Improving the Disturbance Resistance of Magnetic Disk Drives by Using Anti-Windup and Model Following Controls with Initial Value Compensation*

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We have developed a magnetic head positioning control method of a hard disk drive under conditions of variable parameters and disturbances. It consists of model following control for feedforward compensation and anti-windup control for feedback compensation. By using anti-windup control for a feedback controller, slow and large transient responses near the target position are avoided and the actuator settles more quickly on the target position.

Key Words: Positioning, Servo Mechanism, Nonlinear Control, Hard Disk Drives, Two Degrees of Freedom Control

1. Introduction

Magnetic recording density of hard disk drives has increased by more than 60% every year in recent times. To maintain this level of improvement in the operation of disk drives, researchers are developing various technologies in the fields of magnetic heads, disks, data processing, interfaces, head disk assembly mechanisms, tribology, and servo control. Improved servo control requires moving the read-write head as quickly as possible and positioning it precisely on a desired track. To shorten the time to access a target position, we have developed a mode switching control system which has several servo modes designed for a specific purpose. These servo modes consist of a track seeking, a settling, and a following modes. The controller in the track seeking mode is designed for fast

access, the settling controller for fast transient response with less overshoot, and the track following controller for accurate positioning. When each control mode starts, the controller state variables are reset in order to improve the transient characteristics^{(1),(2)}.

But if the head actuator is disturbed by external forces⁽³⁾ or the like, while accessing a target position, the head does not settle on the target position but is slightly offset, increasing the time it takes to access the target position. This offset occurs because the settling controller does not suppress disturbances as well as the track following controller does. Our control system uses feedforward compensation to generate a control input signal and the target position trajectory from a closed loop model. The closed loop model consists of a settling controller and a plant model. At the end of the track seeking mode, the state variables of the settling controller are reset to cancel the undesired poles. The difference between the desired trajectory and the actual position is suppressed by the track following controller, which uses an integrator to suppress disturbance in the low frequency region. If the parameters of the plant model

* Received 15th November, 1999

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differ from those of an actual one, however, the following error becomes large and the integrator generates a large and slow transient response after mode switching. This problem is solved by using an anti-windup control⁽⁴⁾ in the track following controller. The transient characteristics of the track seeking in a hard disk drive are simulated and measured. The results confirm that the combination of anti-windup control and feedforward result in fast and precise head positioning under conditions of variable plant parameters and disturbances.

2. Mode Switching Control and Head Positioning Servo Systems

2.1 Head positioning mechanism and its model

Figure 1 shows a basic schematic diagram of a hard disk drive. In normal operation, several disks are stacked on the spindle motor shaft and rotate. Each disk surface has thousands of data tracks. Magnetic heads are mounted on the disk surfaces, several micro inches apart, and supported by the carriage and head suspensions. The voice coil motor (VCM) actuates the carriage and moves the heads to a desired track. The plant mechanism, which is the object to be controlled, consists of the VCM carriage, the suspension, and the heads. One of the features of the magnetic head positioning system is the method of detecting the head position. The position signals are written at the beginning of every data sector and a selected head detects the signals at a certain sampling period. Hence, the controlled variable is the difference between the head position and the target track written on the disk surfaces. The electronics for servo control comprise a position decoding circuit, a microprocessor to execute the digital servo algorithms, A/D converters, a D/A converter, and a power amplifier. The input for the object to be controlled is the analog command voltage for the power amplifier. The state equation of the controlled object is modeled as follows.

$$\begin{aligned}\dot{X}_p(t) &= A \cdot X_p(t) + B \cdot u(t) \\ y(t) &= C \cdot X_p(t)\end{aligned}\quad (1)$$

Fig. 1 Basic schematic of a hard disk drive

where u : control input, y : head position.

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k_p}{m} & -\frac{d_p}{m} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{k_1}{m} \end{bmatrix}, C = [k_2 \ 0]$$

$$X_p = \begin{bmatrix} pos \\ vel \end{bmatrix}$$

where k_1 comprises the gain of the power amplifier, the force constant of VCM and k_2 is the position detected gain. The symbol m is the equivalent mass at a head position, d_p is the viscous constant, and k_p is the spring constant.

