Recently, the scaling up of the storage capacity and data transfer rate of digital storage media has been required. However, increasing in the storage capacity and transfer rate makes optical head control more difficult. Thus, a tracking control system for optical discs must exhibit a high degree of precision control. Consequently, a new two-stage feedforward control (TSFFC) system for high-precision control is proposed in this paper. The proposed system is constructed using two zero phase error tracking (ZPET) control systems based on error prediction and an error-based disturbance observer (EDOB) that uses a notch filter to suppress non periodic disturbances. The proposed control system is designed for DDU-1000 for digital versatile discs (DVDs). The experimental results demonstrate that the proposed system effectively suppresses tracking errors.

Keywords: optical disc, two-stage feedforward control, error-based disturbance observer

1. Introduction

Recently, the scaling up of the storage capacity and data transfer rate of digital storage media has been required. To meet this demand, the Blu-ray disc (BD) has been developed and adopted as a standard. The storage density of the BD is high because it has small beam spots using a blue laser. The track pitch of a BD is 320 nm, which is smaller than that of a digital versatile disc (DVD), which is 740 nm. Currently, the two-dimensional optical memory of near-field optical recording (NFR), hologram memory, and three-dimensional optical memory devices have been developed for large capacity and high density. Large capacity and high density are essential for the next-generation optical discs. In this paper, we focus on two-dimensional optical memory of NFR in conjunction with the current system. In NFR, the miniaturization of laser beam spots has been achieved using near-field light.[1–6] Thus, the track pitch of NFR is smaller than that of BD, and NFR realizes a high storage density. In addition, a high data rate for optical discs is provided by the high disc rotation speed.

Flexible optical discs that can rotate at rates higher than 10000 rpm are now being developed to realize a high data transfer rate.[7–11] However, increasing the memory capacity and transfer rate makes optical head control more difficult. Thus, tracking control systems for optical discs must exhibit a high degree of precision control.

We have already proposed the tracking control system consisting of an error-prediction-based zero phase error tracking (ZPET) feedforward control system and a double feedforward control (DFFC) system based on error prediction and trajectory command prediction.[12–20] The experimental results for the DFFC system indicated adequate suppression of tracking errors. However, trajectory command signals uses as the feedforward input cannot be obtain directly in the optical disc system. Therefore, in this paper, we propose a new two-stage feedforward control (TSFFC) using only tracking errors. The proposed TSFFC system realizes tracking control with a higher precision than that of a conventional DFFC system. Moreover, when the DFFC system significantly suppresses periodic disturbances, a marked enhancement of the effect of non periodic disturbances is often observed. Exteriorization of these non periodic disturbances affects the estimation of feedforward input signals. In this study, the effect of non periodic disturbances is suppressed by applying an error-based disturbance observer (EDOB) with a notch filter to the TSFFC system.[21–24] Thus, the TSFFC system with the EDOB achieves a fine tracking control performance.

First, we introduce an error prediction mechanism. This mechanism generates a feedforward input signal with a tracking error. Second, the conventional DFFC system is explained. Third, a new TSFFC system based on error prediction is proposed. In addition, the EDOB with a notch filter is applied to the TSFFC system to suppress non periodic disturbances. Finally, the experimental results are presented to show that the TSFFC system with the EDOB is a high-precision tracking control system.

2. Conventional Tracking Control System

2.1 Plant system

A voice coil motor (VCM) is used as the actuator of the optical disc tracking control system. The frequency characteristics of the VCM system used in our study are shown in Fig. 1. Generally, as shown in Fig. 1, a VCM system has two resonance points. However, because the second resonance point typically exists in the vicinity of the Nyquist frequency, any plant model should consider only the first resonance point. The transfer function of a nominal plant system that includes only the first resonance point is defined in Eq. (1):

$$P_2(s) = \frac{y(s)}{I_{\rm cmd}(s)} = \frac{K_{\rm am}}{s^2 + D_{\rm sm}s + K_{\rm sm}}. \quad (1)$$

2.2 Error prediction

Optical discs are subject to periodic disturbances caused

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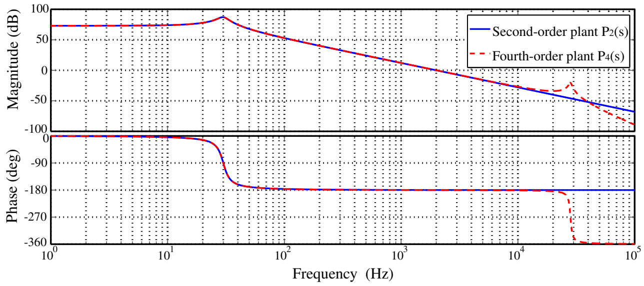

Fig. 1. (Color online) Frequency characteristics of tested tracking actuator (VCM).

