Frequency Adaptive Control Technique for Periodic Runout and Wobble Cancellation in Optical Disk Drives

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ABSTRACT

Periodic disturbance occurs in various applications on the control of the rotational mechanical systems. For optical disk drives, the spirally shaped tracks are usually not perfectly circular and the assembly of the disk and spindle motor is unavoidably eccentric. The resulting periodic disturbance is, therefore, synchronous with the disk rotation, and becomes particularly noticeable for the track following and focusing servo system. This paper applies a novel adaptive controller, namely Frequency Adaptive Control Technique (FACT), for rejecting the periodic runout and wobble effects in the optical disk drive with dual actuators. The control objective is to attenuate adaptively the specific frequency contents of periodic disturbances without amplifying its rest harmonics. FACT is implemented in a plug-in manner and provides a suitable framework for periodic disturbance rejection in the cases where the fundamental frequencies of the disturbance are alterable. It is shown that the convergence property of parameters in the proposed adaptive algorithm is exponentially stable. It is applicable to both the spindle modes of constant linear velocity (CLV) and constant angular velocity (CAV) for various operation speeds. The experiments showed that the proposed FACT has successful improvement on the tracking and focusing performance of the CD-ROM, and is extended to various compact disk drives.

Keywords: Frequency Adaptive Control Technique, Optical Disk Drives, Disk Runout Control, Disk Wobble Control.

1. INTRODUCTION

In many tracking control problems (e.g., robot arms, rotating machinery), a desired output or disturbance input includes periodic signals with a known period. As a result, the system outputs typically involve periodic errors with the same period. The terms "periodic compensation", "repeatable control" and "iterative learning" are often used to describe specialized control algorithms designed to cancel errors which are periodic in time. Specifically, the repetitive control system is a servo system that achieves zero steady-state tracking error for periodic desired outputs and periodic disturbance inputs with a fixed period. The repetitive control scheme was first proposed by Inoue [1] and then there are several methods developed to eliminate periodic disturbances. For example, Cong [2] and Yamada [3] proposed repetitive control systems for DC servomotor applications. Lam [4] utilized the iterative learning control to reduce the speed ripple in permanent magnet (PM) synchronous motor. Especially for cancellation of repeatable runout in disk drives, repetitive controllers and adaptive feedforward cancellation schemes have been applied.

In optical disk drives, the disk runout and wobble effects introduce periodic disturbances with sinusoidal behavior [5, 6]. It causes the deviation on position error at the same frequencies for track-following, focusing, and seeking servo systems. In addition, not only the harmonics but a valuable DC content disturbance exists in track-following and focusing systems because of their special mechanisms used in optical disk drives. DC content is a critical factor in servo performances because it determines the deviation error. Although, there are many ingenious methods to deal with periodic disturbance, the manipulation of DC content was not addressed.

This paper applies a novel adaptive controller, namely frequency adaptive control technique (FACT) [7, 8], for rejecting the periodic runout cancellation for both the CAV and CLV spindle modes of the ODD with multiple playing speeds. The experimental results show that the FACT can remarkably reduce the errors in track-following and focus systems.

2. POSITIONING SERVO SYSTEM

The positioning system consists of track-following and focusing systems. Feedback signals from pick-up head are used to adjust mechanically the position the lens in the horizontal and vertical direction movement, respectively. The focusing servo output the control signal to force the focusing voice coil motors (VCM) in vertical movement while the tracking servo output the signal to the tracking VCM in horizontal direction. The pick-up head assembly sits on a sled and is moved

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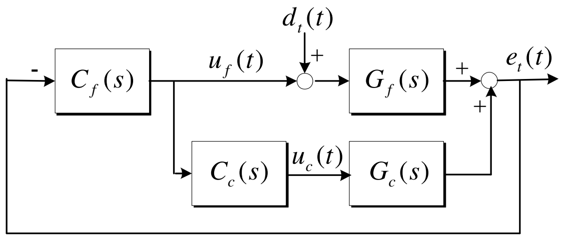

Figure 1: The block diagram of track-following.

by sled motor in horizontal to travel the whole range of the disk surface. Moreover, the disk is clamped on spindle motor and its speed is controlled by CLV or/and CAV control loops.

