論文 한국공작기계학회지 제9권 제1호 2000. 2.
Journal of the Korean Society of Machine Tool Engineers

컴퓨터 하드디스크의 반복 런아웃에서 비롯된 외란의 효율적 제어

용 부 중*

AN ADVANCED DISTURBANCE REJECTION CONTROL FOR REPEATABLE RUNOUT IN DISK DRIVE SYSTEMS

Boojoong Yong*

Abstract

An improved disturbance rejection control scheme is presented for minimizing the position error due to the repeatable runout disturbances in high density disk drive systems. The proposed control algorithm is capable of attenuating repeatable disturbances, which is one of the major detractors to hard disk drive quality and performance. This is achieved by a systematic combination of an optimal feedback component and a feedforward preview component. The feedback component is designed, where the emphasis is placed on robustness. The feedforward component is on the basis of a preview control, comprised of a measured disturbance signals, which leads to better disturbance rejection capabilities. The designed controller is applied as a plug-in module to a high density hard disk drive with a pre-existing conventional servo controller. Simulations have been carried out to demonstrate the effectiveness of this control scheme in the reduction of the periodic disturbances.

Key Words : Repeatable Runout, Position Error Signal (PES), Preview Control

1. INTRODUCTION

Along with the widespread use of information equipment such as personal computers and workstations, the storage capacity of magnetic hard disk drives has grown rapidly in recent years. In order to increase the area density in the disk drive, it is necessary to increase the linear density and the track density, i.e., bits per inch (BPI) and tracks per inch (TPI). In particular, the track density grows some 25%~30% each year, while current products typically have track densities of around 12,000~15,000 TPI. There is a strong upward push, with up to 34,000 TPI anticipated in the next few years. This, in turn, requires much more accurate positioning of the read/write heads as well as advancements in various technologies.

In disk drive systems, two major functions are provided

---

* 경일대학교 기계공학부

by the servo controller: track seeking and track following. Control of track seeking allows minimum time motion from one track to another. Some variants of time-optimal control are usually employed. Track following, on the other hand, attempts to maintain the position of the read/write heads precisely over the center of a selected track with minimum displacement error in the presence of possible disturbances. Track following is trivial if tracks on the disks are perfect circles with their centers accurately at the center of rotation of the spindle. However, perfect positioning of disk is difficult, if not impossible, due to the manufacturing inaccuracy and design tolerance. The error of the position of the head following a data track causes periodic disturbances. The frequencies of the periodic disturbances often appear as integer multiples of the rotation frequency.

Current industrial track following controllers are generally a combination of lead-lag, proportional-integral (PI), and/or notch filters. Although such compensators are adequate for relatively low density disk drives, they may not have good track capabilities in the presence of repeatable runout in high density disk drives. Therefore, intelligent control algorithms are necessary to minimize the effect of these disturbances.

Over the years, many methods have been proposed to attenuate repeatable disturbances. They can be categorized into two groups. In the first group, error rejection signals are generated inside the feedback loop. One well-known method is the internal-model-based repetitive control. To achieve perfect regulation against external disturbances, the internal model principle prescribes the inclusion of the modes of the disturbances in the feedback loop. The prototype repetitive controller, as well as its modified version, is presented in Chew and Tomizuka.(1) This has been demonstrated to be effective in rejecting repeatable disturbances in hard disk drives. However, this approach has the drawback of amplifying nonrepeatable disturbances which may exist at the frequencies between the repeatable runouts. In the second group, errors are rejected by feedforward terms generated outside the main feedback loop. Adaptive feedforward cancellation method for attenuating repeatable runout in commercial magnetic disk drive was proposed by Sacks et al.(7~8) Matsukawa et al.(5) developed a sector servo using a learning method, and described the head positioning control system. Kempf et al.(4) compared four different repetitive control algorithms for cancellation of periodic disturbances, and they evaluated the performance of those algorithms experimentally. Guo and Tomizuka(2) proposed an optimization scheme for the hybrid feedforward controller in high-speed and high-precision digital motion control systems. Otten et al.(6) discussed the design and realization of an on-line learning motion controller for a linear motor. A major disadvantage of these methods is their intensive computational load, especially when rejection of multiple disturbances is needed.