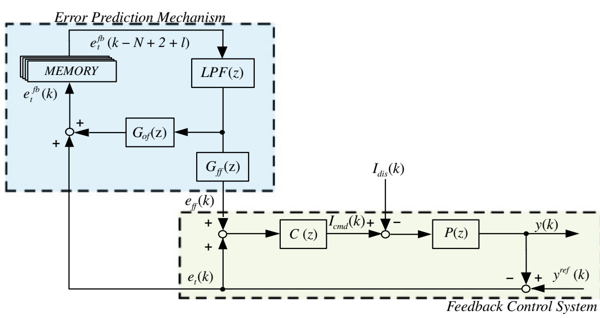

Fig. 2. (Color online) Error prediction feedforward control system.

by disc eccentricity. A feedback control system cannot eliminate periodic disturbances completely by itself. Thus, to achieve high-precision control, a tracking control system is required to further suppress periodic disturbances. Therefore, in the proposed tracking control system, periodic disturbances caused by eccentricity of the disc are suppressed by a feedforward control system. Because the optical disc device cannot measure the position of a beam spot, it cannot constitute a feedforward control system equivalent to a hard disc drive. Therefore, an error prediction mechanism is used to generate a feedforward input.[12,13] A block diagram of the feedforward control system with error prediction is shown in Fig. 2. In Fig. 2, $e_{\mathrm{t}}(k)$ is tracking error, $I_{\mathrm{cmd}}(k)$ is a current command for the tracking actuator, $y(k)$ is the position of a beam spot, and $y^{\mathrm{ref}}(k)$ is the track of a disc. A feedforward input is equivalent to the tracking error of only the feedback control $e_{\mathrm{t}}^{\mathrm{fb}}(k)$. However, it is impossible to directly obtain $e_{\mathrm{t}}^{\mathrm{fb}}(k)$ in cases where feedforward control is being applied. To estimate $e_{\mathrm{t}}^{\mathrm{fb}}(k)$ while applying feedforward control, $e_{\mathrm{t}}^{\mathrm{fb}}(k)$ is generated in the error prediction mechanism. The relationship of the tracking error $e_{\mathrm{t}}(k)$ with the output signal $y(k)$ and the trajectory command signal $y^{\mathrm{ref}}(k)$ is defined by Eq. (2). $y^{\mathrm{ref}}(k)$ is obtained by substituting expression Eq. (3) into Eq. (2), resulting in Eq. (4):

$$e_{\mathrm{t}}(k) = y^{\mathrm{ref}}(k) - y(k), \tag{2}$$

$$y(k) = C(z)P(z)e_{\mathrm{t}}(k) + C(z)P(z)e_{\mathrm{ff}}(k), \tag{3}$$

$$\frac{y^{\mathrm{ref}}(k)}{1 + C(z)P(z)} = e_{\mathrm{t}}(k) + \frac{C(z)P(z)}{1 + C(z)P(z)} e_{\mathrm{ff}}(k). \tag{4}$$

Here, $e_{\mathrm{t}}^{\mathrm{fb}}(k)$ is defined as

$$e_{\mathrm{t}}^{\mathrm{fb}}(k) = \frac{y^{\mathrm{ref}}(k)}{1 + C(z)P(z)}. \tag{5}$$

Therefore, $e_{\mathrm{t}}^{\mathrm{fb}}(k)$ is generated from

$$e_{\mathrm{t}}^{\mathrm{fb}}(k) = e_{\mathrm{t}}(k) + \frac{C(z)P(z)}{1 + C(z)P(z)} e_{\mathrm{ff}}(k). \tag{6}$$

Equation (6) is the basic equation of the error prediction mechanism. Then, we explain a method of error prediction. The feedforward controller $G_{\mathrm{ff}}(z)$ based on error prediction is designed as an inverse of the closed loop system $G_{\mathrm{cl}}(z)$. $G_{\mathrm{cl}}(z)$ is expressed by

$$G_{\mathrm{cl}}(z) = \frac{C(z)P(z)}{1 + C(z)P(z)} = \frac{B_{\mathrm{c}}^{+}(z)B_{\mathrm{c}}^{-}(z)}{A_{\mathrm{c}}(z)}. \tag{7}$$

