Using a Disturbance Observer for Eccentricity Compensation in Optical Storage Systems

Kyung-Soo Kim

Abstract: In this paper, we consider the track-following control problem in the optical data storage systems in the presence of the eccentricity. The eccentricity results in the radial deviation of the objective lens so that it degrades the reliability of the data decoding system. To cope with the eccentricity, an adaptive disturbance compensation technique is newly proposed in the time domain based on a disturbance observer of reduced order, which effectively estimates the low frequency components of the disturbance. The proposed compensator is simply added to the conventional feedback control. The error dynamics of the observer and the sensitivity analysis are given to illustrate the effectiveness of the proposed approach. Finally, through experiments in an optical storage system, the feasibility of the proposed approach is verified.

Keywords: disturbance observer, optical data storage system, eccentricity, track-following performance

I. Introduction

The tracking problem has been one of the major concerns in control theory for several decades because it has arisen in many practical problems such as the trajectory tracking in robot manipulators, the tip control in tooling machines, and the track-following in optical data storage systems (ODSS's) among many. When the reference signal is known, the control design problem may be redefined by the regulation problem by introducing a control term that can cancel out the reference. However, in some cases, the reference may not be known and only the tracking error is available for feedback control, and thus the unknown reference acts as an external disturbance in the closed loop system. It is noted that the track-following problem in ODSS's such as compact disc (CD) or digital versatile disc (DVD) devices corresponds to the case.

In fact, ODSS's operate based on the elaborate combination of several types of feedback control in order to restore (or record) data reliably from (or on) optical discs. For instances, one may consider the following control problems: i) automatic laser power control, ii) focusing control, iii) track-following control, iv) speed control of the spindle motor, v) center error control for stable seek operation and vi) the tilt control for compensating the disc inclination. Since the role of feedback control is essential to achieve the reliability of ODSS's, the application of the recent feedback theories has emerged. For example, in [1], the μ-synthesis has been applied to the tracking controller design for guaranteeing the robustness to the modeling uncertainty. Also, the quantitative feedback theory was used for the focusing control design in [2]. Recently, the center error control was discussed in [3] for obtaining the reliable and silent seek operations for the audio and video applications of ODSS's. We refer to the literature and the references therein for more details. Since all of the control performances contribute to the quality and the reliability of ODSS's, the design should be robust to the system variations possibly existing in practice. Among the issues above, more attention should be paid to the robustness of the tracking control design. Since the track pitch (i.e., the distance between adjacent tracks) is very small (e.g., 1.6 μm and 0.74 μm for CD's and DVD's, respectively), even small amount of disturbance can fail the track-following operation. Moreover, the discs used in practice contain defects that deteriorate the tracking error detection and, the eccentricity due to radial run-out of discs from the rotational center and the geometric distortion of data tracks formed in the manufacturing process. Owing to such difficulties, the tracking control design becomes difficult and, at the end, its performance rules the overall quality of the ODSS's. Hence, much effort has been made to obtain satisfactory performances (e.g., see the references [4], [5] and [1] among many).

In this manuscript, we consider a method to reduce the effect of the eccentricity in the tracking control problem. The eccentricity results in (quasi-) sinusoidal variation of the unknown reference. In literature, it has been shown that the sinusoidal disturbance can be effectively attenuated by using the repetitive control approach [9] or the disturbance observer technique [10]. The repetitive control has been developed for the periodic disturbance rejection and requires the stability analysis when added to the feedback system. The disturbance observer approach is based on the dynamic inversion of the open loop system to estimate the input disturbance. For avoiding the non-realizable system inversion, a low pass filter is needed to compensate the relative degree of the plant.

