

Tracking learning feedforward control for high speed CD-ROM

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TRACKING LEARNING FEEDFORWARD CONTROL FOR HIGH-SPEED CD-ROM

Yu Zhou

*Philips Optical Storage, Singapore
Development Department, Bldg TP4, 5thFloor
620A, Lorong 1 Toa Payoh, Singapore 319762
Tel: 65 - 3517301 / Fax: 65 - 3549040
Email: zhou.yu@philips.com*

Maarten Steinbuch

*Faulty of Mechanical Engineering System & Control Group
Eindhoven University of Technology, WH0.143
P.O.Box 513 5600 MB Eindhoven, The Nertherlands
Tel: 31-40-2472773 / Fax: 31-40 2461418
Email: m.steinbuch@wfw.wtb.tue.nl*

George Leenknegt

*Optical Recording Development
Building SFJ-1.51, P.O.Box 80002
5600 JB Eindhoven, The Nertherlands
Tel: 31-40-2736690 / Fax: 31-40-2733037
Emsil: leenkneg@iclab.ce.philips.nl*

Abstract: The periodic disturbances caused by the inherent eccentricity and unbalancing in compact disc systems is one of the prominent radial tracking problems in high-speed and high density optical storage systems. To compensate these periodic disturbances, a learning feedforward compensation (LFF) method is presented and investigated. Computer simulations and experimental evaluation on the high speed CD-ROM product show that the proposed LFF provides a effective way to improve the radial tracking performance by reducing the radial error by 85%. *Copyright © 1999 IFAC*

Keywords: CD-ROM, Disturbance, Tracking, Adaptive control, Learning algorithms, Feedforward compensation

INTRODUCTION

In optical storage, two major functions are provided by the radial servo system to correctly position the laser spot radially along the desired track: seek and tracking (Sorin, 1998). The seek moves the radial actuator from track to track and the tracking servo tries to keep the radial actuator in the center of the track as precisely as possible during the read (or write) process. However, the inherent eccentricity caused by the discrepancy between the actual center of the spiral tracks and the center of a spindle motor is particularly large (typically 100 μm). This will cause a periodic tracking error (also called radial error) at the same frequency as the rotation of the disc. In addition, the spindle motor "wobbles" during rotation, typically at the fundamental and second harmonic frequencies of the disc rotational frequency, track unroundness, unbalanced platter and disc etc will also add to the radial error. This will influence the tracking performance. It should be effectively rejected in order to maintain the radial error within a tolerance limit, despite such disturbances.

Basically, there are two ways to reduce this periodic radial error. One is to improve the mechanical parts and strictly control the manufacturing process of the drive. However this is very costly, and does not capture the disc quality itself. A more cheap and reasonable way is to design a robust radial tracking controller to correct the periodic radial error and achieve sufficient suppression of the periodic disturbances within the radial servo system.

Due to the variation of actuator dynamics and disturbances from case to case, a control system is needed to adapt itself to the phase and amplitude of the radial error signal. There are several algorithms like "repetitive control" or "learning feedforward control" algorithms for eliminating periodic disturbances of known period. Repetitive controllers are LTI controllers based on the internal model principle (Sacks *et al.*, 1993). The model of the disturbance generation model must be included in the feedback system, and accurate identification of the system is also required for complete disturbance cancellation. Applications of repetitive control in hard disk drives and optical storage systems are presented in (Steinbuch *et al.*, 1996., Tomizuka *et al.*, 1989). Other internal model based controllers like inverted notch filters are accomplished by adding poles and zeros in series with the open loop transfer function of the servo system. An additional phase lag is produced across the frequency of the poles, which can be traded off against the amount of attenuation of the controller by changing the damping gain. Selective harmonic cancellation is not possible. The learning feedforward

controller or adaptive feedforward controller, on the other hand, is a different approach based on the external model principle (Tomizuka *et al.*, 1989). The disturbance model is placed outside the basic feedback loop. A learning or adaptive algorithm is used to estimate the amplitudes and phase of the disturbance and to suppress the disturbance at the input of the actuator. The external model based schemes do not change the loop gain once converged, and allows for selective cancellation of the disturbance harmonics and is more robust to disturbance variations. Several methods to improve the controller's performance are proposed and verified in (Sacks *et al.*, 1993, 1995). In terms of computation and storage requirements, the LMS algorithm is one of the most efficient adaptive algorithms (Emmanuel *et al.*, 1993) and it does not suffer from numerical instability problems. Based on the LMS algorithm, a discrete-time learning feedforward compensation (LFF) algorithm is proposed here to remove the periodic disturbance of the radial error signal (RES) during tracking for high speed CD-ROM drives. Stability analysis of the LFF is conducted in the paper. Computer simulation and experimental will be shown.