Here, $A_{\mathrm{c}}(z)$ is a polynomial comprising all the poles of $G_{\mathrm{cl}}(z)$, $B_{\mathrm{c}}^{+}(z)$ is a polynomial comprising gain and the stable zeros of $G_{\mathrm{cl}}(z)$, and $B_{\mathrm{c}}^{-}(z)$ is a polynomial comprising the unstable zero of $G_{\mathrm{cl}}(z)$. The feedforward controller $G_{\mathrm{ff}}(z)$ is expressed as

$$G_{\mathrm{ff}}(z) = \frac{A_{\mathrm{c}}(z)B_{\mathrm{c}}^{-}(z^{-1})}{[B_{\mathrm{c}}^{-}(1)]^2 B_{\mathrm{c}}^{+}(z)} \cdot \frac{1}{z^2}. \tag{8}$$

The output of $G_{\mathrm{ff}}(z)$ has a two-sample delay relative to the feedforward input. Therefore, the feedforward input signals need to have a two-sample futural tracking error. The input to $G_{\mathrm{ff}}(z)$ is generated from a prediction by the error estimator and memory. The error estimator G_{of} is expressed by

$$G_{\mathrm{of}}(Z) = G_{\mathrm{cl}} \times G_{\mathrm{ff}} = \frac{B_{\mathrm{c}}^{-}(z)B_{\mathrm{c}}^{-}(z^{-1})}{[B_{\mathrm{c}}^{-}(1)]^2}. \tag{9}$$

G_{of} predicts the residual tracking error of only the feedback loop. As a result, Eq. (6) is expressed as

$$e_{\mathrm{t}}^{\mathrm{fb}}(k) = e_{\mathrm{t}}(k) + G_{\mathrm{of}}(z)e_{\mathrm{t}}^{\mathrm{fb}}(k - N + 2 + l). \tag{10}$$

Here, l is the sample position adjustment value that compensates for the phase lag caused by $LPF(z)$, N is the sample number of one rotation cycle.

2.3 *Double feedforward control system*

In addition to the error prediction mechanism, a conventional DFFC system applies the trajectory command prediction mechanism.[19,20] By applying the trajectory command prediction mechanism, the DFFC system can configure a high-gain control system using the two feedforward controllers. The DFFC system is composed of a feedback control system and two ZPET control systems based on both an error prediction mechanism and a trajectory command prediction mechanism, as shown in Fig. 3.[12–20] In Fig. 3, $C(z)$ is a feedback controller based on a high-gain servo controller, and $LPF(z)$ is a second-order low-pass filter.[25]

First, in this paper, we show the design of the ZPET control system based on the trajectory command mechanism. In an optical disc device, it is impossible to directly obtain the output signal $y(k)$ and the trajectory command signal $y^{\mathrm{ref}}(k)$. Therefore, it is impossible to configure a feedforward

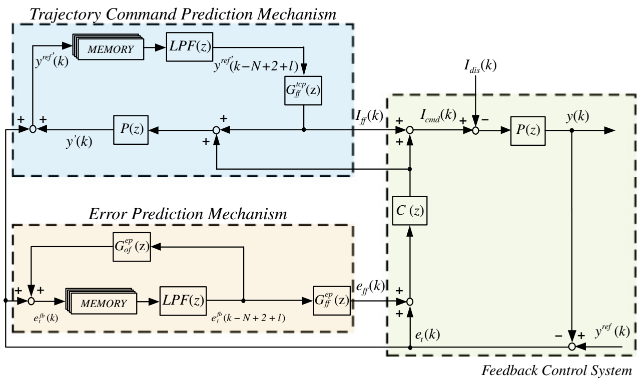

Fig. 3. (Color online) Conventional double feedforward control system.

control system by using the trajectory command signal as the input signal. Although the trajectory command value $y^{\rm ref}(k)$ and the output signal $y(k)$ cannot be obtained directly, they can be predicted from the tracking error signal $e_{\rm t}(k)$. From Fig. 3, $y(k)$ is defined as Eq. (11). Here, $y^{\rm ref}(k)$ is obtained by substituting expression Eq. (11) into (2), as shown in Eq. (12):

$$y(k) = C(z)P(z)e_{\rm t}(k) + C(z)P(z)e_{\rm ff}(k) + P(z)I_{\rm ff}(k), \quad (11)$$

$$y^{\rm ref}(k) = (1 + C(z)P(z))e_{\rm t}(k) + C(z)P(z)e_{\rm ff}(k) + P(z)I_{\rm ff}(k). \quad (12)$$