Our approach relies on the disturbance observer-based compensation scheme. By formulating the track-following problem into a regulation problem with unknown disturbance, we develop a disturbance observer of reduced order in the time domain. The main idea comes from the modification of the nonlinear friction observer approaches [6], [7] which identify the constant Coulomb friction coefficient. In fact, we utilize a generic property of the friction observer capable of estimating the low frequency components of the frictional disturbance. Because the disturbance due to the eccentricity in ODSS's fluctuates mainly with the rotational frequency of the disc, the disturbance observer that can estimate the low frequency compo-

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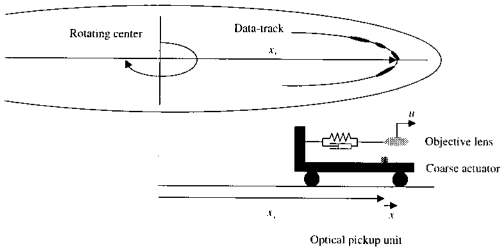

Fig. 1. A schematic showing the track-following operation.

nents would effectively cope with the eccentricity. Note that the rotational frequency in ODSS's is not so high compared to the closed loop bandwidth. For example, the 32x CD-Read Only Memory (ROM) drives, which are widely used in practice, rotate the discs within 100 Hz using the constant angular velocity (CAV) control. The proposed approach is different from the conventional disturbance observer approaches in several aspects. First, the observer is derived in the time domain not in the Laplace domain. It is advantageous that the error dynamics decaying monotonically and exponentially in the time domain can be observed explicitly. Secondly, the dynamic inversion of the plant occurs implicitly. Thus, there no needs to consider the issue of the realizability. Moreover, the observer dynamics does not have the order of the relative degree of the plant. That is, the proposed observer is of first order while the pickup system is of second order.

The paper is constructed as follows. In Section II, the tracking control problem in ODSS's is discussed to set up the system description. Then, we propose the disturbance observer in Section III. Based on the disturbance observer, the feedforward compensator is introduced and the sensitivity analysis is given. In Section IV, a few issues for real implementation are discussed and the effectiveness of the proposed approach is shown by experiments in an ODSS. Finally, concluding remarks follow in Section V.

II. Tracking problem with unknown reference

In order to illustrate the track-following operation in ODSS's, Fig. 1 shows a schematic for an optical pickup unit consisting of an objective lens, actuator coils, the stiffness and damping elements. The pickup unit can be viewed as a sensor measuring the tracking error (or, the focus error) and, at the same time, as an actuator for moving the objective lens. Note that the fine actuator moves on the fixed coordinate at the coarse actuator driven by DC-motors or stepper motors. Refer to the references [1] and [2] for the standard structures of the dual stage pickup unit. In general, the dual stage pickup unit is controlled in the closed loop system to follow the desired data track as shown in Fig. 2. The readout signals from the pickup are conditioned to generate the track error in the RF amplifier. Then, the digital signal processor produces the control outputs for the fine actuator and the coarse actuator, respectively. Note that each of the actuators can be independently controlled due to the dynamic separation of the actuators.

We start with the following equation for the system behavior:

$$\left\{ \begin{array}{l} \dot{x} = v \\ \dot{v} = -2\zeta w_n v - w_n^2 x + \beta w_n^2 u - \ddot{x}_s \\ e = K_o(x_r - x_s - x) \end{array} \right. \tag{1}$$

where x, v are the relative position and the relative velocity of the objective lens, respectively. Note that w_n, ζ and β are the system parameters given by the pickup specification used, and K_o is the optical gain depending on the laser power and the reflectivity of the disc. Here, we assume that the coarse actuator is being controlled appropriately but not perfectly due to the slow dynamics of the coarse actuator. Let us denote the remainder incapable of being cancelled by the coarse actuator control as $x_r^\star \triangleq x_r - x_s$. Then, the purpose of the feedback control for the fine actuator is to obtain the following performance specification:

$$\lim_{t\to\infty} |x_r^\star - x| \le \delta_{max} \tag{2}$$

where δ_{max} is the allowable track deviation. As to the unknown reference, we point out that the rotating data tracks never make exact circle due to the so-called eccentricity resulting from the mechanical deviation of the disc center and the spindle one, and the geometric distortion of the circular tracks. In general, considering the eccentricity, the unknown reference may be assumed as

