Full FPGA Tracking Control System Based on Error-Based Communication Disturbance Observer Considering Time Delay for Optical Disc System

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Currently, a high-precision tracking control system is required for a large-capacity optical disc drive system. This paper proposes a new full field-programmable gate array (FPGA) tracking control system based on an error-based communication disturbance observer (ECDOB) considering the time delay of an optical disc drive system. The FPGA control system may have a large influence on both the integer time delay and the non-integer time delay of the control system. In order to consider the time delay, this study reconstructs the feedback control system by using the limited pole placement method. Moreover, this paper proposes a new ECDOB. The experimental and numerical simulation results confirm that the tracking performance of the proposed system is better than that of a conventional feedback control system. In full FPGA tracking control of optical disc systems, the proposed ECDOB-based tracking controller exhibits good performance.

Keywords: optical disc, motion control, tracking control, time delay, FPGA, communication disturbance observer

1. Introduction

Recently, the data size of digital content has been increasing. Accordingly, the storage capacity of digital storage media, which is an optical disc system such as a DVD or Blu-ray Disc, also needs to increase. The storage capacity of an optical disc system is dependent on data track pitch miniaturization. Therefore, the laser spot miniaturization for applying a narrow track pitch requires a shorter laser wavelength and larger numerical aperture (1) (2). The Blu-ray optical disc drive system utilizes blue lasers, which results in a higher memory density than that of a conventional optical disc. In addition, to increase the data transfer rate, it is necessary to increase the rotation speed of the optical disc. A data transfer rate of 252 MB/s has been realized using a high disc rotation speed higher than 15,000 rpm (2).

An optical disc drive system has periodic disturbances. As the optical disc rotation speed increases, the periodic disturbances also increase. A feedback controller for suppressing the periodic disturbances has been proposed (2) (3). However, it is difficult to perfectly suppress periodic disturbances in a high-rotation disc system using a conventional feedback tracking control system. Therefore, a high-precision tracking control structure is required for the optical disc drive system. To overcome this problem, several high-performance tracking control systems that use the predictive control method have already been proposed (2) (4) (5). Generally, a full FPGA control system does not need to use predictive control because its sampling time is very short.

Tracking control systems are often implemented in digital signal control system such as a Digital Signal Processor (DSP) or Field-Programmable Gate Array (FPGA). The DSP system is the most popular system for preparing a digital control system. However, it is difficult to realize a fast-sampling control system that has a complex structure. On the other hand, the FPGA system realizes a fast sampling period for complicated control systems (10) (11). The high-performance controller is also implemented in the FPGA (11) (12). The high-performance control system of a hard disk drive has been embedded by using the FPGA (10).

Digital control systems usually suffer from time delay, which affect both the calculation and conversion times in a digital control system. In a full FPGA control system, the influence of the conversion time on the time delay increases significantly in a fast-sampling period system. The FPGA control system sometimes has large influence on both the integer time delay and the non-integer time delay of a control system. In a feedforward control system of an optical disc drive system, the feedforward compensation is delayed by the time delay.

Conventional control systems do not consider the delay time (2) (13). Thus, the time delay sometimes causes an unstable phenomenon in optical disc control systems (13). Therefore, a high-precision tracking control system considering the time delay is needed for optical discs. In other words, the control system should consider the time delay. Various methods have been proposed for the propose of realizing the
controller that considers the time delay (14)-(20). The communication disturbance observer (CDOB) is the useful method to compensate for the influence of an unknown time delay (14)-(16). The prediction method has been applied to the feedback controller to consider the time delay (19). However, it is impossible for CDOB to apply the only tracking error-based feedback controller. In order to overcome this problem, this paper proposes a new full FPGA-based error-based communication disturbance observer that considers the time delay of an optical disc drive system. This proposed full FPGA tracking controller based on proposed error-based communication disturbance observer has a quick tracking response against periodic disturbances and time delay.