Thus, it becomes possible to configure a feedforward control system by generating a predicted trajectory command signal $y^{\rm ref'}(k)$, which is equivalent to the trajectory command signal $y^{\rm ref}(k)$. The feedforward controller $G_{\rm ff}^{\rm tcp}(z)$ based on the trajectory command prediction is designed as the inverse model of the nominal plant $P(z)$. However, $G_{\rm ff}^{\rm tcp}(z)$ becomes unstable because $P(z)$ has unstable zero. Thus, $P(z)$ is defined by

$$P(z) = \frac{B_{\rm tcp}^{+}(z)B_{\rm tcp}^{-}(z)}{A_{\rm tcp}(z)}. \quad (13)$$

Here, $A_{\rm tcp}(z)$ is a polynomial comprising all the poles of $P(z)$, $B_{\rm tcp}^{+}(z)$ is a polynomial comprising gain and the stable zeros of $P(z)$, and $B_{\rm tcp}^{-}(z)$ is a polynomial comprising the unstable zeros of $P(z)$. By using these polynomials, $G_{\rm ff}^{\rm tcp}(z)$ is expressed as

$$G_{\rm ff}^{\rm tcp}(z) = \frac{A_{\rm tcp}(z)B_{\rm tcp}^{-}(z^{-1})}{[B_{\rm tcp}^{-}(1)]^2 B_{\rm tcp}^{+}(z)} \cdot \frac{1}{z^2}. \quad (14)$$

From Eq. (14), the output of $G_{\rm ff}^{\rm tcp}(z)$ has a two-sample delay relative to the feedforward input. Thus, the feedforward input signals need the two-sample futural trajectory command signal. In the optical disc recording system, the trajectory command signal is treated as a periodic function. Hence, the present trajectory command signal is approximated by the previous one-period trajectory command, as expressed in Eq. (15):

$$y^{\rm ref'}(k) = y^{\rm ref'}(k - N). \quad (15)$$

By utilizing this periodicity, the two-sample futural trajectory command signals are obtained from the trajectory command signals on the basis of one cycle of past values stored in the memory.

Next, in this paper, we show the design of the ZPET control system based on the error prediction mechanism. The feedforward controller $G_{\rm ff}^{\rm ep}(z)$ based on error prediction is designed as an inverse of the closed loop system $G_{\rm cl}^{\rm ep}(z)$. In designing on the basis of ZPET, $G_{\rm cl}^{\rm ep}(z)$ is decomposed as defined by

$$G_{\rm cl}^{\rm ep}(z) = \frac{C(z)P(z)}{1 + C(z)P(z)} = \frac{B_{\rm ep}^{+}(z)B_{\rm ep}^{-}(z)}{A_{\rm ep}(z)}. \quad (16)$$

Hence, $G_{\rm ff}^{\rm ep}(k)$ is expressed by

$$G_{\rm ff}^{\rm ep}(z) = \frac{A_{\rm ep}(z)B_{\rm ep}^{-}(z^{-1})}{[B_{\rm ep}^{-}(1)]^2 B_{\rm ep}^{+}(z)} \cdot \frac{1}{z^2}. \quad (17)$$

Moreover, the feedforward input signals need to have the two-sample futural tracking error. In the optical disc recording system, the tracking error is treated as a periodic function. Hence, the present tracking error is approximated by the previous one-period error, as expressed by

$$e_{\rm t}^{\rm fb}(k) = e_{\rm t}^{\rm fb}(k - N). \quad (18)$$

The input to $G_{\rm ff}^{\rm ep}(z)$ is generated from a prediction by the error estimator and memory. The error estimator $G_{\rm of}^{\rm ep}(z)$ is expressed as

$$G_{\rm of}^{\rm ep}(z) = G_{\rm cl}^{\rm ep}(z) \cdot G_{\rm ff}^{\rm ep}(z). \quad (19)$$

Here, $e_{\rm t}^{\rm fb}(k)$ is defined as the tracking error in consideration of the feedforward output. $e_{\rm t}^{\rm fb}(k)$ is expressed as

$$\begin{aligned} e_{\rm t}^{\rm fb}(k) &= e_{\rm t}(k) + G_{\rm cl}^{\rm ep}(z) \cdot e_{\rm ff}(k) \\ &= e_{\rm t}(k) + G_{\rm of}^{\rm ep}(z) \cdot e_{\rm t}^{\rm fb}(k + 2 - N + l). \end{aligned} \quad (20)$$

The conventional method has the coupling effect of $I^{\rm ff}(k)$. As this method does not have decoupling regulation on $I_{\rm ff}(k)$, it offen cannot carry out the sufficient suppression control of residual tracking errors. Therefore, we proposes a new control system that takes into account this effect in the next section.

