METHOD AND APPARATUS FOR ADAPTIVE FEEDFORWARD CANCELLATION

REFERENCE TO RELATED APPLICATIONS

The present application claims priority from a United States Provisional Patent Application having serial No. 60/116,071 filed on January 15, 1999 and entitled IMPROVED ADAPTIVE FEEDFORWARD CANCELLATION.

FIELD OF THE INVENTION

The present invention is related to disc drives. In particular, the present invention is related to repeatable runout compensation.

BACKGROUND OF THE INVENTION

In a computer disc drive, data is stored on a computer disc in concentric tracks. In disc drives with relatively high track densities, a servo feedback loop is used to maintain a head over the desired track during read or write operations. This is accomplished by utilizing prerecorded servo information either on a dedicated servo disc or on angularly spaced sectors that are interspersed among the data on a disc. During track following, the servo information sensed by the head is demodulated to generate a position error signal (PES), which provides an indication of the position error of the head away from the track center. The PES is then converted into an actuator control signal, which is fed back to control an actuator that positions the head.

In general, there are two forms of head positioning errors: repeatable and non-repeatable. Non-repeatable errors are generally unpredictable and therefore can not be removed until after they occur. Repeatable errors, which are generally caused by mechanical irregularities in the structure of the disc drive or errors introduced when writing the servo tracks, can be predicted and therefore theoretically can be cancelled out as they occur. In general, these repeatable runout errors (RRO) are

The cancellation signal includes at least one tap weight multiplied by at least one trigonometric function. To form the cancellation signal, the method and apparatus first determine a servo loop transfer function relative to a feedforward cancellation component in the disc drive. The transfer function is then inverted to form filter parameters. A position error value is then measured for a current signal and is passed through a filter formed from the filter parameters. This creates a filtered position error value that is used with the tap weights of a current sector to determine the tap weights for the cancellation signal of the next sector.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a disc drive in which aspects of the present invention may be practiced.

FIG. 2 is a prior art servo loop with an adaptive feedforward cancellation system.

FIG. 3 is a top view of a disc showing a sector layout used in the present invention.

FIG. 4 is a frequency spectrum of a position error signal.

FIG. 5 is a simplified block diagram of a servo loop with adaptive feedforward cancellation.

FIG. 6 is a block diagram of a servo loop with an adaptive feedforward cancellation system of the present invention.

FIG. 7 is a block diagram of the filter of FIG. 6.

FIG. 8 is a flow diagram of a method of adaptive feedforward cancellation under the present invention.

FIG. 9 is a graph of a position error signal at the fundamental frequency using the cancellation techniques of the prior art.

FIG. 10 is a graph of a position error signal at the fundamental frequency using the cancellation techniques of the present invention.

disc. Based on the reference signal, digital controller 204 generates a digital control value that passes through a cancellation summing node 206 (described further below) and into digital-to-analog converter 208. The digital control value is converted into an analog current by digital-to-analog converter 208 and the analog current is amplified by a power amplifier 210 to produce an actuator control current. The actuator control current is provided to a voice coil motor in a head-disc assembly (HDA) 212 and causes the voice coil motor to move based on the magnitude and polarity of the current. As the voice coil motor moves, head-gimbal assemblies attached to the voice coil motor move across the disc thereby changing the positions of the heads relative to tracks on the disc.

Using servo patterns stored on the disc, a head generates an analog signal that indicates the distance from the head to the track center. The analog signal is provided to an analog-to-digital converter 214, which forms a digital signal from the analog signal. The digital signal is then combined with the reference signal to produce a position error signal (PES) that is fed back to controller 204. Controller 204 uses the position error signal to generate a new digital control value. In particular, controller 204 generates a digital value designed to bring the heads toward the desired track position.

In embedded servo systems, the servo information is stored in sectors along the data track. FIG. 3 provides a top view of a disc 300 showing servo sectors 302, 304, 306, 308, and 310 interspersed among data fields 312, 314, 316, 318, and 320 along a track 322. Note that FIG. 3 is not drawn to scale and that most discs have many more servo fields. For example, in one embodiment of the present invention, there are 120 servo fields per track.

Repeatable runout errors can be seen by examining the frequency spectrum of the position error signal measured over several rotations of the

Specifically, a sine and cosine term is added for each harmonic. This results in the generalized equation:

$$U(k) = \sum_{i=1}^{m} W_{i,k}^{\sin} X_{i,\sin}(k) + W_{i,k}^{\cos} X_{i,\cos}(k) \qquad \text{EQ. 6}$$

where:

$$X_{i,\sin}(k) = \sin\left[i \cdot k\left(2\pi/N\right)\right] \qquad \text{EQ. 7}$$

$$X_{i,\cos}(k) = \cos\left[i \cdot k\left(2\pi/N\right)\right] \qquad \text{EQ. 8}$$

and

$$W_{i,k+1}^{\sin} = W_{i,k}^{\sin} + C(k) \cdot PES(k) \cdot X_{i,\sin}(k) \qquad \text{EQ. 9}$$

$$W_{i,k+1}^{\cos} = W_{i,k}^{\cos} + C(k) \cdot PES(k) \cdot X_{i,\cos}(k) \qquad \text{EQ. 10}$$