The primary goal of this paper is to present a method of repeatable runout compensation using a feedforward preview control algorithm. While there are many applications to which the usefulness of the preview control can apply, this paper specifically investigates the application to high density hard disk drives. In Section 2, we discuss the disk drive system and repeatable runout. Next, the design of the disturbance rejection controller based on the preview control algorithm is proposed in Section 3. In order to show the effectiveness of the controller, realistic simulations using a typical periodic disturbance are given in Section 4. The results are compared to a conventional linear control, and the performance is discussed. We end with conclusion in Section 5.

2. COMPUTER DISK DRIVES AND REPEATABLE RUNOUT

Disk drives are comprised of several disks with a swinging-armhead-positioning actuator in a sealed enclosure. Read/write heads are mounted on sliders in a comb structure that can move in and out of the disk stack, in which the data are written in multiple concentric tracks on the surface of each disk. The surfaces of aluminum disks are coated with thin layers of magnetic material and lubricant. An air bearing is established between the slider and disk surface while the disk is spinning at high speed. The positioning of the read/write heads is performed by use of a voice-coil motor, which is controlled by the positioning servo.

The current trend in disk drives is to smaller sizes, and larger data capacity. The increased track density will require stringent positioning accuracy in order to obtain reliable read/write data. One important part of hard disk drive servo control is track following. The object is that once the read/write head is moved to a designated track, it must be able to follow the track motion, while keeping the position error between the head and the track as small as possible. However, it is inevitable for some position error to be introduced during track following. Repeatable runout, one major disturbance to the head position control loop, can be caused by several factors: an eccentricity of the track, an offset of the track center with respect to the spindle center, bearing geometry and wear, and motor geometry, etc. One way of reducing the repeatable runout is to impose strict requirements on each stage of the hard disk drive manufacturing process. However, this will increase manufacturing cost and effort significantly. An alternative way is to develop better servo control algorithms. This paper focuses on the problem of track following for disk drives : large periodic components in the position error signal (PES) spectrum. The controller design will be discussed in the next section.

3. DESIGN OF A DISTURBANCE REJECTION CONTROLLER

To reduce the repetitive error in disk drive systems, two approaches are possible. One method is to redesign the servo controller entirely and take into consideration the existence of repeatable disturbances in the system. The other approach is to enhance the pre-existing controller so that the entire system achieves a better performance, e.g., good disturbance rejection properties, in high density disk drive systems. The emphasis in this paper is on the second approach, where an additional plug-in unit designed by a preview control is installed to eliminate or reduce the repetitive errors.

3.1 An Optimal Preview Control Algorithm

In general, the magnitude and phase of the repeatable disturbance are not known. If information about the disturbance is obtained a priori, it makes sense to use available knowledge of the disturbance signal for better disturbance rejection. The preview control algorithm can be used for that purpose, and is developed by LQ-optimal control principles. The complete preview control system is composed of feedback and feedforward components. In practice, the feedforward disturbance rejection controller is added to the existing servo control loop. The advantage of this kind of structure is that the design of these two loops can be somewhat decoupled. When we design the feedback loop, we can concentrate on the system stability, robustness, and so on. In designing the feedforward loop, we can emphasize the repetitive disturbance rejection.

In order to design the complete control system, determining the feedback component rather than feedforward loop is firstly motivated. Here, the robustness is considered at an intuitive level, since the stability of the controlled system is solely determined by the feedback loop. Ideally, the feedback component should contain the mapping from the disturbance signals to the corresponding control input, such that no position error occurs by applying this control input to the process. As long as this mapping is not perfect, position errors occur, and the feedforward controller is necessary to enhance the disturbance rejection capabilities. In this case, we can interpret the feedback steering as an error measure for the feedforward steering, and the feedforward controller will be designed based on the determined feedback gains. Since the feedforward disturbance rejection controller is placed outside of the basic feedback loop, theoretically it has no effect on the system stability. This means that the stability analysis seems less necessary in the feedforward loop. However, the feedforward structure also incorporates a contribution to the feedback loop, caused by the fact that any error signal will be based on measurements of process output. In other words, the feedforward control with inaccurate preview information may cause stability problems and/or saturation of actuators. Further research regarding this is reported in Yong.(9)

3.2 System Description

As regarding the disk drive actuator, a double integrator representation has been used in industry for years.(3) The existing track following servo controller in this study is a lead-lag compensator designed by a transfer function approach. The lead-lag compensator provides adequate phase and gain margins for stability. This controller is driven by a position error signal derived from the pre-written position information which is embedded in the data track. The specifications of the present system is shown in Fig. 1. Here, the spindle is rotating at a nominal speed of 5400 rpm, which implies a rotational frequency of 90 Hz.

