DIGITAL TRACKING CONTROLLER DESIGN FOR CD PLAYER USING DISTURBANCE OBSERVER

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Abstract

Disturbance rejection is becoming more and more important as optical disk players are being utilized in more applications. This paper considers the design of a tracking servo controller for a CD(Compact Disk) player using the Disturbance Observer(DOB) theory. By adding a DOB to the conventional PID(Proportional, Integral and Derivative) controller, the tracking performance is dramatically improved in the presence of sinusoidal vibrations or a shock disturbance. The effectiveness of the DOB is verified by experimentation using an actual CD player as well as by computer simulations.

1 INTRODUCTION

The first CD player was sold in Japan in the mid-1980's. Since then, the optical disk player has made rapid and remarkable technological advances. Today, both CD/CD-ROM(Read Only Memory) and DVD(Digital Versatile Disk)/DVD-ROM players have been made available to the market and utilized in various applications such as portable CD players, car-mounted CD/CD-ROM players and computers. The wide spread use of these players has made disturbance rejection by the servo controller for track following more and more important. Disturbances arise from the motion of player unit or from the high rotational speed of the spindle motor of the CD-ROM player.

There are several methods for disturbance-rejection implemented on commercial optical audio players to prevent the sound from skipping. For example, a "shock-proof memory" is implemented on portable CD and MD(Mini Disk) players. Car-mounted CD players are installed in a shock-absorption insulator. Both methods have the disadvantages that additional hardware is necessary and that their applications are limited.

In this paper, an application of the disturbance observer(DOB) theory to the design of a tracking controller for CD players is studied. The DOB is considered to be one of the most effective methods to handle disturbances. In this approach, the actual output of the controlled plant is processed by an approximate realizable inverse of the nominal dynamics of the plant, and the difference, which is regarded as the equivalent disturbance, between the processed signal and the control input, is used for disturbance cancellation. As a result, disturbances and model uncertainties in a specified frequency range are removed. Furthermore, the DOB does not require additional sensors such as an accelerometer. Since the control mechanism is similar among almost all the optical disk players, it is expected that the DOB can be utilized in any kind of player from DVD to recordable optical disk drives.

2 TRACKING CONTROL FOR CD PLAYERS

0-7803-4484-7/98/$10.00

2.1 Tracking Control for CD Players[1]

The objective of tracking servo control for CD players is to track the spiral data track properly. Figure 1 shows the basic structure of tracks on CDs and CD-ROMs.

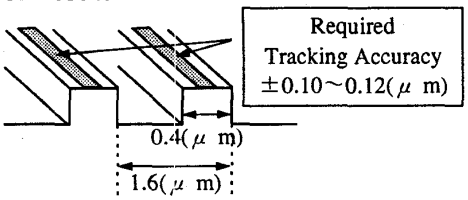
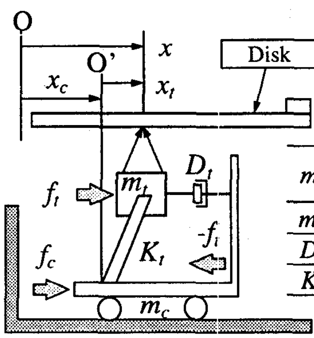


Fig.1 Structure of Tracks on CD

For CDs, CD-ROMs and MDs, the track pitch is 1.6(μ m) and the track width is 0.4(μ m). The track pitch of DVD is shortened to 0.8(μ m) so that it can contain much more data than conventional CDs or CD-ROMs. Tracking control is necessary because every optical disk has eccentricity in a range from ±100(μ m) to ±200(μ m). In order to obtain the proper reflected signal even in the presence of disk eccentricity or disturbance, the accuracy for tracking control has to be less than approximately ±0.10(μ m). Figure 2 illustrates the mechanism of the actuator used for tracking.



m_t	mass of the tracking actuator
m_c	mass of the sled
D_t	spring coefficient
K_t	mechanical resistance

Fig.2 Mechanism of Tracking Actuator

In Fig.2, x, x_t and x_c represent the absolute position of the tracking actuator, the absolute position of the sled, and the relative position of the tracking actuator, respectively. f_t is the force applied to the tracking actuator and f_c is the force applied to the sled. As shown in Fig.2, the tracking actuator is mounted on the sled which is much bigger than the tracking actuator. This sled is controlled only when the tracking actuator has to traverse a long distance which is much wider than the track pitch. From Fig.2, the following equations are obtained.

