Description

Weighted Linearization of a Disc Drive Position Error Signal

Technical Field

This invention relates generally to the field of disc drive data storage devices, and more particularly, but not by way of limitation, to an apparatus and method for providing a linear position error signal in a disc drive through the weighting of selected combinations of servo burst signals.

Background Art

Modern hard disc drives comprise one or more rigid discs that are coated with a magnetizable medium and mounted on the hub of a spindle motor for rotation at a constant high speed. Information is stored on the discs in a plurality of concentric circular tracks by an array of transducers ("heads") mounted to a radial actuator for movement of the heads relative to the discs.

Typically, such radial actuators employ a voice coil motor to position the heads with respect to the disc surfaces. The heads are mounted via flexures at the ends of a plurality of arms which project radially outward from a substantially cylindrical actuator body. The actuator body pivots about a shaft mounted to the disc drive housing at a position closely adjacent the outer extreme of the discs. The pivot shaft is parallel with the axis of rotation of the spindle motor and the discs, so that the heads move in a plane parallel with the surfaces of the discs.

The actuator voice coil motor includes a coil mounted on the side of the actuator body opposite the head arms so as to be immersed in the magnetic field of an array of permanent magnets. When current is passed through the coil, an electromagnetic field is set up which interacts with the magnetic field of the permanent magnets to cause the coil to move in accordance with the well-known Lorentz relationship. As the coil moves, the actuator body pivots about the pivot shaft and the heads are moved across the disc surfaces.

Typically, the heads are supported over the discs by actuator slider assemblies which include air-bearing surfaces designed to interact with a thin layer

of moving air generated by the rotation of the discs, so that the heads are said to "fly" over the disc surfaces. Generally, the heads write data to a selected data track on the disc surface by selectively magnetizing portions of the data track through the application of a time-varying write current to the head. In order to subsequently read back the data stored on the data track, the head detects flux transitions in the magnetic fields of the data track and converts these to a signal which is decoded by read channel circuitry of the disc drive.

Control of the position of the heads is typically achieved with a closed loop servo system such as disclosed in United States Patent No. 5,262,907 issued November 16, 1993 to Duffy et al. In such a system, head position (servo) information is provided to the discs to detect and control the position of the heads. As will be recognized, a dedicated servo system entails the dedication of one entire surface of one of the discs to servo information, with the remaining disc surfaces being used for the storage of user data. Alternatively, an embedded servo system involves interleaving the servo information with the user data on each of the surfaces of the discs so that both servo information and user data is read by each of the heads.

With either a dedicated or embedded servo system, it is common to generate a servo position error signal (PES) which is indicative of the position of the head with respect to the center of a selected track. More particularly, during track following in which the head is caused to follow a selected track, the servo system generates the PES from the received servo information and then uses the PES to generate a correction signal which is provided to a power amplifier to control the amount of current through the actuator coil, in order to adjust the position of the head accordingly.

Typically, the PES is presented as a position dependent signal having a magnitude generally indicative of the relative distance between the head and the center of a track and a polarity indicative of the direction of the head with respect to the track center. Thus, it is common for the PES to have normalized values ranging from, for example -1.0 to +1.0 as the head is swept across the track and

to have a value of 0 when the head is positioned over the center of the track. It will be recognized that the PES is generated by the servo system by comparing the relative signal strengths of burst signals generated from precisely located magnetized servo fields of the servo information on the disc surface.

The servo fields are generally arranged in an offset pattern so that, through manipulation of the magnitudes of the burst signals provided to the servo system as the servo fields are read, the relative position of the head to a particular track center can be determined (and subsequently controlled). More particularly, digital representations of the analog burst signals are typically provided to a servo loop microprocessor, which obtains a digital representation of the value of the PES from a selected combination of the input digital representations of the analog burst signals. The microprocessor then compares the value of the PES to a desired value (indicative of the desired position of the head to the selected track) and issues a digital correction signal to the power amplifier, which in turn provides an analog current to the actuator coil to adjust the position of the actuator.

It follows that an important consideration in digital servo systems is accurately determining the relationship between the value of the PES and the corresponding distance between the head and a known position, for example the center of a track, in order to effectuate accurate control of the head position. Particularly, it is important to provide a nominally linear PES over the width of a track to ensure precise servo control and stability of the servo loop.

A continuing trend in the disc drive industry is to develop products with ever increasing areal densities and decreasing access times, which places greater demands on the ability of modern servo systems to control the position of data heads with respect to data tracks. As track densities continue to increase, a significant problem that results is the ability to manufacture nominally identical heads for use in the disc drive. That is, a disc drive design typically includes the selection of a nominal head width as a selected percentage of the total track width, such as, for example from 50% to 90% of the total track width. The servo system is then designed to operate with a head having a width that is equal or near to the

selected nominal head width, within acceptable tolerances.

However, as track densities increase, it is becoming increasingly more difficult to manufacture heads which meet the tolerances required for new disc drive designs. That is, while track densities continue to increase, manufacturing variations in head widths generally remain constant. Thus, it is increasingly more difficult to supply a population of heads for such increased track densities. This is particularly true with magneto-resistive (MR) heads, which accommodate higher bit densities per track over the thin-film heads of the previous generation, but as a result of increased complexity of MR heads as compared to thin-film heads, MR heads are particularly difficult to manufacture to the strict tolerances needed to accomplish the track densities required by disc drive manufacturers. For example, disc drives of the present generation may require heads to have a nominal width of about 2.2 micrometers, ± 0.25 micrometers (90 microinches, ± 10 microinches). As a result, head manufacturers have engaged in time consuming and expensive measurement and sorting operations in order to supply heads meeting the tolerances required by the manufacturers of new drives. These costs are typically be passed along to the manufacturers of the drives, and ultimately, to the consumer.