In FIG. 2, the adaptive feedforward cancellation system 200 implements equations 6 through 10 using a microprocessor 220, a random access memory 222, and a sine and cosine table 224. Specifically, microprocessor 220 generates a set of new tap weights using the tap weights for the previous sector and the position error signal for the previous sector, which is taken from analog-to-digital converter 214. Microprocessor 220 multiplies the position error signal by the learning rate, which is stored in random access memory 222 and a sine or cosine function for the previous sector stored in sine and cosine table 224. Microprocessor 220 then multiplies each new tap weight by a respective sine or cosine value for the current sector stored in sine and cosine table 224.

The servo loop of FIG. 2 may be simplified by combining elements and assigning a single gain to the combined elements. An example of a simplified block diagram is shown in FIG. 5 where an actuator block 450 with a gain of P is shown in place of digital-to-analog component 208, power amplifier 210, head-disc assembly 212 and analog-to-digital converter 214. Controller 204 of FIG. 2 is shown as controller block 452 in

As mentioned above, ideally this transfer function is equal to one for all frequencies such that a change in the cancellation signal results in an equal change in the position error signal detected by AFC 450. However, in disc drives, this transfer function is rarely if ever equal to one and in many disc drives is highly frequency dependent. As such, the convergence of prior adaptive feedforward cancellation systems is less than ideal.

To overcome this problem, the present invention introduces a new filter between the returned position error signal and the adaptive feedforward cancellation system. The new filter changes the transfer function so that the transfer function approaches unity. FIG. 6 provides a block diagram of an embodiment of the present invention showing the new filter as filter 526, which has a gain of F.

In FIG. 6, the remainder of the servo loop 502 is similar to that of FIG. 2 and consists of a controller 504, summer 506, digital-to-analog converter 508, power amplifier 510, head-disc assembly 512, and analog-to-digital converter 514. The remainder of the adaptive feedforward cancellation system 500 is also similar to the system of FIG. 2 and includes a microprocessor 520, a Random Access Memory 522 and a sine and cosine table 524.

With the new filter, the transfer function detected by the AFC system becomes:

$$\frac{(PES)'}{U} = \frac{F(PES)}{U} = FG \qquad \text{EQ. 13}$$

where (PES)' is the PES signal provided to the AFC system by filter 526. Using Equation 13, the present invention forces the transfer function detected by the AFC system toward unity at all frequencies by setting the gain of filter 526 to the inverse of the transfer function G such that:

$$\frac{(PES)'}{U} = FG = \frac{1}{G}G = 1 \qquad \text{EQ. 14}$$

At step 704 the frequency response of the actuator (P) is combined with the closed-loop response of the servo system to produce the transfer function G such that:

$$G = P \cdot \frac{1}{1 + CP} \qquad \text{EQ. 16}$$

At step 706, the transfer function G is inverted and fit to real numerator and denominator coefficients to form the filter parameters (b_0, b_1, b_2, and a_0) of filter F. This can be achieved using control software such as MATLAB (available from Mathworks, Inc. of Natick, Massachusetts). Specifically, the 'invfreqz' function of MATLAB may be used.

In most embodiments, steps 700 through 706 are only performed once for each disc drive and thereafter the filter remains fixed.

Once the filter has been produced, track following can begin at step 708. As the head passes a servo index, an initial cancellation signal is produced at step 710 that has the form:

$$U(k+1) = \sum_{i=1}^{m} W_{i,k+1}^{\cos} \cos\left[i(k+1)(2\pi/N)\right] + \sum_{i=1}^{m} W_{i,k+1}^{\sin} \sin\left[i(k+1)(2\pi/N)\right] \qquad \text{EQ. 17}$$

where i represents the harmonic of the fundamental sector frequency, m is the total number of harmonics of interest, and $W_{i,k+1}^{\cos}$ and $W_{i,k+1}^{\sin}$ are harmonic specific adaptive tap weights that are initially set to zero.

At step 712, the position error signal produced for the first current sector (k) is passed through the F filter (526 in FIG. 6, 600 in FIG. 7) to produce a filtered PES value $\hat{y}$. This value is then used at step 714 to update the tap weights for the next sector (k+1) for all harmonics using the equations:

$$W_{i,k+1}^{\cos} = W_{i,k}^{\cos} + \mu \hat{y} \cos\left[i(k-1)(2\pi/N)\right] \qquad \text{EQ. 18}$$

$$W_{i,k+1}^{\sin} = W_{i,k}^{\sin} + \mu \hat{y} \sin\left[i(k-1)(2\pi/N)\right] \qquad \text{EQ. 19}$$

As can be seen from FIGS. 9 and 10, the prior art and the present invention cancel the fundamental frequency component in about the same amount of time.