$$x_r^\star = x_o + \epsilon \sin(2\pi f_{op} t + \varphi) \tag{3}$$

where x_o is the unknown offset and f_{op} is the rotational frequency possibly time-varying. It is noted that the rotational frequencies of most of ODSS's are not very high in view of the signal processing. The allowable amount of the eccentricity has been specified by the storage standard specifications such as the so-called Red-Book for CD-digital audio [8]. However, in practice, many of the discs exceed the standard specification so that ODSS's have been required to have more ability to overcome the excessive eccentricity. For instance, playability to discs having the eccentricity of 210 μm can be a measure for evaluating the quality of ODSS's while the specification allows only up to 70 μm.

Now, we rewrite the reference tracking problem above as a regulation problem as follows:

$$\left\{ \begin{array}{l} \dot{e} = \xi \\ \dot{\xi} = -2\zeta w_n \xi - w_n^2 e - K_o \beta w_n^2 u + K_o d \end{array} \right. \tag{4}$$

where $d = \ddot{x}_r + 2\zeta w_n \dot{x}_r^\star + w_n^2 x_r^\star$. Note that the reference tracking problem is equivalently written by a regulation problem with the unknown disturbance, which exists with the control input. Also, the disturbance only contains the reference information affected by the eccentricity.

III. Reduced order disturbance observer

1. Observer algorithm

For developing the disturbance observer, we start with a technical assumption in the following.

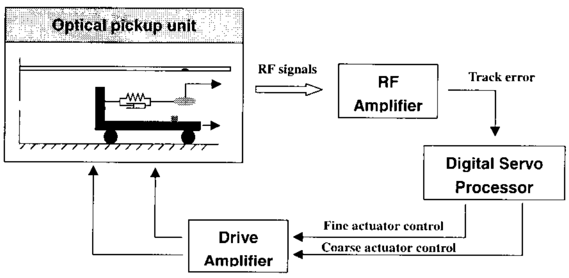

Fig. 2. Track following control system.

Assumption 1: *The derivative of the tracking error is available. That is, $\dot{e}$ ($= \xi$) is measured.*

In general, the RF chip that provides the signals related to the servo operations gives only the tracking error. Hence, to satisfy the above assumption, one may need the real-time differentiation of the tracking error using an analog circuit (or digital signal processing). From experiences, obtaining the derivative of e is of no difficulty because the necessary bandwidth of differentiation is less than a few kHz range so that the differentiation noise can be effectively reduced using a low pass filter.

Under the assumption, consider an algorithm for disturbance observer in the following:

$$\begin{cases} \dot{z} = -\gamma\left(-2\zeta w_n \xi - w_n^2 e - K_o \beta w_n^2 u + K_o \hat{d}\right) \\ \hat{d} = z + \gamma\xi \end{cases} \qquad (5)$$

where γ is a positive scalar. To illustrate the estimation error dynamics, define as $\psi = d - \hat{d}$. Then, we have, from (4) and (5),

$$\begin{aligned} \dot{\psi} &= \dot{d} - \dot{\hat{d}} \\ &= \dot{d} - \dot{z} - \gamma\dot{\xi} \\ &= -\gamma K_o \psi + \dot{d} \end{aligned} \qquad (6)$$

As can be seen above, the estimation error exponentially decreases with the ratio determined by γK_o while the steady state error depends on the time-derivative of the unknown disturbance. It may be shown that, as $t \to \infty$,

$$|\psi(t)| \leq \frac{\mu}{\gamma K_o} \qquad (7)$$

where $\mu \triangleq \max_{t>0} |\dot{d}|$. This shows that the steady state error would decrease if we chose the positive scalar γ to be large (that is, if the observer dynamics is fast enough). Note that, however, the parameter γ is the gain multiplied by the time-derivative of the tracking error in (5), which implies that the observer can be sensitive to the measurement noise with the increased gain. Therefore, there should be the trade-off between the sensitivity to the measurement noise and the disturbance rejection performance when selecting the gain parameter.