Track-following Servo System

During the track-following, as shown in Figure 1, the fine actuator directs the lens moving in radial direction to follow the vibrating track. where the transfer functions of fine and coarse actuators are denoted as $G_f(s)$ and $G_c(s)$, while the variables $u_f(t)$ and $u_c(t)$ are the control inputs to $G_f(s)$ and $G_c(s)$, respectively. The difference between track position and spot position is detected by optical devices and fed to track-following controllers via a constant gain which generally very high. Neither track position nor spot position is available and only the TES, off-track error multiplied by a constant gain, is measurable. Owing to the spiral-shaped track, the displacement of the fine actuator increased as the track-following function carried out continuously. The increasing offset displacement will cause the fine dynamics to be nonlinear and the system performances decreased apparently. To get rid of this situation, the coarse actuator will move the sled slowly as the offset displacement larger than a given threshold, so that the lens always has a narrow displacement and the linearity can be reserved. In this way, the actuators possess different dynamic characteristics. The position of the lens and that of the sled determine the laser spot position, thereby forming a multi-input single-output servo system.

The response of $e_t(t)$ to disturbance signal $d_t(t)$ can be expressed as

$$\frac{e_t}{d_t} = \frac{G_f(s)}{1 + G_f(s)C_f(s) + G_c(s)C_c(s)C_f(s)} \tag{1}$$

Since the bandwidth of the coarse actuator is much smaller than the frequencies of the runout disturbance, only the closed loop dynamic of fine actuator is needed to describe the system performances in track-following process. Hence, Eq. (1) can be simplified as

$$\frac{e_t}{d_t} \equiv \frac{G_f(s)}{1 + G_f(s)C_f(s)} \tag{2}$$

Since the disk runout is the most significate disturbance source and synchronizes with the disk rotation, the TES will have significant excitations at the frequency of disk rotation and its higher harmonics.

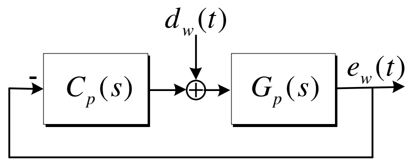

Figure 2: The block diagram of focusing system.

One major problem of the conventional track-following scheme is the disturbance caused by disk runout. The runout results in a low frequency input and has effects both on fine and coarse dynamics. In order to overcome such disturbance, the compensator $C_f(s)$ is designed such that the magnitude of $|G_f(s)C_f(s)|$ within the low frequencies is limited, or else the coarse actuator will be excited by runout disturbance. Widely applied to the consumer ODD, $C_f(s)$ is designed by a parallel type lead-lag compensator where the DC gain always has a finite limit.

Focusing Servo System

The focusing servo uses the reflection from the main laser beam to detect and correct FES, and maintain the laser spot on the disk within its suitable range of focus as shown in Figure 2. The transfer function of the vertical VCM and the stabilizing controller are denoted as $G_p(s)$ and $C_p(s)$, respectively, and the disk wobble effect is depicted as $d_w(t)$. The response of focusing error $e_w(t)$ to the disturbance $d_w(t)$ can then be expressed as

$$\frac{e_w}{d_w} = \frac{G_p(s)}{1 + G_p(s)C_p(s)} \tag{3}$$

It is clear that the compensator $C_p(s)$ can be designed so that the system is stable and $\|e_w(t)\|_\infty$ is bounded in a suitable ranges. To simplify the design of system, however, the compensator $C_p(s)$ can use the same architecture of the track-following compensator but the parameters are replaced for the focus system. With this scheme, two compensators $C_f(s)$ and $C_p(s)$ can be fully implemented by executing the same program in a digital signal processor (DSP). This manner is suitable to a system-on-a-chip (SOC) design for the ODD servo chip. Therefore, similar to track-following servo, it must be kept in mind that the open-loop $G_p(s)C_p(s)$ has a finite DC gain and that the DC component in focusing error can not be minimized exhaustively.