A related problem which occurs as track densities increase is variation in the width of the tracks. Whereas such variations in track width have not been a significant factor in obtaining accurate servo control in previous disc drives having relatively lower track densities, as track densities continue to increase, variations in track width become increasingly significant. Such variations in track width can occur as a result of imperfections in the magnetic media of the discs, or can occur as a result of errors in the servo track writing process during manufacturing.

There is a need, therefore, for an improved approach to generating a PES in a digital servo system of a disc drive which can accommodate ever increasing track densities, while compensating for manufacturing variations in the width of the heads, as well as variations in track width.

Disclosure of Invention

The present invention provides a method and apparatus for providing a nominally linearized position error signal in a disc drive while accommodating relatively large variations in head width, track width and the effects of other factors within the drive tending to cause non-linearities in the position error signal.

In accordance with a first aspect of the present invention, a first servo position error signal is generated by the disc drive as a selected combination of servo burst signals received as a disc drive head passes over servo burst fields of a selected track, the first servo position error signal having a magnitude indicative of the position of the head relative to the selected track. A second servo position error signal is also generated by the disc drive as a selected combination of the servo burst signals, the magnitude of the second servo position error signal being different from the magnitude of the first servo position error signal for at least a portion of the width of the selected track.

A third servo position error signal is generated from a selective weighting of the first and second servo position error signals, the third servo position error signal exhibiting nominally linear characteristics across each track. The servo circuit then proceeds to control the position of the head using the third servo position error signal.

In accordance with a second aspect of the present invention, the selective weighting of the first and second servo position error signals is determined by initially establishing the relative weighting of the first and second servo position error signals and then adjusting the weighting by measuring the gain of the servo loop as the head is positioned at selected locations relative to the selected track; for example, at the center of the selected track and between the center of the selected track and at a selected boundary of the selected track. Alternatively, the selective weighting of the first and second servo position error signals is determined by accurately positioning the head at a selected position relative to the selected track, measuring the first and second servo position error signals and then determining the weighting therefrom.

These and various other features as well as advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of Drawings

FIG. 1 is a top plan view of a disc drive constructed in accordance with the preferred embodiment of the present invention.

FIG. 2 provides a functional block diagram of the disc drive of FIG. 1.

FIG. 3 is a functional block diagram of the servo control circuit of FIG. 2.

FIG. 4 provides a representation of the general format of a servo frame of the disc drive of FIG. 1.

FIG. 5 shows the four position burst fields of the servo frame of FIG. 4.

FIG. 6 provides a graphical representation of the amplitudes of the A, B, C and D burst signals from the four position burst fields of FIG. 5.

FIG. 7 shows an idealized representation of a linear position error signal generated from the burst signals of FIG. 6.

FIG. 8 is a graphical representation of a first type of position error signal generated from the burst signals of FIG. 6 in accordance with the preferred embodiment of the present invention.

FIG. 9 is a graphical representation of a second type of position error signal generated from the burst signals of FIG. 6 in accordance with the preferred embodiment of the present invention.

FIG. 10 is a flow chart illustrating a SERVO CALIBRATION routine performed by the disc drive of FIG. 1 in accordance with the preferred embodiment of the present invention.

FIG. 11 is a flow chart illustrating a BANDWIDTH CAL routine performed in conjunction with the routine of FIG. 10.

FIG. 12 is a flow chart illustrating an ALPHA CALC routine, the ALPHA CALC routine performed as an alternative preferred embodiment of the present invention.

FIG. 13 provides a graphical representation of a set of position error signal curves for head widths of 50%, 60%, 70%, 80% and 90% with respect to track width, the set of position error signal curves generated in accordance with the preferred embodiment of the present invention.

FIG. 14 provides a graphical representation of another set of position error signal curves for the head widths of FIG. 13 generated in part from the set of position error signal curves of FIG. 13 in accordance with the preferred embodiment of the present invention.

FIG. 15 provides a gaussian distribution curve indicative of a population of heads supplied for use by a population of disc drives nominally identical to the disc drive of FIG. 1.

Modes for Carrying Out the Invention

Referring now to FIG. 1, shown therein is a disc drive 100 constructed in accordance with the preferred embodiment of the present invention. The disc drive 100 includes a base deck 102 to which various components of the disc drive 100 are mounted. A top cover 104 (shown in partial cutaway fashion) cooperates with the base deck 102 to form an internal, sealed environment for the disc drive 100 in a conventional manner.

A spindle motor (shown generally at 106) rotates one or more discs 108 at a constant high speed. Information is written to and read from tracks (not designated) on the discs 108 through the use of an actuator assembly 110, which rotates about a bearing shaft assembly 112 positioned adjacent the discs 108. The actuator assembly 110 includes a plurality of actuator arms 114 which extend towards the discs 108, with one or more flexures 116 extending from the actuator arms 114. Mounted at the distal end of each of the flexures 116 is a head 118 which includes a slider assembly (not separately designated) designed to fly in close proximity to the corresponding surface of the associated disc 108.

At such time that the disc drive 100 is not in use, the heads 118 are moved over landing zones 120 near the inner diameter of the discs 108 and the actuator

assembly 110 is secured using a conventional latch arrangement (a latch pin is shown at 122).

The radial position of the heads 118 is controlled through the use of a voice coil motor (VCM) 124, which as will be recognized typically includes a coil 126 attached to the actuator assembly 110 as well as one or more permanent magnets 128 which establish a magnetic field in which the coil 126 is immersed. Thus, the controlled application of current to the coil 126 causes magnetic interaction between the permanent magnets 128 and the coil 126 so that the coil 126 moves in accordance with the well known Lorentz relationship. As the coil 126 moves, the actuator assembly 110 pivots about the bearing shaft assembly 112 and the heads 118 are caused to move across the surfaces of the discs 108.