Now, we examine the physical meaning of the disturbance observer in the Laplace domain. To this end, observe that, from (4), the exact disturbance may be represented as follows:

$$\begin{aligned} D(s) &= \frac{s^2 + 2\zeta w_n s + w_n^2}{K_o} E(s) + \beta w_n^2 U(s) \\ &= \frac{\beta w_n^2}{K_o}\{P(s)^{-1}E(s) + K_o U(s)\} \end{aligned} \qquad (8)$$

where $P(s) = \frac{\beta w_n^2}{s^2 + 2\zeta w_n s + w_n^2}$. It is noted that the dynamic inversion of the plant is necessary to obtain the input disturbance. To investigate the observer operation, consider the disturbance estimate, from (5),

$$\begin{aligned} \hat{D} &= Z(s) + \gamma s E(s) \\ &= \frac{\gamma}{s + \gamma K_o}\left[\begin{array}{c} \{(2\zeta w_n - \gamma K_o)s + w_n^2\}E(s) \\ + K_o \beta w_n^2 U(s) \end{array}\right] \\ &\quad + \gamma s E(s) \\ &= \frac{\gamma K_o}{s + \gamma K_o} D(s) \end{aligned} \qquad (9)$$

It is clear that the disturbance observer would generate the low pass filtered disturbance, which is obtained implicitly through the dynamic inversion of the pickup system.

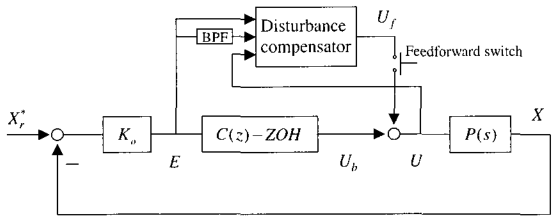

Fig. 3. Control structure with feedforward compensator.

2. Compensation scheme

Now, we are ready to construct the control law using the estimated disturbance. Consider the following control input

$$u = u_b + u_f \qquad (10)$$

where u_b is the control input from the feedback controller, and u_f from the feedforward one. See Fig. 3 for the system structure. The feedback input may be obtained by the conventionally designed compensator while the feedforward input is chosen as

$$u_f = \frac{\hat{d}}{\beta w_n^2} \qquad (11)$$

Then, it follows, from (4), that

$$\dot{\xi} = -2\zeta w_n \xi - w_n^2 e - K_o \beta w_n^2 u_b + K_o \psi \qquad (12)$$

Comparing with (4), the disturbance becomes less effective in the closed loop system depending on the estimation error. This implies that the feedback controller design can be set to be more free from the disturbance with the aid of the feedforward compensator.

To show the effectiveness of the disturbance compensation scheme, let us derive the sensitivity function when the compensator is applied. From (6), we have

$$\Psi(s) = \frac{s}{s + \gamma K_o} D(s) \qquad (13)$$

where $\Psi(\cdot)$, $D(\cdot)$ are the Laplace transformations of the signals ψ and d, respectively. With this and (12), it may be shown that

$$S(s) = \frac{E(s)}{D(s)} = \frac{K_o P(s)}{\beta w_n^2 (1 + K_o C(s) P(s))} \cdot \frac{s}{s + \gamma K_o} \qquad (14)$$

where $C(s)$, $P(s)$ are the transfer functions for the feedback controller and the pickup system, respectively. Observe that the transfer function

$$S_b \triangleq \frac{K_o P(s)}{\beta w_n^2 (1 + K_o C(s) P(s))} \qquad (15)$$

is the sensitivity of the closed loop system when only the feedback compensator is applied. Since the transfer function, $\frac{s}{s + \gamma K_o}$, is the high-pass filter of first order, it would reduce the transmission of the low frequency components of the disturbance.

From the sensitivity function above, the closed loop poles of the compensated system consist of the poles by the feedback loop and the observer dynamics, which implies that the feedforward loop does not affect the feedback loop dynamics.