On the other hand, the free position of the lens cannot guarantee to be a suitable position to initiate the focusing system, additional process to search an appropriate initiating point is necessary for ODD focusing servo system. As a result, the free position always differs from that of focusing point when the focusing system functions properly. This implies that there exists a constant bias force to pull the lens to the free position constantly because of the extension or compression in the vertical spring that holds the lens within a limited stroke. Hence, the FES always contains a significant DC content due to a constant

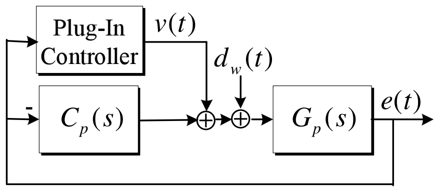

Figure 3: The plug-in wobble cancellation controller.

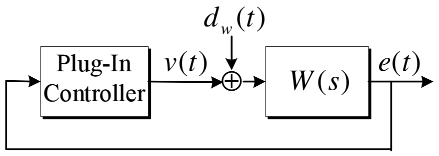

Figure 4: The equivalent plug-in cancellation scheme of Figure 3.

external spring force. Being a finite DC gain in focus servo loop, the constituents of FES include not only the harmonic contents introduced by the disk wobble, but also the valuable DC component.

3. FACT CONTROLLER

The plug-in FACT controller was designed to minimize the error signals in the track-following and focusing systems According to Eq. (2) and Eq. (3), the system dynamics relating the periodic disturbance and the system errors for the focusing and the track-following systems are shown to fall into the same form as

$$\frac{e}{d} = \frac{G(s)}{1 + G(s)C(s)} \tag{4}$$

where $G(s)$ represents the plant dynamic and $C(s)$ denotes the feedback controller. Without loss of generality, the plug-in cancellation for disk wobble effects on the focusing servo system is demonstrated; and the conclusions in the track-following system are straightforward. As shown in Figure 3, the plant $G_p(s)$ contaminated by the disturbance $d_w(t)$ is controlled by the feedback controller $C_p(s)$ as well as the compensation $v(t)$ through the plug-in controller, wherein $C_p(s)$ is designed independently of the plug-in controller and $G_p(s)$ is modeled as a linear time-invariant system. The DC component of $d_w(t)$ causes the plant output having a corresponding constant steady state error, and the sinusoidal disturbances cause the output having the significant excitation of harmonics. Denoting that the transfer function from $v(t)$ to $e(t)$ is expressed as

$$\frac{e}{v} = \frac{G_p(s)}{1 + G_p(s)C_p(s)} = W(s), \tag{5}$$

the equivalent scheme of Figure 3 can be expressed in Figure 4, where the block diagram of FACT for a single frequency at ω_n is shown in Figure 5.

Periodic Cancellation Scheme of FACT

Let the periodic error $e(t)$ be given by the M order sinusoidal functions with fundamental frequency ω_1,

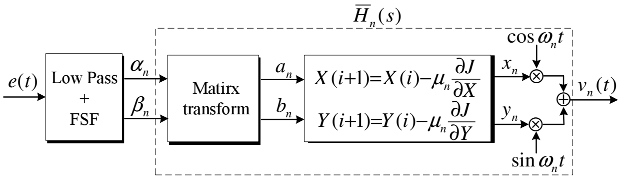

Figure 5: The block representation of the nth bank FACT.

i.e.,

$$e(t) = \sum_{n=0}^{M} (a_n \cos\omega_n t + b_n \sin\omega_n t) \tag{6}$$

where $\omega_n = n\omega_1$, and a_n and b_n are unknown variables. Operated by the frequency sampling filter (FSF), the n'th output responding to $e(t)$ is defined by

$$\xi_n(t) = \frac{N}{2}(\alpha_n + j\beta_n) \tag{7}$$

where N is the number of samples in a fundamental period of $e(t)$ and has a minimum value of $2M+2$. It was shown that the parameters a_n and b_n in Eq. (6) can be identified as

$$\begin{cases} a_n = \alpha_n \cos\omega_n t + \beta_n \sin\omega_n t \\ b_n = \alpha_n \sin\omega_n t - \beta_n \cos\omega_n t \end{cases} \tag{8}$$