2.2 Mode switching control^{(1),(2)}

Figure 2(a) is a basic schematic diagram showing how switching between the track seeking and the track following modes is controlled. Sometimes a settling mode for smooth settlement near a target track center is added. Each servo mode is designed to satisfy a certain cost function independently and is switched under a certain condition. This mode switching control is a kind of the variable structure control system, but the switching is only in one direction.

One example of the track seeking mode is the two

(a) Block diagram of mode switching control

(b) Block diagram of track seeking mode

(c) Block diagram of settling and track following modes

Fig. 2 Basic schematic diagrams of mode switching control

degrees of freedom control shown in Fig. 2(b), where $K(z)$ is a transfer function of a controller. During acceleration, the power amplifier is saturated and the maximum current drives the VCM. During deceleration, a reference velocity trajectory and feedforward acceleration trajectory are generated as a function of the position error, and the velocity servo is controlled within the linear part of the power amplifier.

Examples of the settling and track following modes in the unity output feedback loop with a controller are shown in Fig. 2(c). In the settling mode, the controller consists of a phase compensator, such as a lead filter, band elimination filters (notch filters), and a low-pass filter. In the track following mode, a pseudo integral element to improve steady state error is added when the phase compensator is used.

To improve the transient response after switching to the next control mode, a method for designing the initial values of controller state variables has been developed. The settling and track following controllers operate as a stable single input/output system. The formulae are described in the discrete time domain. The state equations of the controller and the plant are represented as

$$X_p(k+1) = A_p \cdot X_p(k) + B_p \cdot u(k) \quad (2)$$

$$y(k) = C_p \cdot X_p(k)$$

$$X_c(k+1) = A_c \cdot X_c(k) + B_c(r(k) - y(k)) \quad (3)$$

$$u(k) = C_c \cdot X_c(k) + D_c(r(k) - y(k))$$

where X_p is an m th-order state vector of the plant, X_c is an n th-order state vector of the controller, u is a control input to the plant, r is a reference, y is a controlled variable (that is, a head position), and A_p , B_p , C_p , A_c , B_c , C_c , and D_c are the real matrices $m \times m$, $m \times 1$, $1 \times m$, $n \times n$, $n \times 1$, $1 \times n$, and 1×1 , respectively. The expression $k=0$ means a time at mode switching, and r is equal to zero since r is the center of the target track.

The z -transform solution to Eqs. (2) and (3) with the nonzero initial conditions $X_p(0)$ and $X_c(0)$ is

$$y(z) = \frac{N_p(z)}{D(z)} X_p(0) + \frac{N_c(z)}{D(z)} X_c(0) \quad (4)$$

where $D(z)$ is a scalar z polynomial equation, $N_p(z)$ is a $1 \times m$ polynomial matrix, and $N_c(z)$ is a $1 \times n$ polynomial matrix. When the $n \times m$ real coefficient matrix K is introduced, the initial values of the controller state variables can be given as

$$X_c(0) = K \cdot X_p(0) \quad (5)$$

Substituting Eq. (5) into Eq. (4) gives

$$y(z) = \frac{N_p(z) + N_c(z) \cdot K}{D(z)} X_p(0) \quad (6)$$

Equation (6) shows that the zeros of the transfer function from $X_p(0)$ to $y(z)$ can be shifted to the desired values by selecting the values of K . This suggests that the transient characteristics after mode

switching can be improved by shifting zeros in order to cancel undesired poles.

3. Model Following Control and Anti-Windup Control

3.1 Model following control with initial value compensation

To shorten the time to access a target position, we have developed a mode switching control system, which consists of track seeking, settling, and track following modes, for positioning the heads of disk drives and initial value compensation for improving the transient characteristics after mode switching. But when the head actuator is disturbed while moving to a target position by an external force or the like, the head does not settle on the target position but is slightly offset from the target, therefore, access time increases. This offset occurs because the settling controller does not suppress disturbance as well as the track following controller does in the low-frequency region below about 100 Hz. We develop a new track following mode which, compared with conventional track following mode, settles more quickly on a target track and suppresses disturbance better than the current settling mode does.