3. Proposed Two-Stage Feedforward Control System

3.1 Feedforward controller

A DFFC system can suppress significantly periodic disturbances using two feedforward controllers. A DFFC system uses the trajectory command signal. However, it cannot obtain directly in the optical disc system as feedforward input. If the feedforward input signal can be unified with the tracking error, which can be obtained directly in the optical disc system, then a high precise control system could be configured. In this section, we propose TSFFC based on the error prediction system for this purpose.

In the TSFFC system, it is possible to generate the feedforward input signal by using only the tracking error. A block diagram of our proposed system is shown in Fig. 4. The TSFFC system is composed of a primary-component-suppression mechanism and a primary-component-residual-suppression mechanism. First, this paper shows the design of

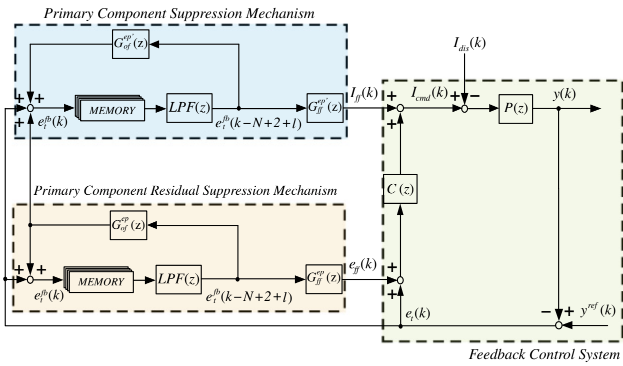

Fig. 4. (Color online) Proposed two-stage feedforward control system.

the ZPET control system based on the primary-component-suppression mechanism. This mechanism operates to suppress the primary component of periodic disturbances. The feedforward controller $G_{\rm ff}^{\rm ep'}(z)$ of the primary-component-suppression mechanism is designed to be the inverse of the closed loop system $G_{\rm cl}^{\rm ep'}(z)$. To design on the basis of ZPET, $G_{\rm cl}^{\rm ep'}(z)$ is defined by

$$G_{\rm cl}^{\rm ep'}(z) = \frac{P(z)}{1 + C(z)P(z)} = \frac{B_{\rm ep'}^{+}(z)B_{\rm ep'}^{-}(z)}{A_{\rm ep'}(z)}. \tag{21}$$

Hence, $G_{\rm ff}^{\rm ep'}(k)$ is expressed as

$$G_{\rm ff}^{\rm ep'}(z) = \frac{A_{\rm ep'}(z)B_{\rm ep'}^{-}(z^{-1})}{[B_{\rm ep'}^{-}(1)]^2 B_{\rm ep'}^{+}(z)} \cdot \frac{1}{z^2}. \tag{22}$$

Next, in this paper, we show the design of the ZPET control system based on the primary-component-residual-suppression mechanism. This mechanism operates to suppress the residual tracking errors that are not suppressed by only the primary-component-suppression mechanism. The composition of the mechanism is equivalent to the error prediction control loop in conventional systems. Hence, the feedforward controller $G_{\rm ff}^{\rm ep}(z)$ of the primary-component-residual-suppression mechanism is expressed as Eq. (17). Moreover, the feedforward input signals require the two-sample futural tracking error. However, because directly obtaining the tracking error is impossible, the mechanism predicts the futural tracking error by using an error prediction mechanism.

3.2 Error prediction

The feedforward input signal in the primary-component-suppression mechanism is the tracking error for only the feedback control $e_{\rm t}^{\rm fb}(k)$. However, it is impossible to directly obtain $e_{\rm t}^{\rm fb}(k)$ in cases where feedforward control is being applied. In order to estimate $e_{\rm t}^{\rm fb}(k)$ while using two feedforward controllers, the primary-component-suppression mechanism uses two error estimators. This enables the estimation of $e_{\rm t}^{\rm fb}(k)$ while applying feedforward control. The error estimator that corresponds to the feedforward controller $G_{\rm ff}^{\rm ep'}(k)$ is expressed by

$$G_{\rm of}^{\rm ep'}(z) = G_{\rm cl}^{\rm ep'}(z) \cdot G_{\rm ff}^{\rm ep'}(z). \tag{23}$$