A flex assembly 130 is provided to provide the requisite electrical connection paths for the actuator assembly 110 while allowing pivotal movement of the actuator assembly 110 during operation. The flex assembly includes a printed circuit board 132 to which head wires (not shown) are connected, the head wires being routed along the actuator arms 114 and the flexures 116 to the heads 118. The printed circuit board 132 typically includes circuitry for controlling the write currents applied to the heads 118 during a write operation and for amplifying read signals generated by the heads 118 during a read operation. The flex assembly terminates at a flex bracket 134 for communication through the base deck 102 to a disc drive printed circuit board (not shown) mounted to the bottom side of the disc drive 100.

Referring now to FIG. 2, shown therein is a functional block diagram of the disc drive 100 of FIG. 1, generally showing the main functional circuits which are resident on the disc drive printed circuit board and used to control the operation of the disc drive 100.

The disc drive 100 is shown to be operably connected to a host computer 140 in which the disc drive 100 is mounted in a conventional manner. Control communication paths are provided between the host computer 140 and a disc drive system processor 142, the processor 142 generally providing top level

communication and control for the disc drive 100 in conjunction with programming for the processor 142 stored in memory (MEM) 143. The MEM 143 can include RAM, ROM and other sources of resident memory for the processor 142.

Data is transferred between the host computer 140 and the disc drive 100 by way of a disc drive interface 144, which typically includes a buffer and associated hardware to facilitate high speed data transfer between the host computer 140 and the disc drive 100. Data to be written to the disc drive 100 is thus passed from the host computer 140 to the interface 144 and then to a read/write channel 146, which encodes and serializes the data and provides the requisite write current signals to the heads 118. To retrieve data that has been previously stored by the disc drive 100, read signals are generated by the heads 118 and provided to the read/write channel 146, which performs decoding and error detection and correction operations and outputs the retrieved data to the interface 144 for subsequent transfer to the host computer 140. Such operation of the disc drive 100 is well known in the art and discussed, for example, in United States Patent No. 5,276,662 issued January 4, 1994 to Shaver et al.

The discs 108 are rotated at a constant high speed by a spindle control circuit 148, which typically electrically commutates the spindle motor 106 (FIG. 1) through the use of back emf sensing. Spindle control circuits such as represented at 148 are well known and will therefore not be discussed further herein; additional information concerning spindle control circuits is provided, for example, in United States Patent No. 5,631,999 issued May 20, 1997 to Dinsmore.

As discussed above, the radial position of the heads 118 is controlled through the application of current to the coil 126 of the actuator assembly 110. Such control is provided by a servo control circuit 150, a functional block diagram of which is provided in FIG. 3.

Referring now to FIG. 3, the servo control circuit 150 includes a preamp circuit 152, a servo data and decode circuit 154, a servo processor 156 with associated servo RAM 158 and a VCM control circuit 160, all of which cooperate

in a manner to be discussed in greater detail below to control the position of the head 118 with respect to the disc 108. For reference, the preamp circuit 152 is typically located on the printed circuit board 132 (FIG. 1) as it has been found to be generally advantageous to locate the preamp circuit 152 in relative proximity to the heads 118.

It will be recognized that servo control generally includes two main types of operation: seeking and track following. A seek operation entails moving a selected head 118 from an initial track to a destination track on the associated disc surface through the initial acceleration and subsequent acceleration of the head 118 away from the initial track and towards the destination track. Once the head 118 is settled on the destination track, the disc drive enters a track following mode of operation wherein the head 118 is caused to follow the destination track until the next seek operation is to be performed. Such operations are well known in the art and are discussed, for example, in the previously referenced Duffy U.S. Patent No. 5,262,907 as well as in United States Patent No. 5,475,545 issued December 12, 1995 to Hampshire et al. In order to clearly set forth the preferred embodiment of the present invention, however, the general operation of the servo control circuit 150 during track following will now briefly be discussed.

With continued reference to FIG. 3, analog burst signals are provided by the head 118 at such time that servo information associated with the track being followed passes under the head 118. The burst signals are amplified by the preamp circuit 152 and provided to the servo data decode circuit 154, which includes analog-to-digital converter (ADC) circuitry that converts the analog burst signals to digital form. The digitized signals are then provided to the servo processor 156, which in the preferred embodiment is a digital signal processor (DSP).

The servo processor 156 determines a position error signal from the relative magnitudes of the digital representations of the burst signals and, in accordance with commands received from the disc drive system processor 142 (FIG. 2), determines the desired position of the head 118 with respect to the track.

It will be recognized that, generally, the optimal position for the head 118 with respect to the track being followed is over track center, but offsets (as a percentage of the width of the track) can sometimes be advantageously employed during, for example, error recovery routines. In response to the desired relative position of the head 118, the servo processor 156 outputs a current command signal to the VCM control circuit 160, which includes an actuator driver (not separately designated) that applies current of a selected magnitude and direction to the coil 126 in response to the current command signal.

The servo information on the discs 108 is recorded during the manufacturing of the disc drive 100 using a highly precise servo track writer. The servo information serves to define the boundaries of each of the tracks and is divided circumferentially into a number of frames, the general format of which is shown in FIG. 4. More particularly, FIG. 4 shows a frame 170 to comprise a plurality of fields, including an AGC & Sync field 172, an index field 174, a track ID field 176 and a position field 180. Of particular interest is the position field 180, but for purposes of clarity it will be recognized that the AGC & Sync field 172 provides input for the generation of timing signals used by the disc drive 100, the index field 174 indicates radial position of the track and the track ID field 176 provides the track address. Of course, other fields may be used as desired and the format of the fields in a servo frame will depend upon the construction of a particular disc drive.