LEARNING FEEDFORWARD COMPENSATION

Figure 1 shows a typical block diagram of CDROM radial servo system with LFF. The actuator $P(z)$ represents the transfer function from radial actuator input to radial position of the lens. The signal d represents the disturbance during tracking. The distance between the actual radial actuator position and the track center is denoted as the Radial Error Signal (RES) $e(k)$. This error is measured using optical means, see (Bouwhuis *et al.*, 1984). The control signal $u(k)$ is composed of the original feedback controller $C(z)$ output $u_m(k)$, and the periodic disturbance cancellation control signal coming from LFF $u_c(k)$. As can be seen from the figure, the LFF controller is a kind of external model controller, which is placed in addition to the normal controller $C(z)$. Depending on the mode of operation of the LFF block, it can be seen as either a feedback structure (during learning) or as feedforward (when learning is off).

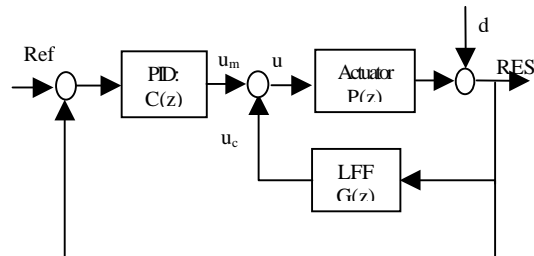


Figure 1. Typical block diagram of CDROM radial servo system with LFF control

STABILITY ANALYSIS

Considering the practical implementation, a discrete-time representation of the signals and the system is required. Assuming that the periodic disturbance at the k th sample consists of a sum of N sinusoids of fundamental and harmonic frequencies of the rotational frequency ω_0 of the disc, we can model the disturbance d as:

$$d(k) = \sum_{i=1}^N \{a_i \cos(\omega_i kT) + b_i \sin(\omega_i kT)\} \quad (1)$$

where T is the sampling time, and with $\omega_i = i\omega_0$. This periodic disturbance observed at the output of the (linear assumed) system can be exactly cancelled by injecting a control signal u_c to the actuator if it has the form of

$$u_c(k) = \sum_{i=1}^N \{w_i^c \cos(\omega_i kT) + w_i^s \sin(\omega_i kT)\} \quad (2)$$

where w_i^c and w_i^s are unknown weighting coefficients at the k th time sample. According to the LMS algorithm, the weight can be adjusted from sample to sample in such a way as to minimize the mean square error between the estimated disturbance and the actual disturbance using the steepest descent algorithm (Stephen *et al.*, 1987, Emmanuel *et al.*, 1993). As shown in figure 1, the radial error signal at the k th sample time can be estimated by combining the actuator response generated by the original radial PID control loop and disturbance generated by the LFF controller input. The update rules are:

$$\begin{aligned} w_i^c(k+1) &= w_i^c(k) + \alpha_i y(k) \cos(\omega_i kT + \phi_i) \\ w_i^s(k+1) &= w_i^s(k) + \alpha_i y(k) \sin(\omega_i kT + \phi_i) \end{aligned} \quad (3)$$

where T is the sampling time, α_i is referred to as "learning rate" or convergence rate, which controls the convergence rate to the steady state value. The phase ϕ_i is included to stabilize the overall system during learning. Each weight is updated every sample and the LFF learns the characteristics of the periodic disturbance signal. The output control signal from the LFF controller at the $k+1$ th sample time can be calculated as follows to compensate the periodic disturbance at the $k+1$ th sample time:

$$u_c(k+1) = \sum_{i=1}^N \{w_i^c(k+1) \cos(\omega_i(k+1)T) + w_i^s(k+1) \sin(\omega_i(k+1)T)\} \quad (4)$$