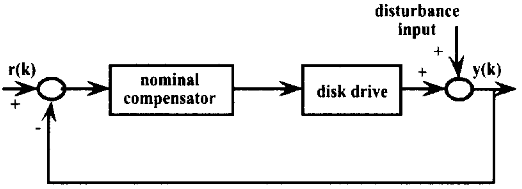

Fig. 1 Disk drive system with lead-lag compensation

A model of the plant is necessary to design the preview control system. We used the existing open-loop transfer function of the position control effort in the discrete-time domain, that is,

$$G(z)=\frac{0.4827z^{-1}-0.3852z^{-2}-0.4824z^{-3}+0.3855z^{-4}}{1-2.6992z^{-1}+2.0976z^{-2}-0.0976z^{-3}-0.3008z^{-4}} \quad (1)$$

Eq. (1) imposes a sampling period of $T_s = 1.55 \times 10^{-4}$ sec., i.e., the sampling frequency of 6450 Hz. The sampling frequency of the position error signal is determined by the disk rotating speed and the number of blocks. Note the open-loop plant already includes an actuator, an integrator, and a lead-lag compensator.

3.3 Controller Design

The preview control algorithm requires a parametric model of the plant. It relies on the fact that the preview controller is developed according to the LQ-optimal control principles. Therefore, the plant model (1) is transformed to an observer canonical form in the state-space representation such as

$$\begin{aligned}\mathbf{x}(k+1)&=\mathbf{\Phi}\mathbf{x}(k)+\Gamma u(k)\\ y(k)&=\mathbf{H}\mathbf{x}(k)\end{aligned} \quad (2)$$

where $\mathbf{x}(k)$ is a state vector, $u(k)$ is a control input, $y(k)$ is a system output, and

$$\begin{aligned}\Phi&=\begin{bmatrix}2.6992 & 1 & 0 & 0\\ -2.0976 & 0 & 1 & 0\\ 0.0976 & 0 & 0 & 1\\ 0.3008 & 0 & 0 & 0\end{bmatrix}\\ \Gamma&=\begin{bmatrix}0.4827\\ -0.3852\\ -0.4824\\ 0.3855\end{bmatrix}\\ \mathrm{H}&=\begin{bmatrix}1 & 0 & 0 & 0\end{bmatrix}\end{aligned} \quad (3)$$

Now, we anticipate the repeatable disturbance signals such that

$$\mathbf{p}(k)=\begin{bmatrix}p(k) & p(k+1)\cdots & p(k+N_p)\end{bmatrix}^{\mathrm{T}} \quad (4)$$

where N_p is the finite preview length, and $(\,\cdot\,)^{\mathrm{T}}$ denotes the transpose of $(\,\cdot\,)$. According to Yong,(9) the preview servo equation can be modeled as

$$\begin{aligned}\mathbf{p}(k+1)&=\tilde{\mathbf{\Phi}}\mathbf{p}(k)\\ p(k)&=\tilde{\mathbf{H}}\mathbf{p}(k)\end{aligned} \quad (5)$$

where $\tilde{\mathbf{\Phi}}$ is an $(N_p+1)\times(N_p+1)$ matrix, $\tilde{\mathbf{H}}$ is an (N_p+1)-dimensional row vector, and $\mathbf{p}(k)$ is an (N_p+1)-dimensional preview state vector. Combining the preview servo model (5) with the plant (2) yields an augmented open-loop system,

$$\begin{aligned}\mathbf{z}(k+1)&=\mathbf{A}\mathbf{z}(k)+\mathbf{B}u(k)\\ e(k)&=\mathbf{C}\mathbf{z}(k)\end{aligned} \quad (6)$$

where

$$\begin{aligned}&\mathbf{A}=\begin{bmatrix}\Phi & 0\\ 0 & \tilde{\Phi}\end{bmatrix},\ \mathbf{B}=\begin{bmatrix}\Gamma\\ 0\end{bmatrix},\\ &\mathbf{C}=\begin{bmatrix}\mathrm{H} & -\tilde{\mathrm{H}}\end{bmatrix},\ \mathbf{z}(k)=\begin{bmatrix}\mathbf{x}(k)\\ \mathbf{p}(k)\end{bmatrix}\end{aligned} \quad (7)$$