The position field 180 comprises four position burst fields arranged in an offset, quadrature pattern for a plurality of adjacent tracks, as shown in FIG. 5. More particularly, FIG. 5 shows the position field 180 to comprise burst patterns A, B, C and D having selected geometries and magnetization vectors, defining a plurality of track boundaries identified as 0-5. Thus, each track comprises the area bounded by two adjacent track boundaries. Additionally, the head 118 of FIG. 1 is represented in FIG. 5 as being centered on the track bounded by track boundaries 0 and 1 (said track being identified at 182). The direction of rotation of the discs 108 (and hence the position field 180) relative to the head 118 is

shown by arrow 184.

Both the A and B burst patterns are shown to extend from the center of one track to the center of an immediately adjacent track, with these patterns offset as shown. Additionally, the C and D burst patterns extend from one track boundary to the next track boundary, with these patterns also offset as shown. Thus, as the head 118 passes over the position field 180 on track 182, the head will pass over portions of the A and B burst patterns (identified as 186 and 188, respectively) and then over C burst pattern 190. However, the head 118 will not encounter D burst pattern 192, as this pattern is on an adjacent track. For reference, tracks having C burst patterns are referred to as "even tracks" and tracks with D burst patterns are referred to as "odd tracks".

Generally, it will be recognized that when the head 118 is centered at the mid-point of track 182, the amplitude of an A burst signal induced in the head 118 by the A burst pattern 186 will be nominally equal to the amplitude of a B burst signal induced in the head by the B burst pattern 188. Moreover, the amplitude of a C burst signal induced by the C burst pattern 190 will have a nominal maximum value and the amplitude of a D burst signal from the D burst pattern 192 will be nominally zero. Further, when the head 118 is positioned over the track boundary 1, the amplitudes of the C and D burst signals from the patterns 190 and 192 will be equal in magnitude, the B burst signal from the pattern 188 will have a maximum value and the A burst from the pattern 186 will be zero. Thus, as the head 118 is swept from one track boundary to the next, the amplitudes of the A, B, C and D burst signals cycle between zero and maximum values, as generally illustrated by FIG. 6.

FIG. 6 provides a graphical representation of the amplitudes of the A, B, C and D burst signals as the head 118 is moved from track boundary 0 to track boundary 4 in FIG. 5. More particularly, FIG. 6 plots each of the burst signals along a common horizontal axis indicative of radial track position and an aligned vertical axis indicative of the amplitude for each of the burst signals from a value of zero to a maximum value. As in FIG. 5, the track 182 is shown in FIG. 6 to

comprise the interval between the values of 0 and 1 on the horizontal axis.

Referring to FIG. 7, shown therein is a graphical representation of an idealized PES curve 194 generated from the burst signals of FIG. 6. The PES curve 194 has an amplitude that generally ranges in a linear fashion from a minimum value of -1 to a maximum value of +1 as the head is positioned across a track from one track boundary to the next. That is, the PES has a nominal value of zero when the head 118 is positioned at the center of a selected track and the PES increases and decreases, respectively, in a linear fashion as the head is positioned toward the track boundaries. In this way, the amplitude and polarity of the PES curve 194 readily indicate the relative distance and direction of the position of the head 118 with respect to a selected track center and can thus be used to generate the appropriate correction signal to move the head to the center of the selected track. It will be understood that, in the digital servo control circuit 150 of FIGS. 2 and 3, the PES comprises a range of digital values across each track from one track boundary to the next; however, it is conventional to express the relative values of the PES in a normalized, analog fashion as shown on the vertical axis of FIG. 7.

With this background concerning the general configuration and purpose of the servo position field 180 of FIG. 3 during servo operation of the disc drive 100, the first aspect of the present invention will now be discussed. Generally, in the practice of the preferred embodiment of the present invention, the servo processor 156 receives digital representations of the burst signals illustrated in FIG. 6 and generates a first type of PES therefrom which will be referred to herein as a "seamless PES" (or "SPES"). Particularly, the SPES value at any given sample of burst signals is determined in accordance with the following relationships:

$$SPES=\frac{(B-A)}{|A-B|+|C-D|} \qquad (1)$$

for odd tracks, and

$$SPES = \frac{(A-B)}{|A-B|+|C-D|} \qquad (2)$$

for even tracks, with A, B, C, and D representing the magnitudes of the A, B, C, and D burst signals, as illustrated in FIG. 6. That is, for each sample of burst signals, and depending upon whether the selected track is an even or an odd track, the servo processor 156 generates an SPES value in accordance with the relationship given above in equation (1) or (2).

Using the head 118 and the track 182 of FIG. 5 by way of example, track 182 being an even track, it will be recognized that the SPES will have a nominal value of zero (SPES = 0) when the head 118 is positioned over the center of the track 182, as the magnitudes of the A and B burst signals will be nominally equal, as shown in FIG. 6. For this reason, track centers are also sometimes referred to as "AB nulls".

It will be further recognized that the SPES will have a nominal value of one (SPES = 1) when the head 118 of FIG. 5 is positioned over the track boundary 1, as the magnitudes of the C and D burst signals will be nominally equal and the magnitude of the A burst signal will be nominally zero. Likewise, the SPES will have a nominal value of negative one (SPES = -1) when the head 118 of FIG. 5 is positioned over the track boundary 0, as the magnitudes of the C and D burst signals will also be nominally equal and the magnitude of the B burst signal will be nominally zero. Thus, track boundaries, such as boundaries 0-5 shown in FIG. 5, are also sometimes referred to as "CD nulls". At each CD null, the SPES will have values of both -1 and +1; however, the particular value used by the servo processor 156 will depend upon whether the track boundary serves as the "innermost" or the "outermost" boundary for the selected track. For reference, such dual values of $\pm$ 1 are illustrated in the idealized PES curve 194 of FIG. 7.