The transfer function of the LFF controller as shown in figure 2 can be written as:

$$G(z) = \frac{U(z)}{E(z)} \quad (5)$$

Where $U(z)$ and $E(z)$ are the Z-transform of the LFF control output $u_c(k)$ and the radial error input $e(k)$ to the LFF, respectively. Letting k go to infinity, assuming zero initial conditions, and taking the Z transforms of (3) and (4), and substitute them into (5), and we obtain:

$$\begin{aligned} U(z) &= \sum_{i=1}^N \frac{\alpha_i}{4} \left\{ \frac{1}{ze^{j\omega_i T} - 1} (e^{-j\phi_i} E(ze^{2j\omega_i T}) + e^{j\phi_i} E(z)) + \frac{1}{ze^{-j\omega_i T} - 1} (e^{-j\phi_i} E(z) + e^{j\phi_i} E(ze^{-2j\omega_i T})) \right\} \\ &- \sum_{i=1}^N \frac{\alpha_i}{4} \left\{ \frac{1}{ze^{j\omega_i T} - 1} (e^{-j\phi_i} E(ze^{2j\omega_i T}) - e^{j\phi_i} E(z)) - \frac{1}{ze^{-j\omega_i T} - 1} (e^{-j\phi_i} E(z) - e^{j\phi_i} E(ze^{-2j\omega_i T})) \right\} \\ &= \sum_{i=1}^N \frac{\alpha_i}{2} \left(\frac{e^{j\phi_i}}{ze^{j\omega_i T} - 1} + \frac{e^{-j\phi_i}}{ze^{-j\omega_i T} - 1} \right) E(z) \end{aligned} \quad (6)$$

Where $E(ze^{j\omega_i T})$ is the Z-transform of $E(z)$ rotated counterclockwise around the unit circle through the angle $\omega_i T$. Similarly, $E(ze^{-j\omega_i T})$ represents a clockwise rotation through $\omega_i T$.

For analysis simplicity, consider the compensation of the fundamental harmonic of disc rotating frequency ω_0 . Substitution of (6) into (5) then gives the open-loop transfer function of the LFF function:

$$G(z) = \frac{\alpha_1}{2} \left(\frac{z \cos(\omega_1 T - \phi_1) - \cos \phi_1}{z^2 - 2z \cos \omega_1 T + 1} \right) \quad (7)$$

It has two complex-conjugate poles located on the unit circle at $z = e^{\pm j\omega_1 T}$ and a real zero at $z = 1/\cos \omega_1 T$. The transfer function from d to e of the closed-loop system shown in figure 1 can be written as follow:

$$\begin{aligned} \frac{E(z)}{D(z)} &= \frac{1}{1 + G(z)H(z)} \cdot \frac{1}{1 + C(z)P(z)} \\ &= 1 - 2z \cos(\omega_1 T) + z^2 / (1 - 2z \cos(\omega_1 T) + z^2 + \frac{\alpha_1}{2} H(z)(z \cos(\omega_1 T - \phi_1) - \cos \phi_1)) \end{aligned} \quad (8)$$

in which $H(z) = \frac{P(z)}{1+C(z)P(z)}$ is the process sensitivity of the servo system composed of the controller $C(z)$ and plant $P(z)$. Assume the original closed-loop system is stable, the closed-loop poles of the original system (i.e. $1+C(z)P(z)=0$) are stable. Then the stability of the close-loop system with the LFF controller are mainly depend on the roots of poles given by:

$$(z - e^{j\omega_1 T})(z - e^{-j\omega_1 T})D_H(z) + \frac{\alpha_1}{2}(z \cos(\omega_1 T - \phi_1) - \cos \phi_1)N_H(z) = 0 \quad (9)$$

Where $H(s) = N_H(z)/D_H(z)$, $N_H(z), D_H(z)$ are the numerator and denominator polynomials. According to the root-locus argument, the closed-loop poles will be stable for small α_1 as long as the poles on the unit circle of radius 1 move into the unit. The movement of the poles at the $e^{j\omega_1 T}$ for small learning rate can be determined by the $\frac{\partial z}{\partial \alpha_1}$ at $\alpha_1 = 0$ and $z = e^{j\omega_1 T}$. Then

$$\left[\frac{\partial z}{\partial \alpha_1} \right]_{\alpha_1=0, z=e^{j\omega_1 T}} = \frac{\alpha_1 \cos \phi_1 - e^{j\omega_1 T} \cos(\phi_1 - \omega_1 T)}{4 \sin(\omega_1 T)} \times H(e^{j\omega_1 T}) \quad (10)$$

The necessary and sufficient condition for the poles at $e^{j\omega_1 T}$ to move inward the unit circle is:

$$\frac{\alpha_1}{4} \operatorname{Re} \left[\frac{\cos \phi_1 - e^{j\omega_1 T} \cos(\phi_1 - \omega_1 T)}{\sin(\omega_1 T)} H(e^{j\omega_1 T}) \right] > 0 \quad (11)$$

For a stable system, the adding with LFF will be stable if the learning rate α_1 is small enough and the phase ϕ_1 is chosen such that the equation (11) is satisfied, where the transfer function of the closed-loop response H is evaluated at the respective frequency.