The composition of the error estimator that corresponds to the feedforward controller $G_{\rm ff}^{\rm ep}(z)$ is equivalent to that of the error prediction control loop of a conventional system. The error estimator $G_{\rm of}^{\rm ep}(z)$ is expressed by Eq. (19). Here, the present tracking error of only the feedback control is approximated by the previous one-period error, as expressed by

$$e_{\rm t}^{\rm fb}(k) = e_{\rm t}^{\rm fb}(k - N). \tag{24}$$

Therefore, $e_{\rm t}^{\rm fb}(k)$ is generated from Eq. (25):

$$\begin{aligned} e_{\rm t}^{\rm fb}(k) = e_{\rm t}(k) &+ G_{\rm of}^{\rm ep'}(z) \cdot e_{\rm t}^{\rm fb}(k + 2 - N + l) \\ &+ G_{\rm of}^{\rm ep}(z) \cdot e_{\rm t}^{\rm fb}(k + 2 - N + l). \end{aligned} \tag{25}$$

The feedforward input signal in the primary-component-residual-suppression mechanism $e_{\rm t}^{\rm fb}(k)$ requires consideration of the feedforward output of the primary-component-suppression mechanism. Therefore, it is possible to estimate $e_{\rm t}^{\rm fb}(k)$ by using only the error estimator $G_{\rm of}^{\rm ep}(z)$. By using the periodicity of the tracking error, the two-sample futural $e_{\rm t}^{\rm fb}(k)$ is obtained from the tracking error on the basis of past error values stored for one cycle as defined by Eq. (20).

4. Two-Stage Feedforward Control System with Error-Based Disturbance Observer

The TSFFC system can suppress significantly periodic disturbances. However, significant suppression of the periodic disturbances enhances the effect of non periodic disturbances. As a result, exteriorization of the non periodic disturbances affects the estimation of feedforward input signals. Consequently, the error-based disturbance observer is applied to the TSFFC system in order to suppress the effect of non periodic disturbances. To construct a disturbance observer, the output signal of the control system is needed. However, the output signal $y(k)$ cannot be obtained from the optical disc system. Therefore, in order to apply the disturbance observer to the optical disc system, an EDOB system has to be constituted.[21–24)]

A block diagram of the feedback control system that is applied the disturbance observer is shown in Fig. 5. Here, $Q(z)$ is a second-order low-pass filter similar to $LPF(z)$. The estimated disturbance of the general disturbance observer $\hat{I}_{\rm dis}(k)$ can be expressed as

$$\hat{I}_{\rm dis}(k) = Q(z)I_{\rm cmd}(k) - Q(z)P(z)^{-1}y(k). \tag{26}$$

Further, the estimated disturbance of the EDOB $\hat{I}'_{\rm dis}(k)$ can be expressed as

$$\hat{I}'_{\rm dis}(k) = Q(z)I_{\rm cmd}(k) + Q(z)P(z)^{-1}e_{\rm t}(k). \tag{27}$$

EDOB is composed of Eq. (27). In addition, Eq. (28) is an expansion of Eq. (27):

$$\begin{aligned} \hat{I}'_{\rm dis}(k) &= Q(z)I_{\rm cmd}(k) + Q(z)P(z)^{-1}(y^{\rm ref}(k) - y(k)) \\ &= \hat{I}_{\rm dis}(k) + Q(z)P(z)^{-1}y^{\rm ref}(k). \end{aligned} \tag{28}$$

From Eqs. (26) and (28), $\hat{I}'_{\rm dis}(k)$ becomes the synthesized feedforward output signal and the estimated disturbance of the general disturbance observer. The feedforward output is dominated by the periodic disturbance component that synchronizes with the disc rotation speed. Thus, by

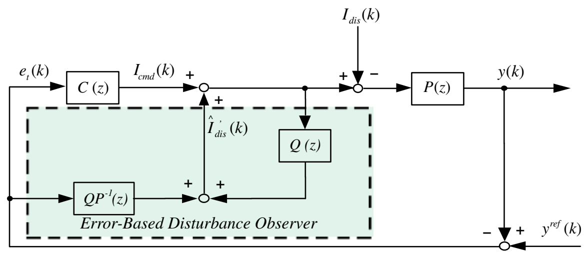

Fig. 5. (Color online) Error-based disturbance observer control system.