2. Conventional Method and Design Conditions

2.1 Tested Optical Disc Drive System The tracking actuator of an optical disc is a Voice-Coil Motor (VCM). Figure 1 shows the frequency characteristics of the VCM. The tracking control drives the object lens using the VCM. In general, a VCM is represented by a spring model with some resonance frequency. Because there is usually a second resonance frequency near the Nyquist frequency, the plant model should consider only the first resonance frequency. The transfer function of a nominal plant system that includes only the first resonance is shown in (1) and (2). (2) is discretized from (1) by using zero order hold whose sampling period is 2\( \mu \)s.

\[
P_a(s) = \frac{2.288 \times 10^8}{s^2 + 52.95s + 7.151 \times 10^4} \quad \cdots (1)
\]

\[
P_a(z) = \frac{k_pz + k_{pd}}{z^2 + k_{pd}z + k_{pd0}}
= \frac{4.576 \times 10^{-4}z + 4.576 \times 10^{-4}}{z^2 - 2z + 0.9999} \quad \cdots (2)
\]

The ODU-1000 for Blu-ray is an experimental machine, as shown in Table 1. The FPGA system configuration is shown in Fig. 2. The resolution of the A/D and D/A converter is 16 bits. An FPGA performs high speed processing for a complicated control system. However, the calculation device generates a calculation time delay. The time delay is generated by the calculation time of the A/D and D/A converters and the control system; therefore, the control performance is degraded by the time delay. The control system has one sample delay based on digital feedback. This calculation time delay should be considered in the design of the control system. The qualification of an optical disc drive system for a feedback control system is shown in Table 1. The FPGA clock speed is 70 MHz, and the D/A conversion time is 200 ns. The processing time of the operation is 2\( \mu \)s. Therefore, the time delay is 2.2\( \mu \)s in the FPGA. In this paper, the control system that considers the time delay is designed. Where \( l_1 \) is the integer order and \( l_{\text{int}} \) is the non-integer order.

2.2 Design of Feedback Controller without Considering Time Delay A digital feedback control system without consideration of the time delay is shown in Fig. 3. The feedback controller uses a high-gain servo controller (HGSC) (3), which is designed using the pole placement method. The HGSC \((C(z))\) is represented by (3).

\[
C(z) = \frac{z - \omega_c(z - \omega_d)}{(z - \omega_c)(z - \omega_d)} \quad \cdots (3)
\]

The closed loop transfer function is shown in (4), where \( p_c \) is the pole arrangement.

\[
G_{\text{closed}}(z) = \frac{P_a(z)C(z)}{1 + P_a(z)C(z)} = \left( k_p(z - \omega_c)(z - \omega_d)(k_{pm1}z + k_{pd0}) \right) (z - p_c)^2 \quad \cdots (4)
\]

The poles are placed using a factor comparison method. Table 2 shows the pole placements of the tested feedback control systems. The poles of the control systems are designed for 25 krad/s \( \simeq \) 4 kHz, as shown in Table 2.

2.3 Design of Feedback Controller with Considering Time Delay In Table 2, an ideal control system is designed to the desired poles. However, the control system has a time delay. The digital feedback control system with consideration of the time delay is shown in Fig. 4. A feedback control system without consideration of the time delay cannot be designed for the desired poles, since the closed-loop transfer functions cause model mismatching. The characteristic...
The number of dependent poles is determined by the number of coefficients of the denominator polynomial \((n_q + 1)\) minus the number of coefficients of the rational function \((n_a, n_b)\).

Here, \(n_q\) is the order of the denominator polynomial. Thus, the number of dependent poles \(n_p\) is determined by (16).

\[
n_p = n_q - n_a - n_b - 1 \quad \text{(16)}
\]

(15) is expressed by the matrix equation (17).

\[\gamma^T = \begin{bmatrix} a_0 & a_1 & b_0 & b_1 & b_2 & Q_0 & Q_1 \end{bmatrix}, \]

\[\delta^T = \begin{bmatrix} 0 & 0 & 0 & P_0 & P_1 & P_2 & P_3 \end{bmatrix}, \]

\[\zeta = \begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & 1 & 0 \\ b_0 & b_1 & b_2 & b_3 & b_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -P_0 & -P_1 & -P_2 & -P_3 & -1 & 0 & 0 \\ 0 & -P_0 & -P_1 & -P_2 & -P_3 & -1 & 0 \end{bmatrix}, \]

\[\gamma^T = \delta^T \zeta^{-1} \quad \text{(17)}\]
The controller parameters $\alpha_0, \alpha_1$, and $\beta_0, \ldots, \beta_2$ are determined by using (17). In addition, the dependent poles coefficients $Q_0, \ldots, Q_{n-1}$ are determined by using (17). If a dependent pole is unstable, the control system is unfeasible. For the feedback controller, the design parameters are shown in Table 2. In the LPFM, the control system is designed according to the desired poles.