By defining the output $v(t)$ as

$$v(t) = \sum_{n=0}^{M} v_n(t) = \sum_{n=0}^{M} (x_n \cos\omega_n t + y_n \sin\omega_n t) \tag{9}$$

and the total energy J of $e(t)$ as

$$J = \sum_{i=0}^{M} J_i = \sum_{i=0}^{M} \frac{1}{2}(a_i^2 + b_i^2) = \frac{1}{2}(\mathbf{A}^T\mathbf{A} + \mathbf{B}^T\mathbf{B}) \tag{10}$$

the adaptation law of x_n and y_n that are used to reduce the energy J can be formulated as

$$\begin{cases} \dot{x}_n &= -\mu_n[W_r(\omega_n)a_n + W_i(\omega_n)b_n] \\ \dot{y}_n &= -\mu_n[-W_i(\omega_n)a_n + W_r(\omega_n)b_n] \end{cases} \tag{11}$$

where $W_r(\omega_n)$ and $W_i(\omega_n)$ are the real and imaginary parts of $W(s)$ at $s = j\omega_n$, respectively. Since the adaptation rate is faster than twice the highest harmonic frequency, i.e.,

$$N\omega_1 \geq (2M+2)\omega_1 = 2(\omega_M + \omega_1) > 2\omega_M \tag{12}$$

it is sufficient to approximate the adaptation law in Eq. (11) with a backward Euler method as

$$\begin{cases} x_n(i+1) &= x_n(i) - \mu_n[W_r(\omega_n)a_n + W_i(\omega_n)b_n] \\ y_n(i+1) &= y_n(i) - \mu_n[-W_i(\omega_n)a_n + W_r(\omega_n)b_n] \end{cases} \tag{13}$$

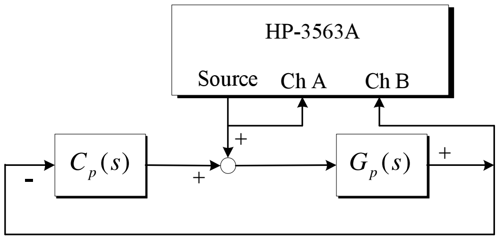

Figure 6: The frequency response measurement setup for plant $W(s)$ in Figure 4.

Stability and Convergence of FACT

In steady-state condition, the input-output relationship of the algorithm in Fig. 5 was shown to be equivalent to the following linear time-invariant (LTI) controller [9],

$$\frac{v(s)}{e(s)} = \sum_{n=0}^{M} \mu_n \frac{W_r(\omega_n)s - W_i(\omega_n)\omega_n}{s^2 + \omega_n^2} \tag{14}$$

The controller includes M pairs of poles at $\pm j\omega_n$ to achieve runout rejection by guaranteeing an infinite loop-gain at the frequencies of runout disturbance. By choosing an approximated LTI zero-order holder $Z_o(s)$ as

$$Z_o(s) = \frac{2N\omega_1}{s + 2N\omega_1} \tag{15}$$

and defining the variables $W_A(\omega_n)$ and $W_B(\omega_n)$ as, respectively, the real and imaginary parts of $Z_o(s)W(s)$ at ω_n, the upper limit of μ_n's in Eq. (13) can be determined analytically as

$$\mu_n = \frac{\omega_p^2 - \omega_n^2}{2\pi N\omega_1 \left|Z_o(j\omega_p)W(j\omega_p)\right| \sqrt{W_A^2(\omega_n)\omega_p^2 + W_B^2(\omega_n)\omega_n^2}} \tag{16}$$

where ω_p is the frequency such that

$$\arg\left[Z_o(j\omega_p)W(j\omega_p)\right] = -90^\circ \tag{17}$$

Furthermore, it is also shown that the overall system is stable and the feedforward gains x_n and y_n in Eq. (9) converge exponentially if the adaptation gain μ_n is less than the value given in Eq. (16).

4. EXPERIMENTAL IMPLEMENTATION AND RESULTS

The experimental system used for implementation consists of a commercial high-speed CD-ROM drive and an Field Programmable Gate Array (FPGA) device [10]. Besides the controllers $C_p(s)$, $C_f(s)$ and $C_c(s)$, the proposed FACT algorithms and additional interfacing signals are implemented digitally into the FPGA chip. Figure 6 shows the setup for the identification of parameters of $W_r(\omega_n)$ and $W_i(\omega_n)$ that are used in the implementation of FACT. The experimental disks are standard testing disks with $1 \pm 0.05mm$ in vertical deviation in focusing system and $140\mu m$ runout in track-following system. When the disk is running at CAV-16X (4,500rpm) and CAV-24X (6,780rpm), Figure 7 shows their results in focus servo system while Figure 8 shows the corresponding results in track-following servo system. It is seen that the amplitude of FES and TES can be reduced significantly. When the disk speeds up to a higher CAV speed with the same feedback controller as that in CAV-16X case, the track-following system fails when the disk speeds up to CAV-24X . As the FACT is applied, however, the disk can be speed up to CAV-24X and CAV-32X (8,940rpm) and the track-following system performs successfully, as shown in Figure 9.