The new track following mode uses model following control for feedforward compensation and anti-windup control for feedback compensation. Figure 3 shows the block diagram of the new mode. After the mode begins operating at the end of the track seeking mode, the feedforward compensator generates the control input u_0 and the target position trajectory y_0 from a closed loop model. The closed loop model consists of the settling controller $C(z)$ and the plant model $P_0(z)$. The plant model $P_0(z)$ is set with the same state variables as the actual plant $P(s)$ at the end of the track seeking mode and acts like the actual plant. The state variables of the settling controller are set to cancel the undesired poles of the closed loop model after mode switching. With the feedforward input u_0 , the actual position settles on the target more quickly and with less overshoot than previous following

Fig. 3 Model following control system with initial value compensation

Fig. 4 Anti-windup control applied to the integrator part of a track following controller

mode.

The formula representing the plant model $P_0(z)$ must be described in a discrete time domain. The plant transfer function is already described in Eq. (1). When describing the plant model in the discrete time domain, the delay in time from detecting a position to calculating the control input is taken into account. The plant model is described.

$$X_p(k+1) = \Phi \cdot X_p(k) + \Gamma_0 \cdot u(k) + \Gamma_1 \cdot u(k-1) \quad (7)$$

$$y(k) = C \cdot X_p(k)$$

where

$$\Phi = e^{A \cdot T_s}, \Gamma_0 = \int_0^{T_s-L} e^{A\tau} d\tau \cdot B,$$

$$\Gamma_1 = e^{A(T_s-L)} \cdot \int_0^L e^{A\tau} d\tau \cdot B$$

where T_s is the sampling period, and L is the time delay. The solution of Eq. (7) can be expressed in terms of u and y

$$y(k) = q_1 \cdot u(k-1) + q_2 \cdot u(k-2) + q_3 \cdot u(k-3) + p_1 \cdot y(k-1) + p_2 \cdot y(k-2) \quad (8)$$

The control input u given by three samplings and the detected position y given by two samplings therefore enable present position y to be predicted.

3.2 Anti-windup control for the following controller

Feedback compensation is executed by the track following controller $F(z)$, which consists of a lead filter and an integrator in parallel as shown in Fig. 4 (a). Figure 4(b) shows a block diagram of the anti-windup control⁽⁴⁾ used with the track following controller. The difference between desired trajectory y_0 and actual position y is suppressed by the track following controller $F(z)$. The track following controller needs an integrator to suppress disturbance in the low-frequency region, however if the parameters of the plant model differ from those actual plant and the following error is too large, the integrator generates a large and slow transient response after mode switching. This problem is solved by using an anti-windup control applied to the integrator part of a track fol-

Fig. 5 Illustration of controller windup⁽⁴⁾

(a) Track following mode when integrator is saturated

(b) Track following mode when integrator is in operation

Fig. 6 Schematic block diagram of track following mode

lowing controller.

Figure 5 shows the controller windup phenomenon⁽⁴⁾ when the controller contains an integrator. The response of each controller to rectangular input e is shown. Method 1 generates controller windup because it simply saturates the value computed from the controller. Method 2 is used to eliminate the windup. The denominator $D_i(z)$ polynomial in the controller must be monic.

The closed loop of the track following mode is described in Fig. 6. Figure 6(a) shows the mode when the integrator is saturated and only the lead filter operates. In this mode, the poles of the closed loop are $0.697 \pm 0.185i$, 0.580, -0.316. Figure 6(b) shows the mode when both the integrator and the lead filter operate. In this mode, the poles of the closed loop are 0.945, $0.732 \pm 0.167i$, 0.564, and -0.316. Therefore, adding an integrator has the effect of generating the pole of 0.945 which makes the transient response slowly. Figure 7 shows the frequency characteristics

Fig. 7 Bode diagram of the track following controller

of the track following controller. When the integrator is in operation, the controller gain in the low frequency region is higher than that of only the lead filter as shown in Fig. 7. The stability of the track following mode is maintained whether the integrator is saturated or not.

4. Simulation Results

To predict the effectiveness of the control method, the transient responses after the settling mode starts are simulated. The initial conditions of position, velocity, and acceleration are set. The sampling period is 132.3 μ s. The influence of modeling error on the transient characteristics depends upon the acceleration of the actuator. Since the settling mode starts before the acceleration decreases to zero, the error from the desired trajectory y_0 becomes large. Hence, anti-windup control is used for a few samplings after the settling mode starts.