3. Robustness to the modeling uncertainty

The plant model must include the parameter uncertainties. Especially, the optical gain, K_o, definitely depends on reflectivity of discs being played. Note that reflectivity of discs is not uniform over the types of the coated materials on disc surfaces. Suppose that, instead of (4), the system is written as

$$\dot{\xi} = -2\zeta w_n \xi - w_n^2 e - K_o \beta w_n^2 u + K_o d + g(\xi, e, u) \quad (16)$$

where $g(\cdot)$ represents the existing model uncertainty, which is Lebesgue-measurable and bounded. It is easy to see that the disturbance observer would produce an estimate for the equivalent disturbance

$$d_{eq} \triangleq d + g(\xi, e, u)/K_o \quad (17)$$

This shows that the compensation scheme with the proposed observer would drive the system to follow the nominal plant model while the accuracy depends on the time-derivative of the equivalent disturbance d_{eq} as illustrated in (7). Such a property is expected to increase the robustness of the feedback system (e.g., the gain and phase margins). Nevertheless the qualitative illustration, the robustness issue still remains open.

IV. Application to an optical storage system

In this section, we implement the proposed approach in a CD-ROM/ReWritable disc drive with 4x operating speed. For a disc with the eccentricity of 210 μm, we realize and simply add the proposed feedforward compensator to the conventional feedback system. In the following, we discuss a few issues for real implementation.

1. Time-derivative of the tracking error

To obtain the time-derivative of the tracking error, we designed the band-pass filter as shown in Fig. 4. The first cutoff frequency was chosen considering the disc operating speed (e.g., 4x constant linear velocity (CLV) control in this experiment). The x1-CLV speed in CD-ROM drives means that the relative velocity of the pickup lens and the disc surface is within 1.2 – 1.4 (m/s) by the standard specification [8]. Since the radii of data tracks range from 2.5 cm to 6 cm in case of the discs with 12 cm diameter, the rotational frequency of the discs in the 1x-CLV mode should be around 3 Hz (at the outermost track) to 8 Hz (at the innermost track). Hence, in the 4x-CLV mode, the maximum rotational frequency becomes 32 Hz. Also, the closed loop bandwidth is designed to be within 2 kHz. Therefore, the effective range of differentiation specified by 7.2 kHz is enough. It is noted that to reduce the signal noise, we appended a low pass filter with the cutoff frequency at 18.2 kHz. The circuit can be described as

$$\xi_a \cong -R_2 C_1 \dot{e} = -R_2 C_1 \xi \quad (18)$$

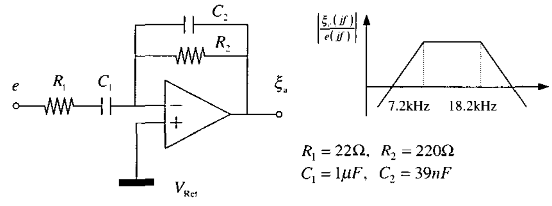

Fig. 4. A circuit for differentiating e.

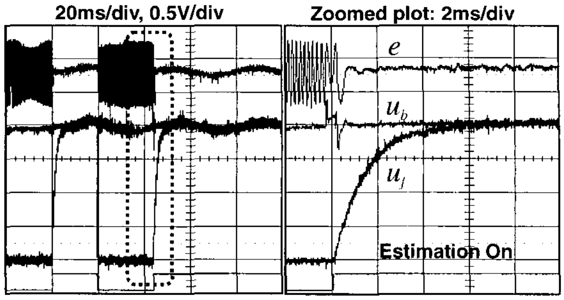

Fig. 5. Experimental results: the observer performance.

in the low frequency range. Indeed, one may design a digital filter instead of the analog circuit. However, we used this to reduce the computational burden in the micro-processor we used.