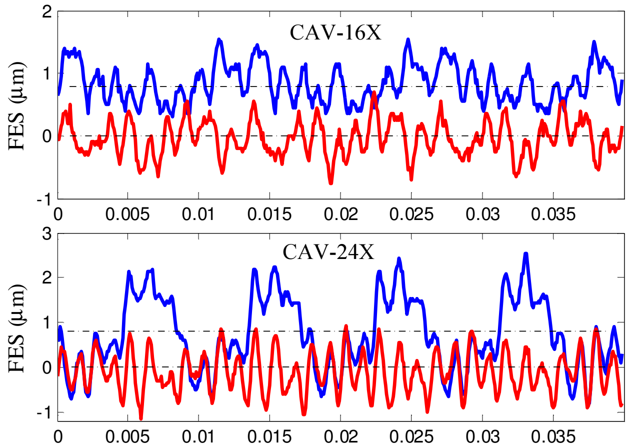

Figure 7: The experimental results for CAV-16X and CAV-24X without (blue) and with (red) FACT function.

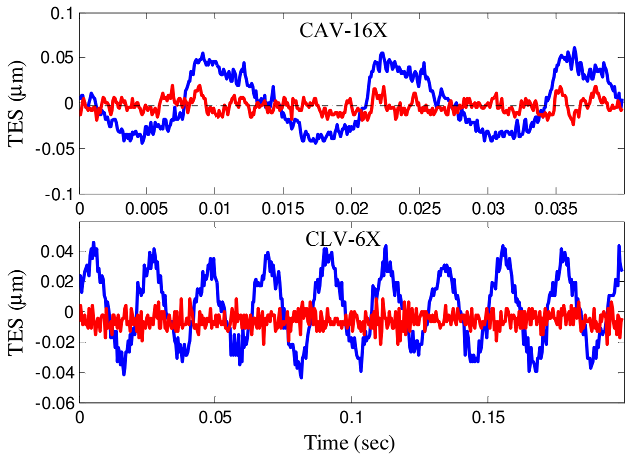

Figure 8: The experimental results for CAV-16X and CLV-6X without (blue) and with (red) FACT function.

5. CONCLUSION

A novel frequency adaptive control technique is examined on a optical disk drive. The experiments are conducted on a high speed commercial CD-ROM drive with an FPGA-based development system. The experimental results show that the periodic harmonics in track-following and focus systems can be rejected simultaneously and efficiently for both CAV and CLV

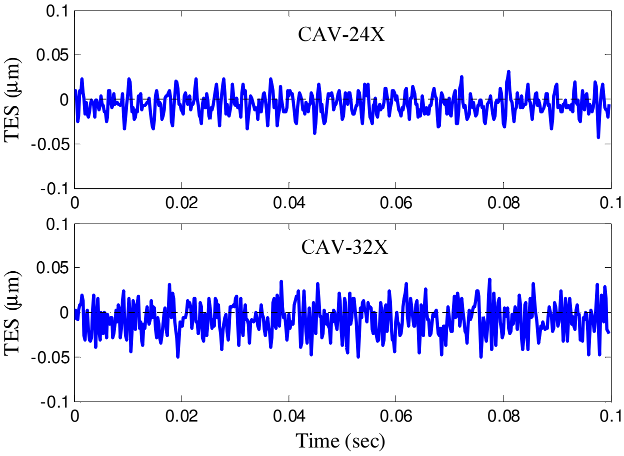

Figure 9: The experimental results for CAV-24X and CAV-32X with FACT function.

spindle modes under variable playing speed. Successful reduction in the harmonics and DC content verifies that the FACT is promising in the application of industrial ODD systems, especially for disk runout and wobble compensation.

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