### 2.4 Experimental Results of Feedback Controller

The experimental evaluation of the residual tracking error is described. The experimental results for the digital feedback control without consideration of the time delay are depicted graphically in Fig. 5. The digital feedback control with consideration of the time delay is shown in Fig. 6.

In the digital feedback control without consideration of the time delay, many tracking errors remain at a high frequency. These tracking errors are increasing due to time delay components. In the digital feedback control with consideration of the time delay, the errors are suppressed at a high frequency. This means that there is a 2.35 nm reduction in the $3\sigma$ value of the feedback control with consideration of the time delay system as compared to that of the feedback control without consideration of time delay. The effect of time delay is not removed completely. The model of time delay is required for accurate modeling. Therefore, this paper uses the feedback control system a new such as communication disturbance observer.

### 3. Error-based Communication Disturbance Observer

The Smith method (20) and CDOB (14) have been proposed as time delay compensation methods. Time delay is a factor that causes control systems to lose stability. It is necessary that control systems avoid being affected by time delay. The CDOB handles delays as network disturbances. It is not necessary to design a time delay model for the CDOB. Its control performance is equal to that of the Smith method. This paper focuses on the CDOB, which considers a time delay as a Network Disturbance $ND(t)$.

#### 3.1 Communication Disturbance Observer

This paper discusses network disturbance. A time delay is placed on the input side of the plant system. The CDOB considers a time delay to be a network disturbance. Therefore, $ND(t)$ is shown by (18). $I_{cmd}(t)$ is the input value of the time delay, and $T_d$ is the time delay. $ND(t)$ is calculated by estimating the difference between the input and output of the time delay.

$$ND(t) = I_{cmd}(t) - I_{cmd}(t - T_d) \cdots \cdots \cdots \cdot (18)$$

Figure 7(a) shows that the structure uses for control systems to estimate the value of $ND(t)$. The output of a plant is represented as (19). The estimated $\hat{ND}(t)$ is shown in (20).

$$y(t) = P(s)(I_{cmd}(t) - ND(t)) \cdots \cdots \cdots \cdot (19)$$

$$\hat{ND}(t) = I_{cmd}(t) - P^{-1}(s)P(s)(u(t) - ND(t))$$

$$= I_{cmd}(t) - (I_{cmd}(t) - ND(t)) \cdots \cdots \cdots \cdot (20)$$

The CDOB is shown in Fig. 7(b). $P^{-1}(s)$ used for the estimation is not a proper system. For implementation, a second-order low-pass filter is applied to $P^{-1}(s)$. This makes $P^{-1}(s)LPF(s)$ into a proper system. The estimated $\hat{ND}(t)$ is added to the feedback value. The closed-loop transfer function of the CDOB is shown in (21). $LPF(z)$ represents the low-pass filter. The cut-off frequency of $LPF(z)$ is 4 kHz in this paper, which is the same cut-off frequency of feedback controller. On condition that $LPF(z) = 1$ (ideal case), as the

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**Fig. 5.** Experimental results of conventional digital feedback control system without consideration of time delay

**Fig. 6.** Experimental results of conventional digital feedback control system with consideration of time delay

**Fig. 7.** Block diagram of communication disturbance observer
CDOB removes the time delay from the denominator of the closed-loop transfer function, the CDOB closed-loop transfer function is shown in (22). Its time delay is compensated by the CDOB. CDOB needs not have the accurate time delay model. Therefore, CDOB is a robust control system on the time delay variation. Here, \( D(z) = z^{-T_f} \).

\[
G_{\text{closed-cDOB}}(z) = \frac{C(z)P(z)D(z)}{1 + C(z)LPF(z)P(z) - (LPF(z) - 1)C(z)P(z)D(z)} \quad \cdots \cdots \cdots \quad (21)
\]

when: \( LPF(z) = 1 \)

\[
G_{\text{closed-cDOB}}(z) = \frac{C(z)P(z)}{1 + C(z)P(z)}D(z) \quad \cdots \cdots \cdots \quad (22)
\]