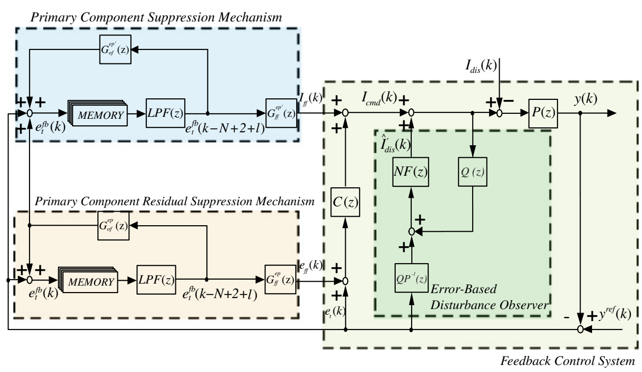

Fig. 6. (Color online) Proposed two-stage feedforward control system with new error-based disturbance observer.

removing the periodic disturbance component, it is possible to extract the non periodic disturbance component. The periodic disturbance component is removed by applying a notch filter to the output of the EDOB. In this paper, the filter that uses the output of the EDOB is configured by using only a notch filter that removes the fundamental frequency. A block diagram of the TSFFC system that uses an EDOB with a notch filter is shown in Fig. 6. Here, $NF(z)$ is the notch filter that removes the fundamental wave component.

5. Experimental Results

To confirm the validity of our proposed tracking control system, experiments are conducted with DDU-1000 as a DVD system. The configuration of the experimental device is shown in Fig. 7. The experimental conditions are summarized in Table 1. The experimental results for the conventional DFFC system are shown graphically in Fig. 8. The residual tracking error is 10.95 $\mathrm{nm_{p\text{-}p}}$ and 3σ is $\pm$5.30 nm, where σ is the standard deviation. The experimental results for the proposed TSFFC system are shown graphically in Fig. 9. In this case, the residual tracking error is 10.50 $\mathrm{nm_{p\text{-}p}}$ and 3σ is $\pm$5.03 nm. This means that there is a 5% reduction in the 3σ of the TSFFC system in comparison with that of the DFFC system which equates to an increase in performance. The reason of the increase in performance may be thought to be due to the increase of estimation accuracy of feedforward input signals by unifying the prediction mechanism.

In addition, the experimental results for the TSFFC system with the EDOB using a notch filter are shown graphically in Fig. 10. The residual tracking error is 8.50 $\mathrm{nm_{p\text{-}p}}$ and 3σ is $\pm$4.44 nm. Table 2 shows summary and comparison of experimental results. The TSFFC system with the EDOB reduces the 3σ achieved when the DFFC system is used by 16%. Furthermore, the estimated disturbance $\hat{I}'_{\mathrm{dis}}(k)$ is the fundamental component signal cleared by the notch filter. Figures 9(a) and 10(a) show that the sudden error component caused by the superposition of the high-order harmonics component and non periodic

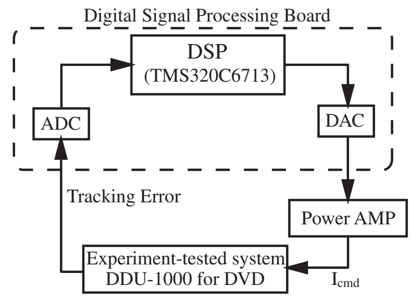

Fig. 7. Configuration of tested experiment device.

Table 1. Experimental conditions.

Wavelength (nm)	405
NA	0.65
Media type	DVD+R
Track pitch (μm)	0.74
Rotation speed (rpm)	7200 (120 Hz)
Sampling frequency (kHz)	75
DSP	TMS320C6713

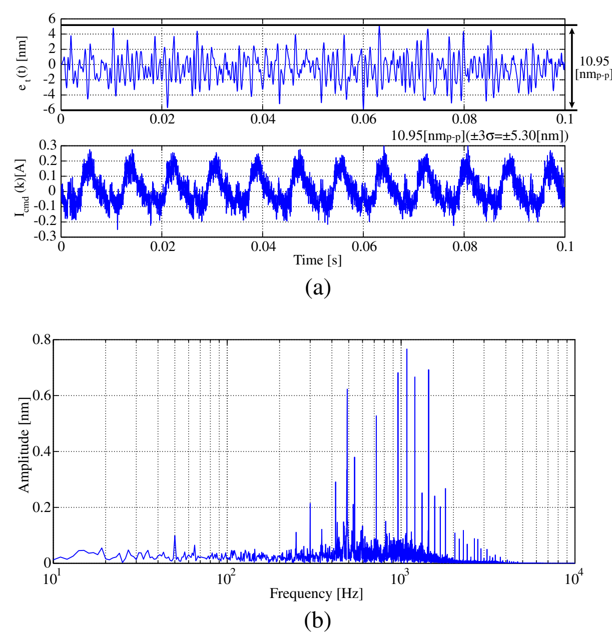

Fig. 8. (Color online) Experimental results for conventional double feedforward control system: (a) tracking error signal and (b) the FFT results on $e_t(t)$.