Finally, it will be recognized that at locations halfway between each AB null and each CD null (i.e., halfway between the center of the tracks and the track

boundaries), the SPES will have nominal values of ± 0.5; that is, where the absolute value of the term (A - B) is nominally equal to the absolute value of the term (C - D), then equation (1) reduces to either +0.5 or -0.5, depending upon the values of A and B. For reference, these locations are sometimes referred to as "quarter-track positions", as the distances from track boundaries to the quarter-track positions nominally comprise 25% of the entire track width.

In summary, the SPES of equations (1) and (2) will have known values of {-1, -0.5, 0, 0.5, 1} at selected locations as the head 118 moves across the track 182 from the track boundary 0 to the track boundary 1. FIG. 8 provides a generalized SPES curve 202, which illustrates this relationship between the SPES value and the position of the head 118.

Particularly, the graph of FIG. 8 includes a horizontal axis corresponding to the track 182 of FIG. 5 and a vertical axis representing the corresponding value of the SPES curve 202. As shown in FIG. 8 (and with reference to FIGS. 5 and 6), the SPES curve 202 has a value of -1 (at point 204 on the SPES curve 202) at the track boundary 0, a value of -0.5 (at point 206) at the quarter-track position adjacent the track boundary 0, a value of 0 (at point 208) at the track center, a value of +0.5 (at point 210) at the quarter-track position adjacent the track boundary 1, and a value of +1 (at point 212) at the track boundary 1.

However, as shown in FIG. 8, the SPES curve exhibits significant curvature between points 204, 206, 208, 210 and 212. Although the amount of the curvature is a function of the relationship between the head width with respect to the track width, an SPES generated in accordance with equations (1) and (2) will generally provide a shape such as shown by the SPES curve 202. Of particular interest is the fact that the portions of the SPES curve 202 between points 204 and 206 and between points 208 and 210 have "convex" characteristics, in that the midpoints of these portions lie above straight lines (not shown) defined by the points 204 and 206 and by the points 208 and 210, respectively. Further, the portions of the SPES curve 202 falling between the points 206 and 208 and between the points 210 and 212 have "concave" characteristics, in that these

portions have midpoints which fall below straight lines (not shown) defined by the points 206 and 208 and by the points 210 and 212. Again, the amount of such curvature will generally be determined by the relationship between the head width and the track width, but other factors, such as electrical and mechanical offsets and changes in system gain with respect to track position can also affect the curvature of the SPES.

In addition to generating an SPES, the servo processor 156 generates a second type of PES from the burst signals illustrated in FIG. 6, which will be referred to herein as a "seamless-one PES" (or "S1PES"). The S1PES value at each sample of burst signals is determined in accordance with the following relationships:

$$S1PES = \frac{(B-A)|A-B|}{(|A-B|)^2 + (|C-D|)^2} \qquad (3)$$

for even tracks, and

$$S1PES = \frac{(A-B)|A-B|}{(|A-B|)^2 + (|C-D|)^2} \qquad (4)$$

for odd tracks, with A, B, C, and D representing the magnitudes of the A, B, C, and D burst signals, as illustrated in FIG. 6. That is, for each sample of burst signals received by the servo processor 156, an S1PES value is generated in accordance with the relationship given above in equations (3) or (4), depending upon whether the track is even or odd.

From equations (3) and (4), it will be recognized that at each AB null (track center) the S1PES will have a value of zero (that is, S1PES = 0), and at each CD null (track boundary) the S1PES will have a value of positive or negative one (S1PES = $\pm$ 1). Furthermore, at each quarter-track position, wherein $|A - B| = |C - D|$, it will be recognized that the S1PES will have a value of positive or negative 1/2 (that is, S1PES = $\pm$ 0.5). Thus, like the SPES of equations (1) and (2), the S1PES of equations (3) and (4) will have values of

{-1, -0.5, 0, 0.5, 1} at known locations.

However, the S1PES will exhibit characteristics which are different from the characteristics of the SPES at other locations across the width of the track. Particularly, FIG. 9 has been provided to show an S1PES curve 222, determined in accordance with equations (3) and (4) above. As with FIG. 8, the horizontal axis of FIG. 9 represents the track position with respect to track 182 of FIG. 5 and the vertical axis of FIG. 9 shows the corresponding values of the S1PES curve 222. As with the SPES curve 202 of FIG. 8, the S1PES curve 222 has a value of -1 (at point 224) at the track boundary 0, a value of -0.5 (point 226) at the quarter-track position adjacent the track boundary 0, a value of 0 (point 228) at the track center, a value of +0.5 (point 230) at the quarter-track position adjacent the track boundary 1, and a value of +1 (point 232) at the track boundary 1.

However, the S1PES curve 222 exhibits different curvature between points 224, 226, 228, 230 and 232, as compared to the SPES curve 202 of FIG. 8. Particularly, portions of the S1PES curve 222 are concave between the points 224 and 226 and between the points 228 and 230, and portions of the S1PES curve 222 are convex between the points 226 and 228 and between the points 230 and 232. Again, the amount of curvature at these portions is dependent primarily upon the relationship between the head width and the track width, but other factors can affect the amount of curvature as well. It will be recognized, though, that the relationship between the head width and the track width and other factors affecting the generation of the curves 202, 222 will generally be consistent for both of the curves 202, 222 in the same disc drive 100.