Design of the preview control system requires a performance index, typically defined by

$$J(i) = \frac{1}{2}\sum_{k=i}^{\infty}\left[e^{\mathrm{T}}(k)Qe(k) + u^{\mathrm{T}}(k)Ru(k)\right] \tag{8}$$

where $e(k)$ represents a system error, R and Q are positive scalar penalty functions. In the cost function, Q penalizes the error quantity, and R does large values of the control input. With the given performance index for the augmented system, the optimal feedback controller and the feedforward disturbance rejection controller will be designed by solving an associated Riccati equation such that

$$\mathbf{S} = \mathbf{A}^{\mathrm{T}}\mathbf{S}\mathbf{A} - \mathbf{A}^{\mathrm{T}}\mathbf{S}\mathbf{B}\left[\mathbf{B}^{\mathrm{T}}\mathbf{S}\mathbf{B} + R\right]^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{S}\mathbf{A} + \mathbf{C}^{\mathrm{T}}Q\mathbf{C} \tag{9}$$

where

$$\mathbf{S} = \begin{bmatrix} \mathbf{S}_{11} & \mathbf{S}_{12} \\ \mathbf{S}_{21} & \mathbf{S}_{22} \end{bmatrix}, \quad \mathbf{S}_{21} = \mathbf{S}_{12}^{\mathrm{T}} \tag{10}$$

If the plant model (2) is completely controllable for all time, $\mathbf{S}_{11}$ allows a constant optimal feedback gain for the plant, that is,

$$\mathbf{K} = \left[\Gamma^{\mathrm{T}}\mathbf{S}_{11}\Gamma + R\right]^{-1}\Gamma^{\mathrm{T}}\mathbf{S}_{11}\Phi \tag{11}$$

The optimal feedback component, **K**, assures a good system dynamic performance as well as a closed-loop system stability. Now, the time-invariant feedforward controller yields

$$\begin{aligned} \mathbf{K}_{ff} &= \left[\Gamma^{\mathrm{T}}\mathbf{S}_{11}\Gamma + R\right]^{-1}\Gamma^{\mathrm{T}}\mathbf{S}_{12}\tilde{\Phi} \\ &= \left[0 \quad \mathbf{K}_{pr}\right] \end{aligned} \tag{12}$$

Finally, the control input, $u(k)$, for the plant (2) becomes

$$\begin{aligned} u(k) &= -\mathbf{K}_{sys}\ \mathbf{z}(k) \\ &= -\left[\mathbf{K} \quad \mathbf{K}_{ff}\right]\mathbf{z}(k) \\ &= -\mathbf{K}\mathbf{x}(k) - \mathbf{K}_{pr}\bar{\mathbf{p}}(k) \end{aligned} \tag{13}$$

where $\bar{\mathbf{p}}(k) = [p(k+1)\, p(k+2) \cdots p(k+N_p)]^{\mathrm{T}}$. The feedforward component, $\mathbf{K}_{pr}$, is equipped to acquire and utilize the knowledge of the repeatable disturbance signal which is not taken into account (quantitatively) in feedback design, so that the system performance optimized during control.

As the position error signals of the feedback controller will be reduced by the feedforward disturbance rejection controller, the demands on the tracking performance of the feedback are not strict. Hence, the most important goal of the feedback controller is to realize a stable robustness. In designing the feedback gains, proper choice of the weighting factor ratio, $\rho_c = \frac{Q}{R}$, in the defined performance index (8) assures a good transient performance. The higher weighting factor ratio, the lower damping ratio - it yields higher percent overshoot, and the system presents unstable behavior. Decreasing the weighting function ratio stabilizes the preview control system, but implies some loss of performance as well. Determining the value of $\rho_c = 8.5$, the feedback controller maintains the damping ratio of the feedback system $\zeta = 0.707$. With this value, although the system will be oscillatory, it will be well damped out and we can avoid resonant peak. Also, from simulations, this turns out to be a proper choice.