2. Discretization of the observer dynamics

In order to implement the disturbance observer, we adopted a commercial microprocessor of low cost and, designed to support the 20 kHz sampling rate, which was chosen considering the closed loop bandwidth around 2 kHz. When the operating speed is higher, one may need to design the closed loop bandwidth larger. In this case, the computational power would be needed more than in this experiment. From (5), we have

$$\dot{z} = -\gamma K_o z + f(t) \quad (19)$$

where

$$f(t) = \frac{\gamma^2 K_o - 2\zeta w_n \gamma}{R_2 C_1} \xi_a + \gamma w_n^2 e + \gamma K_o \beta w_n^2 u$$

Since the exact solution for z at $t = kT_s$ is given by

$$\begin{aligned} z(kT_s) &= e^{-\gamma K_o T_s} z((k-1)T_s) \\ &\quad + \int_{(k-1)T_s}^{kT_s} e^{-\gamma K_o (kT_s - \tau)} f(\tau) d\tau \end{aligned} \quad (20)$$

the trapezoidal approximation of the 1st order is as follows:

$$z_k \approx e^{-\gamma K_o T_s} z_{k-1} + \frac{T_s}{2}(f_k + e^{-\gamma K_o T_s} f_{k-1}) \quad (21)$$

As a matter of fact, we had also implemented the second order approximation that utilized a series of quantities $\{f_k, f_{k-1}, f_{k-2}\}$ to obtain z_k. However, the difference was observed to be negligible.

3. Estimation performance

To investigate the estimation performance, we solved the difference equation while the feedforward switch was turned off in Fig. 3. Since we do not know the existing disturbance, the direct comparison between the disturbance estimate and the real disturbance is impossible. Instead, we calculated the fictitious feedforward control from the estimated disturbance. As can be seen in Fig. 5, the feedforward control (u_f) follows almost the feedback control input, which implies that the feedforward control can take the role of the feedback one for suppressing the periodic disturbance. Also, the estimation dynamics is asymptotically (and monotonically) stable without the overshoot as illustrated in (6). We simply start the estimation at $u_f(0) = 0$ V to clearly observe the estimation dynamics even though the reference voltage is 2 V. Note that the estimation should be turned off during the off-track operations such as the track-jump operation and the traverse state. When the objective lens is not near the data track, the plant dynamics in (4) is not valid, which may result in a wrong estimation.

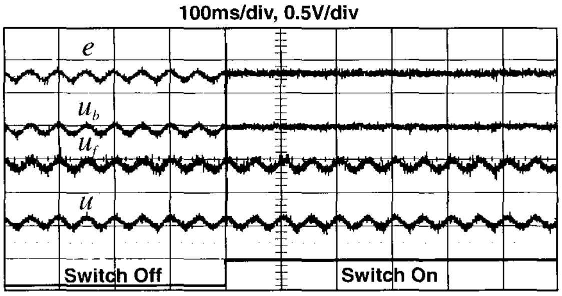

Fig. 6. Experimental results: feedforward switch is turned on.

4. Control performance with feedforward input

Now, the results are shown in Fig. 6 when the feedforward switch is turned on in Fig. 3. Before the feedforward control is applied, there exists the periodic deviation of the tracking error regardless of the feedback control. However, it can be seen that the tracking error deviation drastically reduces just after the application of the feedforward control. Observe that the feedforward control takes the role to attenuate the periodic disturbance on behalf of the feedback one. This implies that one may have more freedom for designing the feedback controller because the design constraint imposed by the eccentricity can be relaxed with the feedforward compensator.

V. Conclusions

In this paper, a novel algorithm for the disturbance observer of reduced order has been proposed for handling the eccentricity in optical data storage systems. The observer is derived in the time domain analysis and shown to be monotonically (and exponentially) stable in the transient response. The disturbance estimate would have steady state error according to the derivative of the disturbance, however, the estimation error can be reduced by properly choosing the observer dynamics. The advantages of the proposed approach are the simplicity of the observer, the apparent estimation dynamics in the time domain and the efficient disturbance rejection performance. We discussed the sensitivity analysis and some of practical issues. Also, through an application to an optical storage system, the feasibility of the proposed approach has been proven.

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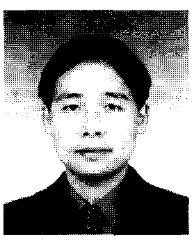

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