Once the SPES and S1PES are generated, the servo processor 156 proceeds to generate a third type of PES therefrom, which will be referred to herein as a "seamless-two PES" ("S2PES"). More particularly, the S2PES is generated in accordance with the following relationship:

$$S2PES = (\alpha)\,(SPES) + (1-\alpha)\,(S1PES) \qquad (5)$$

where SPES is generated in accordance with equation (1) or (2) above, S1PES is

generated in accordance with equation (3) or (4) above, and α is a value determined in a manner to be described below. Generally, however, the value of α is selected to provide the same gain (slope) across the width of each track so as to exhibit the nominally linear characteristics represented by the PES curve 194 of FIG. 7.

In accordance with a second aspect of the present invention, two preferred, alternative methodologies are disclosed hereinbelow to select the appropriate value of α, each of which will be discussed in turn. Generally, however, the first methodology comprises setting α to an initial value and then repetitively adjusting the value of α until the average of the gain at the AB nulls is equal to the gain at the quarter-track locations. The second methodology comprises accurately positioning the head with respect to a selected track, measuring SPES and S1PES at this position, and then calculating an appropriate value of α therefrom. For both methodologies, once α is determined, it is thereafter used by the servo control circuit 150 to generate the S2PES signal, from which positional control of the head 118 is achieved.

Referring now to FIG. 10, shown therein is a flow chart for a SERVO CALIBRATION routine to carry out the first methodology to determine α. The routine is representative of programming stored in RAM 158 and used by the servo processor 156. Alternatively, the SERVO CALIBRATION routine can be stored in disc drive memory (such as MEM 143 of FIG. 2) and performed by the system processor 142 in conjunction with the servo processor 156. As will be recognized, the SERVO CALIBRATION routine will preferably be performed during the manufacturing of the disc drive 100, and can further be performed as desired on a selectively periodic basis during the operational life of the disc drive 100.

The routine of FIG. 10 begins at block 240, wherein the value of α is initialized for each head to a selected value (such as $\alpha = 1$). The flow continues to block 242, wherein the first head to be measured is selected. It will be recognized that in a dedicated servo system only the servo head will be selected,

whereas in an embedded servo system all heads will be selected in turn.

Next, the selected head is moved to a selected track, as shown in block 244. Although the routine of FIG. 10 could be performed for a plurality of tracks, in the preferred embodiment the selected track is located substantially in the center of the recording band of the disc 108. For purposes of illustration, the first selected head will be considered to be the head 118 and the selected track will be considered to be track 182.

The head 118 is then further positioned over the center of the track 182, as shown in block 246. The servo control circuit 150 utilizes the S2PES described above to position the head 118 at this time.

Continuing with FIG. 10, once the head 118 is positioned over the selected track 182, the routine proceeds to measure the gain of the servo control circuit 150 a total of four successive times, as indicated by block 248. More particularly, block 248 calls a BANDWIDTH CAL routine, which is illustrated in FIG. 11.

As shown in FIG. 11, the BANDWIDTH CAL routine operates to measure the gain of the servo control circuit 150, which can be defined as the localized slope of the PES curve; that is, the gain represents the change in the PES value with respect to track position. Accordingly, the idealized PES curve 194 of FIG. 7 exhibits constant gain across the width of each track.

Generally, the BANDWIDTH CAL routine of FIG. 11 measures the gain by injecting a sinusoidal test signal of a predetermined frequency and amplitude into the S2PES. The resulting sinusoidal test signal will cause the head to oscillate about the track center at the frequency of the test signal. The routine then measures the gain by measuring the change in the value (voltage, v) of the S2PES with respect to the resulting change in track position (x). That is, the gain is measured by determining Δv, which is the change in magnitude of the S2PES at each maximum excursion of the head 118 about the center of the track 182, determining Δx, which is the total radial distance the head 118 moves between successive maximum excursions, and then taking the ratio of $\Delta v / \Delta x$. The injection of sinusoidal test signals into a PES is discussed, for example, in

copending United States Patent Application 08/498,621 filed July 7, 1995 by Hobson et al.

Referring now to FIG. 11, a test signal of predetermined frequency and amplitude is injected into the S2PES at block 250. More particularly, a cosine table resident in MEM 143 (or other disc drive memory not shown in the drawings) is utilized to generate digital samples representative of the test signal. In the preferred embodiment, a frequency of 450 hertz (Hz) is used. As will be recognized, the head 118 will oscillate about the center of the track 182 as the servo control circuit 150 operates to correct the position of the head 118 in response to the combined S2PES and injected test signal.

As the head 118 oscillates, the value (voltage, v) of the S2PES at the extremity of each excursion is measured and the difference (Δv) is calculated, as shown in block 252. Next, the gain is calculated in block 254 from the relationship $(\Delta v)/(\Delta x)$, with Δx representative of the distance that the head 118 moves between successive extreme excursions about the center of the track 182. The calculated gain is then temporarily stored, as indicated by block 256.

As previously discussed, the operation of block 248 of FIG. 10 results in the operation of the BANDWIDTH CAL routine of FIG. 11 a total of four successive times, and the temporary storage of four successive gain measurements. The flow of FIG. 10 then continues at block 258, where an average gain at the track center (AVGTC) is determined from the four previously stored gain measurements.

Once the value of AVGTC is determined, as shown by block 260 the head 118 is moved to a first quarter-track position halfway between the center of the track 182 and the track boundary 0, as shown in FIG. 5. Once the head 118 is positioned over the first quarter-track position, as set forth by block 262 the BANDWIDTH CAL routine of FIG. 11 is performed twice, so that two gain measurements are temporarily stored as a result of the operation of block 262.