Since the full system state, $\mathbf{x}(k)$, is not directly accessible, a state estimator is required in the feedback loop. Following the same procedure as presented in Yong,(9) an adequate optimal estimator can be found. Let the estimator model be described by a linear time-invariant discrete-time equation considering noise effects on the system,

$$\begin{aligned} \mathbf{x}(k+1) &= \Phi\mathbf{x}(k) + \Gamma_u(k) + \Gamma_w w(k) \\ y(k) &= \mathbf{H}\mathbf{x}(k) + v(k) \end{aligned} \tag{14}$$

where the process noise $w(k)$ and the measurement noise $v(k)$ are random sequences with zero mean, $E[w(k)] = E[v(k)] = 0$, and white noise. Note that $E[\cdot]$ is an expected value or mean value of $(\cdot)$. Suppose that $w(k)$ and $v(k)$ are uncorrelated with each other and normal (Gaussian), and have covariances defined by

$$E\left[w^2(k)\right] = R_w, \quad E\left[v^2(k)\right] = R_v \tag{15}$$

Then, a Kalman gain will be determined corresponding to R_w and R_v. If we feed back the error signal, $e(k)$, we can obtain the estimated state vector $\hat{\mathbf{x}}(k)$ such as

$$\hat{\mathbf{x}}(k) = \bar{\mathbf{x}}(k) + \mathbf{L}\{e(k) - \mathbf{H}\bar{\mathbf{x}}(k)\} \tag{16}$$

where **L** is the constant Kalman gain, and $\bar{\mathbf{x}}(k)$ is the time updated state from

$$\bar{\mathbf{x}}(k+1) = \mathbf{\Phi}\hat{\mathbf{x}}(k) + \Gamma u(k) \tag{17}$$

It may be necessary to repeat the design process several times to determine the most effective preview steps to cancel the repeatable runout. In this investigation, 5-steps of preview is found to be the best. Corresponding feedback gain **K**, feedforward preview gain $\mathbf{K}_{pr}$, and optimal estimator are :

$$\begin{aligned} \mathbf{K} &= [4.3808 \ \ 1.9035 \ \ 0.3448 \ \ -0.1228] \\ \mathbf{K}_{pr} &= [-0.7505 \ \ -0.5503 \ \ 0.0960 \ \ -0.0736 \ \ 0.0314] \\ \mathbf{L} &= [0.7580 \ \ -1.0001 \ \ -0.0586 \ \ 0.3013]^{\mathrm{T}} \end{aligned} \tag{18}$$

Figure 2 shows an entire control system with the preview add-on. The dashed lines indicate the injection and observation of the repeatable runout through the preview controller. From Fig. 2, it becomes clear how the feedforward component is incorporated with a feedback loop. The repetitive disturbance rejection controller herein is implemented in a "plug-in" fashion, meaning the feedforward compensator using preview control scheme is used to augment the existing servo.

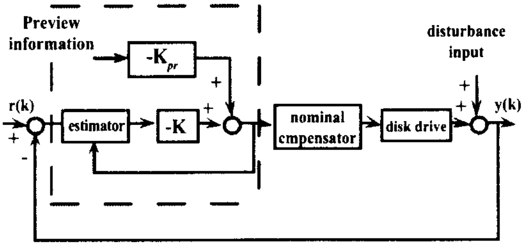

Fig. 2 "Plug-in" disturbance rejection controller

4. SIMULATION RESULTS AND DISCUSSIONS

The simulation is performed to be as close to the real implementation as possible. In this simulation, the disk drive is spinning 5400 rpm, which results in a first harmonic at 90 Hz (11.1 milliseconds per revolution), and provides a position signal at 6450 Hz. An external reference input is assumed be a setpoint position. The system is supposed to allow for complete access to the voice coil motor (VCM) digital-to-analog current input, and to the position error signal coming directly from the position signal demodulator. The position error signal used in this paper does not take into account relative offset of the data track with respect to the servo track. It is simply the error in the position of the servo head above the centerline of the servo track. For performance measurement, disturbance rejection characteristics will be verified numerically, based on the root-mean-square (rms) error of the PES.