$$m_t\ddot{x} + D_t(\dot{x} - \dot{x}_c) + K_t(x - x_c) = f_t \qquad (1)$$

$$m_c\ddot{x}_c + D_t(\dot{x}_c - \dot{x}) + K_t(x_c - x) = f_c - f_t \qquad (2)$$

From Eqs.(1) and (2), for f_c=0

$$\ddot{x}_c = -\frac{m_t}{m_c}\ddot{x} \qquad (3)$$

This relation implies that the sled is not effected by the motion of the tracking actuator if $m_c >> m_t$. Thus, if the mass of the sled is significantly larger than that of the tracking actuator, Eq.(1) can be simplified to

$$m_t\ddot{x} + D_t\dot{x} + K_t x = f_t \qquad (4)$$

By applying the Laplace transformation to this equation, we obtain

$$X_t(s) = \frac{1}{m_t s^2 + D_t s + K_t} F_t(s) \qquad (5)$$

The force $F_t(s)$ is derived from the driving current $I(s)$ by the following equation

$$F(s) = BlN \cdot I(s) \qquad (6)$$

where B is the magnetic density, l is the effective length of the coil, and N is the number of windings of the coil. The current is related to the input voltage by

$$I(s) = \frac{1}{R_a + sL_a} V(s) \qquad (7)$$

where R_a is the resistance and L_a is the inductance of the moving coil. From Eqs.(5), (6) and (7), the transfer function of the voltage-driven tracking actuator is given by

$$G(s) = \frac{X_t(s)}{V(s)} = \frac{BlN}{m_t s^2 + D_t s + K_t} \cdot \frac{1}{R_a + sL_a} \qquad (8)$$

3 DISTURBANCE OBSERVER

3.1 Disturbance Observer[2][3]

The principle of the DOB is explained using Fig.3.

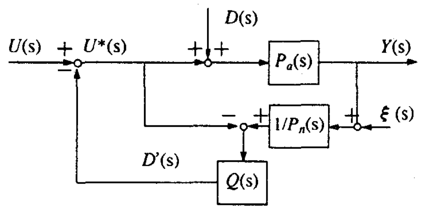


Fig.3 Principle of the DOB

In Fig.3, $P_n(s)$ is the nominal transfer function and $P_a(s)$ is the actual transfer function. $U^*(s)$, $Y(s)$, $U(s)$ and ξ (s) are the input, output, control input and measurement noise, respectively. $D(s)$ represents the disturbance and $D'(s)$ is the estimated value of $D(s)$. $Q(s)$ is a filter. It plays a significant role in determining the disturbance rejection characteristics in the DOB. Note that the DOB is not implementable in the form of Fig.3 because $1/P_n(s)$ is normally not realizable. The relative degree of $Q(s)$ must be chosen so that $Q(s)/P_n(s)$ is realizable. Also, $Q(s)$ is typically designed as a low pass filter. The principle of the DOB can be seen by examining the transfer functions from the inputs of the DOB loop (i.e. U, D, ξ) to the output of the plant Y.

$$Y(s)=G_{uy}U(s)+G_{dy}D(s)+G_{\xi y}\xi(s) \tag{9}$$

where

$$G_{uy}=\frac{P_aP_n}{Q(P_a-P_n)+P_n},\quad G_{dy}=\frac{P_aP_n(1-Q)}{Q(P_a-P_n)+P_n}$$

$$G_{\xi y}=\frac{P_aQ}{Q(P_a-P_n)+P_n}$$

At frequencies where $Q(s)$ is close to 1, the frequency response G_{dy} is close to 0, (i.e. the disturbance is rejected completely). Also, G_{uy} approximates $P_n(s)$, which indicates that the input-output character of this system behaves like the nominal plant. The DOB structure in Fig.3 can be transformed to the one in Fig.4. Note that the transformed structure is impelementable.