Next, the head 118 is moved to a second quarter-track position by block 264 of FIG. 10, the second quarter-track position halfway between the center of

the track 182 and the track boundary 1, as shown in FIG. 5. The BANDWIDTH CAL routine of FIG. 11 is then performed twice with the head 118 at this position, so that two gain measurements are also temporarily stored for the second quarter-track position as a result of the operation of block 266.

The flow of FIG. 10 continues at block 268, wherein an average (AVGQT) of the gain measurements for the first and second quarter-track positions from blocks 262 and 266 is determined. The flow proceeds to block 270 wherein an alpha-correction value (αc) from the values of AVGTC and AVGQT; more particularly, αc is determined from the difference between AVGTC and AVGQT, divided by eight (8). Using eight (8) as a divisor establishes a suitable time-constant for the convergence of the value of α, as it has been found desirable to converge the value of α at a controlled rate to account for the effects of noise in the system and to minimize the time required to reach a final, converged solution.

Once αc is determined, a new value for α is determined by subtracting αc from the previous value of α, as shown in block 272. Additionally, a new value for $(1-\alpha)$ is also determined by block 272, as shown.

As the routine of FIG. 10 operates to iterate to a final solution for α, decision block 274 determines whether α has been calculated a total of 10 times, in order to determine a final, converged solution for α. If not, the routine passes from the decision block 274 back to block 246, so that a new value for α is obtained, in accordance with the foregoing description. In the preferred embodiment, the routine of FIG. 10 determines the value of α a total of 10 consecutive times to ensure a converged solution; however, it will be readily understood that other suitable conversion methodologies could be performed, such as using another total number of passes, or continuing testing until the difference between successively obtained values of α falls below a predetermined acceptance threshold. It will be recognized that the selected methodology in any particular application should desirably provide a converged solution in a controlled manner, while requiring a minimum amount of time.

Continuing with FIG. 10, the routine then passes to decision block 276,

wherein the routine determines whether the selected head is the last head to be measured. If not, the routine passes to block 278, wherein the next head is selected and the routine continues as described hereinabove to determine α and $(1-\alpha)$ values for each selected head, in turn. Once all of the heads have been selected and values determined, the routine ends at block 280.

It will be recognized that the embodiment described above with reference to FIGS. 10 and 11 can advantageously be performed by the disc drive 100 without the need for external test equipment and thus is suitable for use during disc drive manufacturing, as well as during subsequent disc drive operation, as desired.

Having concluded the discussion of the first embodiment for determining the value of α, the second preferred embodiment will now be discussed with reference to FIG. 12, which provides an ALPHA CALC routine. As described below, it is contemplated that the ALPHA CALC routine will be performed during manufacturing of the disc drive 100 in conjunction with an external positioning system to accurately position the heads, such as a laser-based positioning system used to write the position field 180. One such laser based positioning system is model 137K15, manufactured by Teletrak, Inc., Santa Barbara, California, United States of America.

Referring to FIG. 12, the ALPHA CALC routine begins at block 302, wherein the value of α is set to a selected value, such as $\alpha = 1$, for each head. The first head to be measured is then selected at block 304; again, for purposes of illustration, the first head will be considered to be the head 118, as shown in FIG. 5.

At block 306, the selected head 118 is positioned over a selected track, which again can be any track, but preferably is a track substantially in the middle of the recording band of the disc 108. For purposes of illustration, in the present example the selected track will be considered to be the track 182 shown in FIG. 5.

Once the head 118 is positioned over the track 182, the flow passes to block 308, wherein the head 118 is moved to an eighth-track position, which comprises a position halfway between the first quarter-track position and the track

boundary 0. The positioning system is used to place the head to the eighth-track position, preferably by moving the head 118 to the center of the track 182 (determined by locating the AB null) and then accurately moving the head 118 a distance equal to 3/8 of the track away from the center of the track 182. Once so positioned, a plurality of both SPES and S1PES values are obtained, as indicated by block 310. Preferably, at least four SPES values and four S1PES values are measured and stored by block 310. The flow of FIG. 12 then passes to block 312, where the measured values are averaged to obtain AVGSPES and AVGS1PES values, as shown.

Thereafter, once the average values AVGSPES and AVGS1PES are determined, the value of α is determined by block 314 in accordance with the following relationship:

$$(\alpha)\,(AVGSPES) + (1-\alpha)\,(AVGS1PES) = 0.125 \qquad (6)$$

which reduces to

$$\alpha = \frac{0.125 - AVGS1PES}{AVGSPES - AVGS1PES} \qquad (7)$$

with 0.125 indicative of 1/8 of a track width. Once α is determined from block 314, the values of α and $(1-\alpha)$ are stored for the selected head 118 in block 316.

The flow of FIG. 12 then passes to decision block 318, which queries whether the selected head is the last head. If not, the flow passes to block 320 wherein the next head is selected and the routine is performed for the next head. At such time that the last head has been measured, the flow passes from the decision block 318 and ends at block 322.

It will be recognized that both of the preferred methodologies presented above will provide a resulting α value for each selected head, but the first methodology is suitable for both manufacturing as well as during subsequent use of the disc drive 10, whereas the second methodology is generally limited to use during disc drive manufacturing. Additionally, although particular examples of

SPES and S1PES have been presented above, it will be recognized that different PES models, including higher order PES models, can be identified and weighted to generate the desired linearized PES. Moreover it is contemplated that more than two position error signals can be weighted in order to determine the final, linearized PES used in the operation of the servo control circuit 150.