### 3.2 Error-based Communication Disturbance Observer

Generally, it is impossible to obtain the control output \( y(t) \) and the reference \( y_{ref}(t) \) of actual plant system such as optical disc system. An optical disc drive system has only tracking error and no tracking reference signal. Therefore, in order to estimate a network disturbance, this paper newly construct the communication disturbance observer using only tracking error of the optical disc drive system. The new CDOB using a tracking error is the proposed error-based communication disturbance observer (ECDOB). The ECDOB is shown in Fig. 8(a). The ECDOB estimates Equivalent Time Delay Disturbance \( ETDD(t) \) as shown in Fig. 8(a). The ECDOB uses a current command \( I_{\text{cmd}}(k) \) and error value \( e_r(k) \) to estimate \( ETDD(k) \). The tracking error is shown as (23).

\[
e_r(s) = y_{ref}(s) - (P(s)I_{\text{cmd}}(s) - P(s)ND(s)) \quad \cdots \cdots \cdots (23)
\]

In order to estimate \( ND(s) \), \( P^{-1}(s) \) is applied to the tracking error. The tracking error is shown as (24).

\[
P^{-1}(s)e_r(s) = P^{-1}(s)y_{ref}(s) - (P(s)I_{\text{cmd}}(s) - P(s)ND(s)) \quad \cdots \cdots \cdots (24)
\]

\[
LPF(z)P^{-1}(z)e_r(z) = LPF(z)P^{-1}(z)y_{ref}(z) - I_{\text{cmd}}(z) + ND(z) \quad \cdots \cdots \cdots (25)
\]

\( P^{-1}(z) \) used for the estimation is not a proper system. \( P^{-1}(z) \) is multiplied by a second-order low-pass filter and transformed into a proper system. Therefore, \( LPF(z)P^{-1}(z)e_r(z) \) is shown in (25). Moreover, when \( LPF(z)P^{-1}(z)e_r(z) \) is added to \( LPF(z)I_{\text{cmd}}(z) \), (26) is obtained in (25). In this paper, (25) is ECDOB. The ECDOB estimates \( P^{-1}(z)y_{ref}(z) \) and \( ND(z) \).

\[
LPF(z)P^{-1}(z)e_r(z) + LPF(z)I_{\text{cmd}}(z) = LPF(z)P^{-1}(z)y_{ref}(z) - I_{\text{cmd}}(z) + ND(z) + I_{\text{cmd}}(z) = LPF(z)P^{-1}(z)y_{ref}(z) + ND(z) = LPF(z)ETDD(k) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots (26)
\]

The \( ETDD(k) \) is shown in (27). A block diagram of the ECDOB is shown in Fig. 8(b).

\[
I_{\text{ecob}}(k) = ETDD(k) = LPF(z)ETDD(k) = LPF(z)P^{-1}(z)y_{ref}(z) - LPF(z)ND(z) \quad \cdots \cdots \cdots (27)
\]

Hence, \( ND(k) \neq ETDD(k) \). The network disturbance and trajectory commands are estimated by the ECDOB system. The closed loop transfer function is expressed as (28). On condition that \( LPF(z) = 1 \) (ideal case), the ECDOB closed-loop transfer function is shown in (29). ECDOB compensates all time delay including the dead time and dynamics. The ECDOB reduces the influence on all time delay the time delay.

\[
G_{\text{closed-ecDOB}}(z) = \frac{((C(z)P(z) + LPF(z))D(z))}{(1 - LPF(z)) + (C(z)P(z) + LPF(z))D(z)} \quad \cdots \cdots \cdots (28)
\]

when: \( LPF(z) = 1 \)

\[
G_{\text{closed-ecDOB}}(z) = \frac{D(z) + C(z)P(z)D(z)}{D(z) + C(z)P(z)D(z)} = 1 \quad \cdots \cdots \cdots (29)
\]

On condition that \( LPF(z) = 1 \), the characteristic polynomial has no time delay element. Several closed loop transfer functions which has LPF of different band-width are expressed as (9). The bandwidth of control system depends on the bandwidth of LPF.

### 3.3 Numerical Simulation Results

The cut-off frequency of \( LPF(z) \) is 4 kHz which is also the same cut-off frequency of feedback controller. Figure 10 shows the simulation results of the feedback control without consideration of time delay. Figure 11 shows the simulation results of the feedback control with consideration of time delay. Figure 12
shows the simulation results of the CDOB without consideration of time delay. Figure 13 shows the simulation results of the CDOB with consideration of time delay. Table 3 summarizes and compares the simulation results. The output values of a plant system are obtained by simulation. Actually, CDOB cannot implement, because the optical disc system cannot detect the position of actuator.