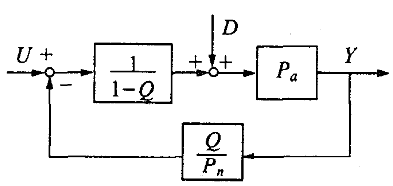


Fig.4 Implementation of DOB

3.2 Control Algorithm

As seen in Figs.3 and 4, it is necessary to obtain the output of the controlled plant, Y, to implement the DOB. In optical disk players, however, the position error signal(PES) is the only signal available for control. Therefore, it is necessary to modify the DOB structure for implementation on the current CD player controller. PES is the difference between the reference, R and the actual output, Y. Thus, the DOB is implemented as shown in Fig.5, where C represents the main loop controller. In the current CD players, C is normally a PID (Proportional, Integral and Derivative) controller.

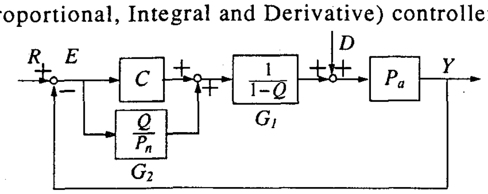


Fig.5 Implemented Block Diagram of Tracking Controller for CD player using the DOB

In Fig.5, the disturbance rejection characteristic is preserved after modification while the enforcement of the input/output characteristics of the plant to act as the nominal plant is lost.

The control algorithm will be implemented by using a DSP(Digital Signal Processor). For digital implementation, $G_1(s)$ and $G_2(s)$ in Fig.5 can be converted to digital filters by the bilinear transformation.

$$G_i(z^{-1})=G_i(s)\Big|_{s=\frac{2}{T_s}\frac{1-z^{-1}}{1+z^{-1}}},\quad i=1,2 \tag{10}$$

where T_s is the sampling time. In this paper, the sampling frequency is f_s=1/T_s=44.1(kHz). Q/P_n should be transformed as one unit so that it will be realizable.

A detailed block diagram of the closed loop system is shown in Fig.6. Here, the variable G_{drv}, G_{opt}, and G_{head} represent the gain of the driver, the gain of the optical pick-up to transform the position signal to an equivalent current signal, and the gain of the head-amplifier which generates the PES by comparing the reflected signal with the reference voltage R (V_{ref}:2.5(V)). E_c is the eccentricity of the optical disk. The three blocks C, G_1 and G_2 in Fig.5 are implemented on the DSP.

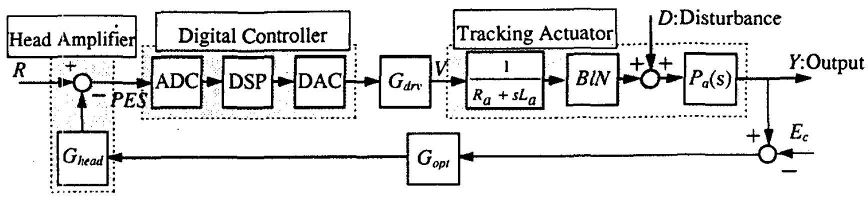


Fig.6 A Block Diagram of the Plant and Control Loop

4 COMPUTER SIMULATION

A computer simulation was performed in order to predict the effectiveness of the DOB. Comparison of the proposed method to the conventional method(PID only) reveals significant differences between the two. In this paper, a butterworth LPF with a bandwidth of 500(Hz) is used for the Q filter.

4.1 Frequency Response

Figure 7 shows the comparison of the frequency response between the system with and without the DOB.

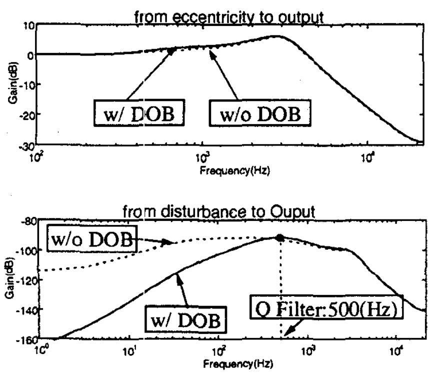


Fig.7 Frequency Response

Although the frequency characteristic from eccentricity to output does not change very much, disturbances are significantly suppressed by the DOB at frequencies lower than 500(Hz), which is the cutoff frequency of the Q filter. This shows that the disturbance rejection performance depends on Q filter.

4.2 Time Response

Simulation results in Figs.8, 9 and 10 show the effectiveness of the DOB for sinusoidal and shock disturbances.