SIMULATION AND MEASUREMENT

The feasibility and reliability of the LFF control for the radial error compensation in the CDROM are demonstrated and verified in this section by both computer simulation and experimental testing.

The computer simulation was conducted on our commercial product 32X CDROM driver. The LFF compensation is added onto the original radial control

system to minimize the variance of the RES during tracking. The fundamental harmonic of the disc rotational frequency of 110Hz is injected to the actuator to simulate the periodic disturbance coming from the eccentricity of the disc, track roundness, and motor wobbles etc. The LFF controller is activated only when the actuator enters radial tracking mode, and was always synchronized to the spindle motor speed through the spindle motor hall sensor signal.

Figure 2 is the transient response of radial error signal with and without the implementation of the learning feedforward compensation. As can be seen that the radial error signal RES is greatly reduced by using the LFF after 1 revolution of the spindle. The sampling rate used here is 7040 Hz. The maximum learning rate α_i is 3.0, which is limited by the convergence. The simulated open loop transfer function of the whole radial control system with LFF is plotted in figure 3. As can be seen in figure 5, there is at least 10dB reduction around the harmonic frequency.

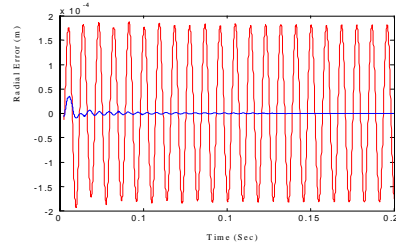


Figure 2. Simulated transient response of the RES with and without add-on LFF ("---" without LFF; "—" with LFF)

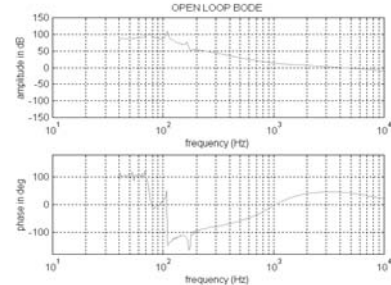


Figure 3 Open loop transfer function of learning feedforward

Experimental evaluation was also conducted in our commercial 32X CDROM product. The LFF controller was implemented in a dedicated microprocessor. A disc with an eccentricity of 150 μ m was used.

Figure 4 shows the measured power spectrum of the uncompensated radial error signal. The elapsed time per revolution for a 32X CDROM drive is 9.09 msec and the fundamental frequency of rotation is about 110Hz. The disturbance occurs at harmonics of the fundamental frequency (i.e. 110Hz, 220Hz, 330Hz,

440Hz, 550Hz, 660Hz etc.). As we see in the figure 4, the first harmonic component is the most dominant one and it is eliminated by LFF. The compensated radial error signal in the frequency domain is shown in figure 5. The contribution of the first harmonics on the radial error signal was reduced about 16dB. However there's about 5 dB average noise level increase when LFF was added in figure 8, and this was found caused by the calculation accuracy limit by the present μP solution when considering timing. If 16-bit processing was used instead of 8-bit, this noise level increase will be eliminated. The steady-state compensation was achieved within two revolutions. This also verified that the desired frequency component can be selectively eliminated as mention before. The LFF compensation implemented here was conducted without reference to the physical index, the estimated values of w_i^c and w_i^s converges to different values depending on the initial condition.

Figure 4. The power spectrum of radial error signal (RES) without the LFF compensation

Figure 5. The power spectrum of RES with LFF compensation on the fundamental harmonic

CONCLUSION

The LFF controller implemented here is very effective in removing the periodic disturbance of the radial error to about 85%. Since the LFF control signal operates as feedforward after learning, the performance of the existing servo controller in the feedback loop is maintained. A multiple LFF controller can be parallel added to the system to remove a few large harmonics (Francis *et al.*, 1975) present in the error signal. However the learning rate, which will influence the convergence time of the system, is practically difficult to decide beforehand because of the noise of the radial error signal. Some trial and error testing is needed to final decide the learning rate for real system. Although the LFF described here has been applied to a high-speed CD-ROM system, the method is also applicabable to other compact disc systems, like CD-R/CD-RW or DVD.

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