A typical repeatable disturbance, $d(t)$, consisted of a sum of sinusoidal frequencies is represented such as

$$d(t) = \sin(2\pi \times 90t) + \sin(2\pi \times 180t) \tag{19}$$

where $90t$ and $180t$ depict 1st harmonic and 2nd harmonic of disk repeatable runout, respectively. The first harmonic or other relatively low-frequency repeatable disturbances are usually dominant. It is assumed that this repetitive disturbance signal is available as a preview information.

Fig. 3 and Fig. 4 show a repeatable disturbance and its frequency spectrum in the disk drive system, respectively. As evident in both figures, there is a very significant repetitive component in the error signal, which is a major source of track following error. It is desired to remove the disturbance observed at the output of the system by forming a control input that exactly cancels the disturbance.

Controlled by a lead-lag compensator (i.e., a nonpreview control method), Fig. 5 provides a position error signal with

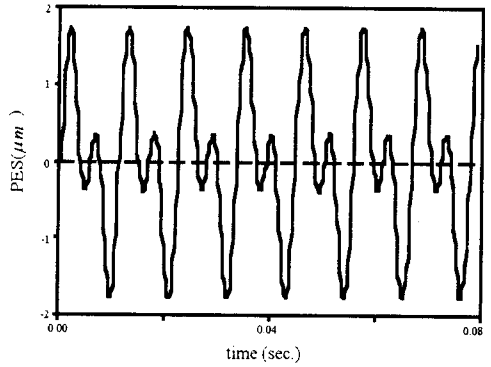

Fig. 3 Nominal position error signal

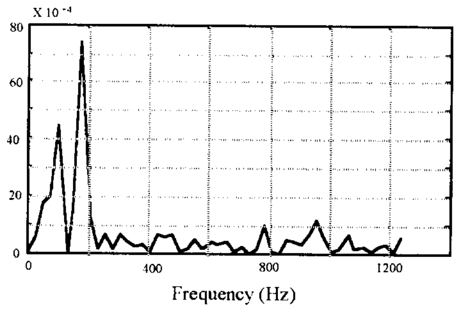

Fig. 4 Nominal PES power spectrum

rms_error = 0.1240, and Fig. 6 shows the power spectrum of PES. In Fig. 6, the repeatable runout at harmonics of 90 Hz and 180 Hz still exists, although the amplitudes are reasonably attenuated.

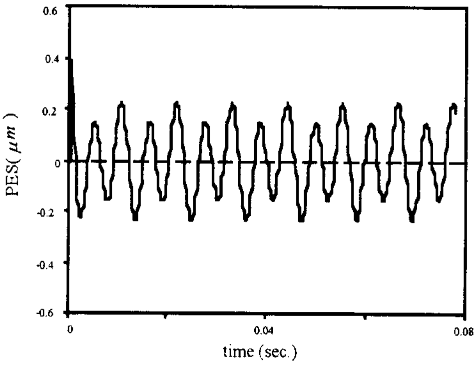

Fig. 5 PES with lead-lag compensator

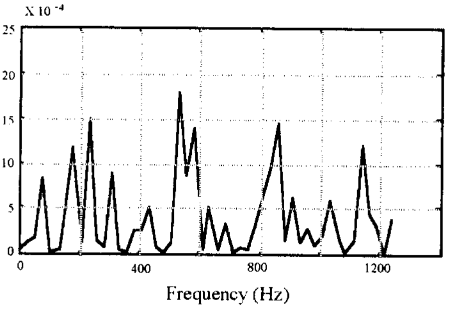

Fig. 6 Normalized power spectrum of PES with lead-lag compensator

The system enhanced by the feedforward disturbance rejection controller is given in Figs. 7~8. The simulation result presents that the rms error (rms_error = 0.0637) is reduced to about 50% compared to the nonpreview control system.