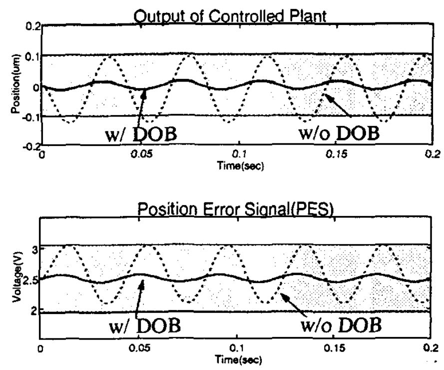


Fig.8 Time Response
(Sinusoidal Disturbance:25(Hz), 3.1(m/s^2))

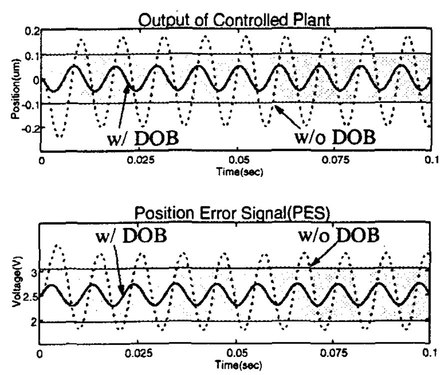


Fig.9 Time Response
(Sinusoidal Disturbance:100(Hz),2.9(m/s^2))

The shaded area in the upper plot of Figs.8, 9 and 10 shows the required accuracy region mentioned in 2-1. This region is equivalent to a range from 2(V) to 3(V) in terms of PES(lower plot). From these figures, the output signal of the system without the DOB exceeds ± 0.1(μ m) when subjected to the disturbances, which indicates that the tracking actuator may fail to read data or is unable to follow the track properly. On the other hand, the PES obtained from the system with the DOB remains small and meets the tracking requirement.

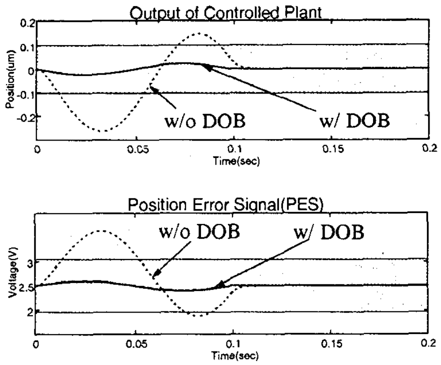


Fig.10 Time Response
(Shock Disturbance(Duration:100(ms)))

5 EXPERIMENTS

5.1 Experimental Setup

In order to verify the effectiveness of the DOB and the results obtained by computer simulations, an experiment using an actual CD player and a vibration generator has been conducted. Figure 11 shows the block diagram of the experimental system.

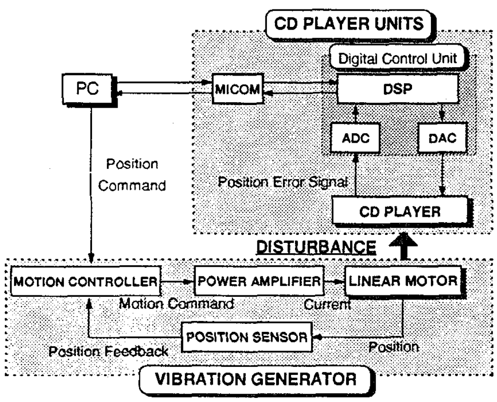


Fig.11 Block Diagram of Experimental System

A Personal Computer(PC) was equipped with a 16bit fixed-point DSP(Clarkspur Design, Inc.) which was used to calculate the control input, an analog to digital converter(ADC) for receiving the PES and a digital to analog converter(DAC) for sending the control input. A linear motor(Galil Motion Control, Inc.) is used as a vibration generator and provides a disturbance to the CD player. The PC sends commands to the Galil controller to set the disturbance parameters. Figure 12 shows the schematic of the actual experimental set-up.