Figure 14 shows the simulation results of the ECDOB without consideration of time delay. Figure 15 shows the simulation results of the ECDOB with consideration of time delay. In order to confirm the validity of the ECDOB and CDOB, this paper performs the numerical simulation. In the numerical simulation results, the trajectory command $y_{ref}(k)$ of tracking actuator is created by experimental results ($^9$). In

<table>
<thead>
<tr>
<th>Control Method</th>
<th>$\pm 3\sigma$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback control (without consideration of time delay)</td>
<td>20.37</td>
</tr>
<tr>
<td>Feedback control (with consideration of time delay)</td>
<td>20.26</td>
</tr>
<tr>
<td>CDOB (without consideration of time delay)</td>
<td>20.26</td>
</tr>
<tr>
<td>CDOB (with consideration of time delay)</td>
<td>20.14</td>
</tr>
<tr>
<td>ECDOB (without consideration of time delay)</td>
<td>7.01</td>
</tr>
<tr>
<td>ECDOB (with consideration of time delay)</td>
<td>7.00</td>
</tr>
</tbody>
</table>

The CDOB and the feedback control system have the almost same tracking error as shown from Fig. 10 to Fig. 13. The results of the ECDOB feedback control system are shown in Fig. 14 and Fig. 15. From simulation results, the residual tracking errors are suppressed within 7.00 [nm]. Therefore,
the ECDOB performs its functions regardless of the feedback controller. ECDOB suppresses the time delay and Periodic disturbances. Therefore, ECDOB exhibits good performance.

The pole placement diagram of the ECDOB is shown as Fig. 16. When the plant system has the natural frequency mismatching of ±30% and the delay time variation such as 1.2, 2.4 and 3.6 sampling. In these condition, all poles of Fig. 16 are located within the unit circle. Therefore, the ECDOB is stable on condition that the plant system has parameters mismatching as shown in Fig. 16.

3.4 Implementation Using FPGA In this paper, the proposed control system is implemented by using an FPGA. The FPGA is used the Cyclone V (5CEFA9F31C8), and the control system is implemented using the Very High-Speed Integrated Circuit Project Hardware Description Language (VHDL).

3.5 Experimental Results Figure 17 and Fig. 18 show the experimental results of the proposed tracking control system by using the ECDOB. In Fig. 17, the feedback controller without consideration of time delay. In Fig. 18, to consider the time delay, the feedback controller is designed by an LPPM. Table 4 summarizes and compares the experimental results. These control systems are realized by FPGA. From the experimental results, the residual tracking errors are suppressed within 16.82 [nm] by using the ECDOB. Moreover, a comparison between Fig. 17 and Fig. 18 shows that the ECDOB eliminates the influence of the time delay of an FPGA. As for the results, the ECDOB is performed its functions regardless of the feedback controller structure. When the ECDOB is implemented, the feedback controller is not necessary to considering time delay.
Table 4. Evaluation of Experimental results of tested tracking control

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Δσ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback control (without consideration of time delay)</td>
<td>31.45</td>
</tr>
<tr>
<td>Feedback control (with consideration of time delay)</td>
<td>29.10</td>
</tr>
<tr>
<td>ECDOB (without consideration of time delay)</td>
<td>17.09</td>
</tr>
<tr>
<td>ECDOB (with consideration of time delay)</td>
<td>16.82</td>
</tr>
</tbody>
</table>

4. Conclusions

This paper proposes a new full FPGA tracking control system based on an error-based communication disturbance observer considering the time delay for an optical disc system. The FPGA control system reduces the calculation time and realizes a high sampling frequency. However, the FPGA control system often has a large influence on the time delay. In this paper, in order to consider both the non-integertime delay and the integer time delay, the feedback control system is newly reconstructed by using Padé approximations and the limited pole placement method. Moreover, this paper proposes a new error-based communication disturbance observer considering the time delay for an optical disc system. The proposed full FPGA tracking control system based on error-based communication disturbance observer has a quick tracking response against periodic disturbances and the time delay. In the experimental results, the proposed error-based communication disturbance observer based tracking controller has the residual tracking error Δσ is ±16.82 nm whose size is about 58% of feedback controller. The experimental results confirm that the proposed full FPGA tracking control system has a fine tracking control performance on the condition that the rotation speed of the optical disc is 10,000 rpm.

References

Tracking Control of Error-Based Communication Disturbance Observer (Keisuke Yoshida et al.)

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