FIGS. 11 and 12 show the cancellation effects of the prior art and present invention, respectively, with regard to the fourth harmonic of the position error signal. In FIGS. 11 and 12, the position error signal is shown along vertical axes 1000 and 1100 and time is shown along horizontal axes 1002, and 1102. To avoid instability, the prior art learning rate was limited to .001. However, as shown by FIG. 11, even at this maximum learning rate, the prior art is unable to fully cancel the fourth harmonic of the position error signal. In contrast, under the present invention, the same learning rate of .1 that was used for the fundamental frequency is used for the fourth harmonic. This results in a cancellation of the fourth harmonic in about the same amount of time that was required to cancel the fundamental frequency component using the present invention. Thus, the present invention improves the cancellation of higher frequency components of the repeatable runout and cancels all of the frequency components in about the same amount of time. Under one embodiment, all of the frequency components were nearly reduced to null within one revolution of the disc.

In summary, a method is provided for generating an adaptive feedforward cancellation signal, U, for a next sector 304 of a disc 300 in a disc drive 100. The cancellation signal includes at least one tap weight, $W_{i,k+1}^{\cos}$, multiplied by at least one trigonometric function, $\cos[i(k+1)(2\pi/N)]$. The method of generating the cancellation signal includes determining a servo loop transfer function, G, relative to a feedforward cancellation component 454 and inverting the transfer function to form filter parameters. A position error value is then measured at a current sector, k, and the position error value is passed through a filter 526 to create a

WHAT IS CLAIMED IS:

1. A method of generating an adaptive feedforward cancellation signal for a next sector of a disc in a disc drive, the cancellation signal comprising at least one tap weight multiplied by at least one trigonometric function, the method comprising steps of:

(a) determining a servo loop transfer function relative to a feedforward cancellation component in the disc drive;

(b) inverting the transfer function to form filter parameters;

(c) measuring a position error value at a current sector;

(d) passing the position error value through a filter formed from the filter parameters to create a filtered position error value; and

(e) determining the tap weight for the cancellation signal for the next sector based in part on the filtered position error value and a tap weight for the current sector.

2. The method of claim 1 wherein the servo loop comprises an actuator component having a transfer function of P that is capable of moving a head in response to a control signal and of generating a position error signal based on the position of the head, and wherein the servo loop further comprises a controller having a transfer function of C that is capable of generating a control signal based on a position error signal and wherein the step of determining a servo loop transfer function comprises determining a transfer function of the form $\frac{P}{1+CP}$.

3. The method of claim 1 wherein inverting the transfer function to form filter parameters comprises generating filter parameters for a filter function of $\hat{y} = b_0 PES(k) + b_1 PES(k-1) + b_2 PES(k-2) + a_0 \hat{y}_0$ where b_0, b_1, b_2, and a_0, are the filter parameters, PES(k) is a position error value for a current sector, PES(k-1) is a position error value for a preceding sector,

8. In a disc drive, a servo system for positioning a head over a track, the servo system comprising:

a controller capable of generating a control signal based in part on a position error signal generated by the head;

an actuator-head assembly comprising an actuator and the head and capable of moving the head based at least in part on the control signal from the controller and capable of generating the position error signal based on the position of the head over a track;

an adaptive feedforward cancellation component capable of receiving a filtered position error signal for a current sector and capable of producing a cancellation signal for a next sector based in part on the filtered position error signal, the cancellation signal being provided at an output of the cancellation component and comprising at least one tap weight multiplied by at least one trigonometric function; and

a filter receiving the position error signal at its input and producing the filtered position error signal that is provided to the adaptive feedforward cancellation component, the transfer function of the filter approaching the inverse of the transfer function measured from the output of the adaptive feedforward cancellation component to the input of the filter.

9. The servo system of claim 8 wherein the adaptive feedforward cancellation component produces a cancellation signal of the form $U(k+1) = W_{k+1}^{\cos} \cos[(k+1)(2\pi/N)] + W_{k+1}^{\sin} \sin[(k+1)(2\pi/N)]$ with $W_{k+1}^{\cos}$ and $W_{k+1}^{\sin}$ representing tap weights for the next sector k.

position error value for a second preceding sector, $\hat{y}_0$ is a filtered position error value for a preceding sector and $\hat{y}$ is a filtered position error value for the current sector.

14. The servo system of claim 9 wherein the controller has a transfer function of C, the actuator-head assembly has a transfer function of P and the transfer function of the filter approaches $\frac{1+CP}{P}$.

15. A disc drive for storing data in tracks along a disc, the disc drive comprising:

a servo loop for positioning a head relative to a track; and

adaptive feedforward cancellation means coupled to the servo loop for canceling repeatable runout positioning errors based on a filtered position error signal.