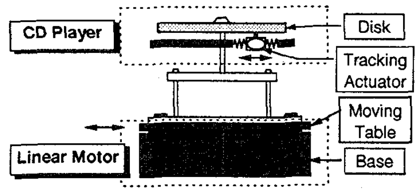


Fig.12 Schematic of the Experimental System

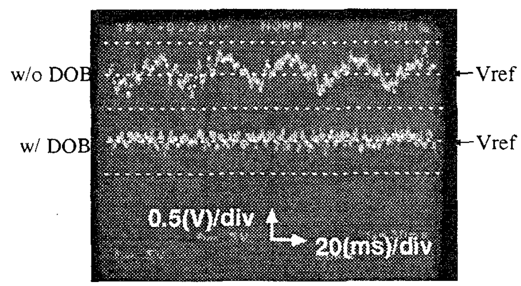
The CD player is mounted on the linear motor. The direction of motion of the tracking actuator and that of the linear motor are aligned so that the effect of the disturbance is maximized.

5.2 Experimental Results

Some representative experimental results are presented in this subsection.

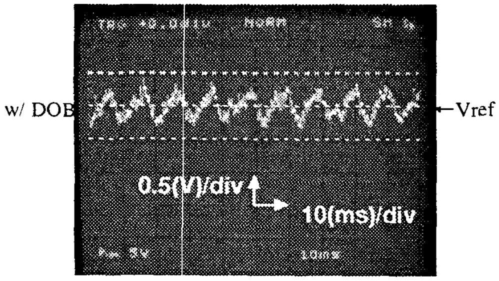
5.2.1 Sinusoidal Disturbance

Figures 13 and 14 show the actual PES measured in the systems with and without the DOB when subjected to sinusoidal disturbances of 25(Hz) and 100(Hz), respectively.



Sinusoidal Disturbance:25(Hz), 3.1(m/s^2)
Fig.13 Comparison of the Measured PES

As can be seen clearly in Fig.13, the PES obtained from the system without the DOB subjected to a 25(Hz) disturbance is strongly affected. On the other hand, the disturbance effect is drastically reduced in the system with the DOB. Figure 13 corresponds to Fig.8.



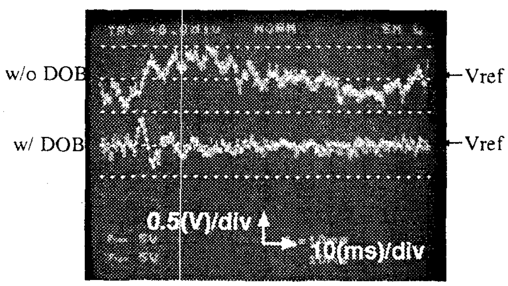
Sinusoidal Disturbance:100(Hz),2.9(m/s^2)

Fig.14 Measured PES of the system w/ DOB

When subjected to a 100(Hz) sinusoidal disturbance, the acceleration reaches 2.9(m/s^2) and the CD player with only the conventional PID controller stops working. The DOB has enabled the tracking actuator to remain within the required range of $\pm 0.10(\mu m)$ as shown in Fig.14. Figure 14 corresponds to Fig.9.

5.2.2 One Cycle Sine-wave Disturbance

In order to verify the effectiveness of the DOB against the shock disturbance, the experiment with one cycle sine wave disturbance has also been conducted. The test signal for results in Fig.15 is a one cycle sine wave with a duration of 100(ms).



Disturbance Duration:100(ms)

Fig.15 Comparison of the Measured PES

The system with the DOB rejects the effect of the disturbance within 10(ms) after the disturbance is added and quickly goes back to its normal state. It has also been verified that the DOB is effective for band-limited random disturbances. Fig.15 corresponds to Fig.10.

6 CONCLUSIONS

This paper has proposed a disturbance rejection method for CD players using a disturbance observer. The DOB was simply added to an existing PID controller. It has been shown by both simulation and experiment that the DOB can effectively eliminate the effect of both sinusoidal disturbances and shock disturbances. It is noted here that the DOB has also been applied to the focus servo controller (the controller to keep the objective lens at the proper distance from the disk to maintain focus) of the same CD player.

It is still under investigation whether the proposed approach is effective to other optical drives such as a CD-ROM player. As long as the tracking or focusing actuator has similar structure, the method is expected to improve the disturbance rejection performance of other disk drives.

Reference

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3. Bickel, R.J. and Tomizuka, M. "Design of a Robust Tracking Controller in the Discrete Time Domain," Proceedings of the 3rd International Workshop on Advanced Motion Control, March 1994, pp.-648-659