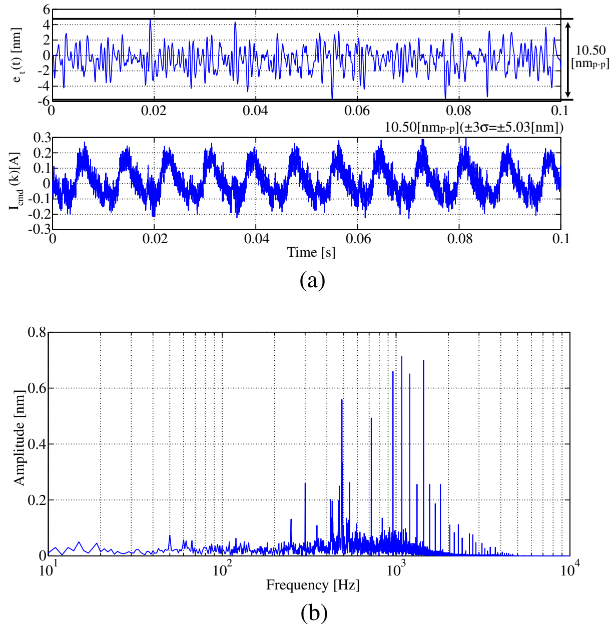

Fig. 9. (Color online) Experimental results for proposed two-stage feedforward control system without new error-based disturbance observer: (a) tracking error signal and (b) the FFT results on $e_t(t)$.

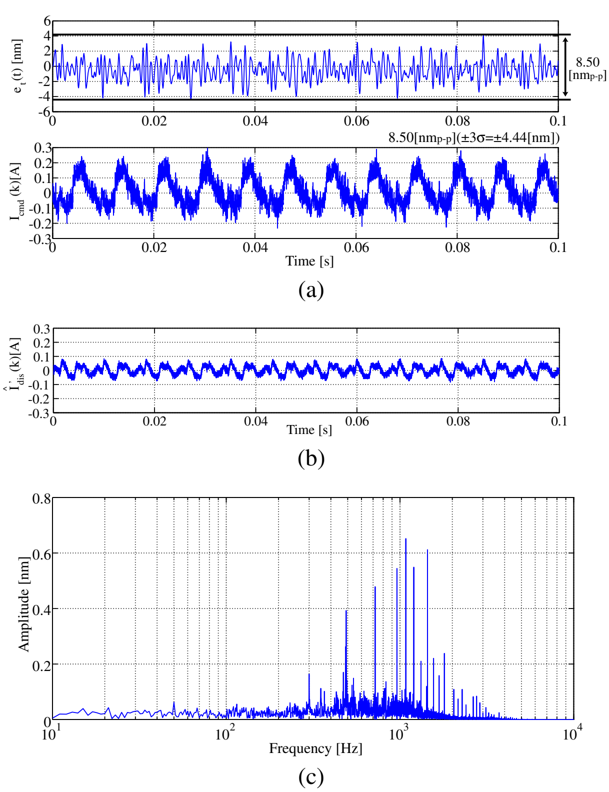

Fig. 10. (Color online) Experimental results for proposed two-stage feedforward control system with new error-based disturbance observer: (a) tracking error signal, (b) estimate disturbance and (c) the FFT results on $e_t(t)$.

Table 2. Total experimental results.

Control system	Tracking error ($nm_{p\text{–}p}$)	$\pm 3\sigma$ (nm)
Double feedforward control system	10.95	±5.30
Two-stage feedforward control system	10.50	±5.03
Two-stage feedforward control system with error-based disturbance observer	8.50	±4.44

disturbances is suppressed by using the EDOB. Therefore, the TSFFC system with the EDOB improves the suppression performance of tracking control and the periodicity of tracking errors.

6. Conclusions

In this paper, we propose a new tracking control system with a two-stage feedforward control system. The primary-component-suppression mechanism operates to suppress the primary component of periodic disturbances, whereas the primary-component-residual-suppression mechanism operates to suppress any residual tracking errors not suppressed by using only the former. The experimental results indicate that the proposed TSFFC system realizes precision control superior to that of the conventional system. In addition, the TSFFC system uses the EDOB with a notch filter in order to suppress the effect of non-periodic disturbances. The experimental results confirm that the proposed TSFFC system shows a fine tracking control performance.

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