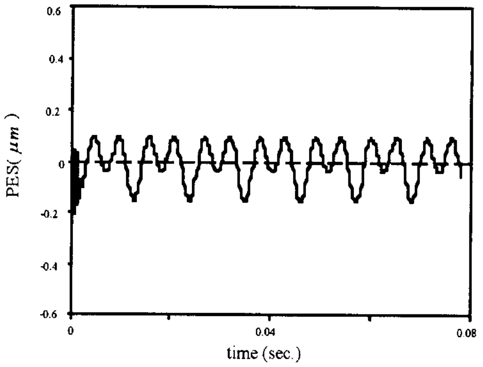

Fig. 7 PES with preview control

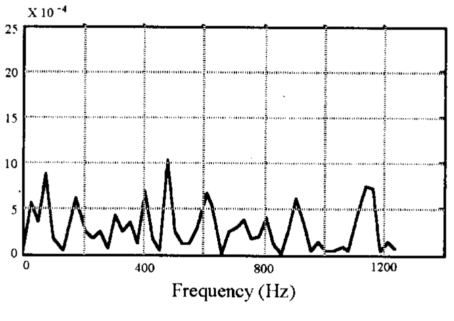

Fig. 8 Normalized power spectrum of PES with preview control

In Fig. 7, the first and second harmonics are greatly attenuated, and the amount of amplification has been reduced considerably. The preview controller reduces all multiples of the fundamental frequency of rotation in the disk drive. Figure 8 shows the PES spectrum controlled by the preview control algorithm. The power spectrum of the enhanced system, when compared to that of the nominal system, also shows strong attenuation of the disturbance at the fundamental and harmonic frequencies.

5. CONCLUSION

This paper has demonstrated the usefulness of a feedforward disturbance rejection controller in commercial hard disk drives. In high density disk drives, the effect of repeatable runout is more prominent, and the repetitive disturbances cannot be easily removed using conventional control methods. The preview control algorithm is investigated for reducing the effect of periodic disturbances. The disturbance rejection capabilities of the proposed control system are well suited for high density disk drives which experience repetitive disturbances. The control scheme overcomes the drawback of conventional control methods, and its performance is evaluated by simulations. The addition of a preview term to the conventional feedback control can improve the response of the hard disk drive system to disturbances drastically, such that the position error reduces by a factor of approximately two. The results of this paper significantly enhance the ability of the control engineer to design and analyze preview control algorithm for a variety of applications where periodic disturbances are encountered. Also, further work toward actual experiments is under development.

REFERENCES

(1) Chew, K. and Tomizuka, M., "Digital Control of Repetitive Errors in Disk Drive Systems," IEEE Control Systems Magazine, pp. 16~19, Jan. 1990.

(2) Guo, L. and Tomizuka, M., "High-Speed and High-Precision Motion Control with an Optimal Hybrid Feedforward Controller," IEEE/ASME Trans. On Mechatronics, Vol. 2, No. 2, pp. 110~122, June 1997.

(3) Franklin, G., Powell, J., and Workman, M., Digital Control of Dynamic Systems, 2nd. Ed., Reading, MA: Addison-Wesley, 1990.

(4) Kempf, C., Messner, W., Tomizuka, M., and Horowitz, R., "Comparison of Four Discrete-Time Repetitive Control Algorithms," IEEE Control Systems, pp. 48~54, Dec. 1993.

(5) Matsukawa, S., Yoshiura, T., Wakabayashi, N., and Tanimura, T., "An Advanced Sector Servo Using a Learning, Estimating and Over-Sampling Method for a 3.5″ 28MByte FDD," IEEE Trans. On Magnetics, Vol. 27, No. 6, pp. 4484~4489, Nov. 1991.

(6) Otten, G., de Vries, T., Amerongen, J., Rankers, A., and Gaal, E., "Linear Motor Motion Control Using a Learning Feedforward Controller," IEEE/ASME Trans. On Mechatronics, Vol. 2, No. 3, pp. 179~186, Sep. 1997.

(7) Sacks, A., Bodson, M., and Messner, W., "Advanced Methods for Repeatable Runout Compensation," IEEE Trans. On Magnetics, Vol. 31, No. 2, pp. 1031~1036, Mar. 1995.

(8) Sacks, A., Bodson, M., and Khosla, P., "Experimental Results of Adaptive Periodic Disturbance Cancellation in a High Performance Magnetic Disk Drive," ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 118, pp. 416~424, Sep. 1996.

(9) Yong, B., "Preview Control For Edge-Following Using Robot Force Control," Journal of the Korean Society Machine Tool Engineers, Vol. 8, No. 1, pp. 100~111, Feb. 1999.