Figure 8 shows the settling response when a force -10 mN acts on the head. Figure 8(a) shows model following control when anti-windup control is used with the track following controller. Figure 8(b) shows model following control without anti-windup control. Figure 8(c) shows conventional mode switching control of the settling and track following modes when the modes are switched 2 ms after the settling mode starts. The left column of Fig. 8 shows the head position errors in the distance from the target track ($PES = r - y$) when the head settles on a target track. The right column shows the integrator outputs u_i described in Fig. 4. The anti-windup control for the integrator is used for 10 samplings to limit the output within ± 16 counts after the settling mode starts. The integrator output compensates for the force which acts at the head. The effect of suppressing the force disturbance by the model following control is shown in Fig. 8(b). Comparing the

Fig. 8 Settling response when force (-10 mN) acts at the head

response shown in Fig. 8(a) with that shown in Fig. 8(b) indicates that, in terms of force disturbance, the anti-windup control does not degrade the performance of the model following control. As shown in Fig. 8(c), switching from settling mode to track following mode delays the settling onto the target track.

Figure 9 shows the settling response when the gain of the plant falls 5%. Figure 9(a) shows the model following control when anti-windup control is used with the track following controller. Figure 9(b) shows the model following control without anti-windup control. Figure 9(c) shows conventional mode switching control using the settling and track following modes when switching from settling to track following mode is executed 2 ms after the settling mode starts. The left column of Fig. 9 shows the head position errors in the distance from the target track ($PES = r - y$). The right column shows the integrator outputs u_i described in Fig. 4. Anti-windup control is used with the integrator for 10 samplings to limit the output within ± 16 counts as in Fig. 8(a). If there is gain variance in the plant, the control input calculated from the plant model shifts the head position from the desired position trajectory. The offset of the head position from the trajectory increases depending on the amount of gain variance; therefore, the large acceleration during the early period after the track seeking mode ends causes a large deflection of the

Fig. 9 Settling response when the loop gain falls 5%

settling response. As shown in Fig. 9 (a), when anti-windup control is used, the integrator is saturated and the error from the desired trajectory y_0 is suppressed more quickly by the lead filter. As shown in Fig. 9 (b), the model following control without anti-windup control results in a large following error that originates in the slow closed loop pole caused by the integrator. A comparison of the response shown in Fig. 9 (a) with that shown in Fig. 9(c) indicates that the performance of the model following control is as good as that of the settling control even though it has an integrator. Figures 8 and 9 indicate that the use of anti-windup control for a few samples after the settling mode starts should effectively suppress both gain variance and force disturbance in a real situation.

5. Experimental Results

A hard disk drive with 3.5 inch disks was used in experiments in which the head position was sampled every 132.3 μ s. The improvement of settling accuracy by using the model following and anti-windup controls can be evaluated from Fig. 10, which shows the envelope of the head position error including about two thousand of transient waveforms toward the target tracks given at random.

The waveforms of model following control with anti-windup control shown in Fig. 10(a) are less variable than those of model following control with-

Fig. 10 Transient response giving target tracks at random

out anti-windup control shown in Fig. 10(b) and those of conventional mode switching control shown in Fig. 10(c). These waveforms in Fig. 10 indicate that, as expected from the simulation results, model following control with anti-windup control is effective for suppressing both gain variance and force disturbance

6. Conclusion

Magnetic disk drives require both precise track following and fast track seeking capabilities. We have developed a control system to improve settling characteristics under conditions of variable parameters and disturbance. The feature of our control system is feedforward compensation generated from a closed loop model and anti-windup control applied to the integrator part of the track following controller. The transient characteristics of the track seeking in a hard disk drive are simulated. Our control system is superior to a conventional mode switching control under conditions of variable parameters and disturbance. Transient characteristics are measured by using a 3.5 inch hard disk drive. The results confirm that the combination of feedforward and anti-windup control realizes more precise head positioning compared to a conventional mode-switching control method.

Acknowledgments

The authors would like to thank Kazuhisa Shi-

shida, Yousuke Hamada, and Yuuji Hata for their cooperation in this study. They are members of the Data Storage & Retrieval Systems Division, Hitachi, Ltd.

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