To provide an example of the benefits of the present invention in accommodating variations in head width with respect to the nominal width selected for the design of the disc drive 100, reference is now made to FIGS. 13-15, which consider the effects of head widths of 50%, 60%, 70%, 80% and 90% with respect to track width upon the generation of position error signals in the disc drive 100.

Beginning with FIG. 13, shown therein is a set of SPES curves (generally identified as 332) for a selected track, which for purposes of illustration will be considered to be the track 182 of FIG. 5. More particularly, as with FIGS. 7-9 above, FIG. 13 provides a horizontal axis indicative of track position from track boundary 0 to track boundary 1 for the track 182. The vertical axis of FIG. 13 likewise illustrates the values of the SPES curves 332 with respect to position of the head 118 as it is swept across the track 182.

The SPES curves 332 of FIG. 13 were generated using equation (1) above for head widths of 50%, 60%, 70%, 80% and 90% of the width of the track 182. As shown in FIG. 13, head width is an important factor in the curvature of each curve in the set of SPES curves 332. Particularly, curve 334 represents the SPES for a head having a width of 50% of the track 182 and, as shown, exhibits the greatest nonlinearity from the set of SPES curves 332. For reference, curves 336, 338, 340 and 342 correspond to head widths of 60%, 70%, 80% and 90%, respectively, for the head 118.

As shown in FIG. 13, only the curves 338 and 340, corresponding to head widths of 70% and 80%, respectively, are sufficiently linear from the set of the SPES curves 332 for use as a position error signal. That is, the remaining curves 334, 336 and 342 exhibit sufficient nonlinearities to cause problems in servo

control by the servo control circuit 150.

However, through the use of the present invention to selectively weight the SPES curves 332 of FIG. 13 with a second set of S1PES curves (not shown) determined in accordance with equation (3) given above, a sufficiently linearized position error signal can be achieved for each head width. Referring now to FIG. 14, shown therein is a set of S2PES curves (identified generally as 344) for the head widths of head 118 discussed in FIG. 13. As shown in FIG. 14, the set of S2PES curves 344 are all sufficiently linear to provide robust servo control by the servo control circuit 150, and nominally correspond to the idealized PES curve 194 of FIG. 7. Although several of the curves from the set of S2PES curves 344 overlap, making individual identification of the curves difficult, it will be noted that even curve 346, corresponding to a head width of 50%, is sufficiently linear to provide robust control by the servo control circuit 150.

The practical significance of FIGS. 13 and 14 is illustrated more fully when considered in view of FIG. 15, which provides a graphical representation of a gaussian distribution curve 350 representing a population of heads manufactured for use in disc drives nominally identical to the disc drive 100 of FIG. 1. FIG. 15 provides a horizontal axis indicative of track width, so that distances measured from the origin to the right indicate percentage (up to 100%) of track width. The vertical axis of FIG. 15 correspondingly represents the number of heads in the population of heads defined by the curve 350.

As shown in FIG. 15, in this particular example a nominal head width of 75% has been selected for the disc drive 10. Thus, the servo control circuit 150 has been designed to accommodate head widths of 75% of the nominal track width, and the procurement specifications for the heads call for this value. As a result, the curve 350 has a maximum value at 75% of the track width, indicative of the fact that the heads from the population of heads will generally have head widths which vary about the nominal value of 75%. For disc drives of the present generation, this nominal head width value will be about 2.2 micrometers (90 microinches); the corresponding track width will be about 3 micrometers (120

microinches).

Continuing with FIG. 15, vertical lines (denoted generally at 352) provide cutoff points for the percentage of the population of heads identified by the curve 350; that is, vertical line 354 corresponds to those heads from the population of heads having a width equal to 50% of the track width. Vertical lines 356, 358, 360 and 362 likewise correspond to heads in the population of heads having widths of 60%, 70%, 80% and 90%, respectively.

It will be recalled from FIG. 13 that head widths of from about 70% to 80% provided sufficiently linear SPES curves (338 and 340) to provide adequate control by the servo control circuit 150. Thus, from FIG. 15 it will be recognized that only heads from the population of heads falling between the vertical lines 358 and 360 would be acceptable for use in the disc drive 100, using the SPES defined by equations (1) and (2) above. In the present example, this would correspond to heads having widths of from about 2.1 micrometers to about 2.4 micrometers (84 microinches to 96 microinches).

However, from FIG. 15 it will be recognized that a significantly larger percentage of heads from the population of heads represented by the curve 350 can be utilized in the disc drive 100 as a result of the present invention; more particularly, heads having widths that fall between the vertical lines 354 and 362 (50% to 90%) will provide sufficiently linear position error signals with the use of the S2PES defined above, as shown in FIG. 14. In the present example, this range of head widths would generally be from about 1.5 micrometers to about 2.7 micrometers (60 microinches to 108 microinches).

Moreover, heads from the population of heads falling outside of the vertical lines 354 and 362 will, in many cases, provide sufficiently linear position error signals as a result of the present invention.

Thus, by linearizing each head in the disc drive 100, the present invention accommodates a significantly larger variation in head width, allowing the use of a significantly greater percentage of heads provided by a head manufacturer, and significantly increasing the manufacturing yields for the disc drive manufacturer.

As the heads are typically the most expensive components in a disc drive next to the discs, the advantages of the present invention to the disc drive manufacturer, and ultimately the consumer, are significant.

Accordingly, in view of the foregoing discussion it will be understood that the present invention provides an apparatus and method whereby a nominally linear position error signal is provided regardless of variations in head width and other factors tending to cause non-linearities in the position error signal. Such result is generally accomplished by a servo control circuit (such as 150) generating a first position error signal (such as 202) in a first selected combination of burst signals from servo position fields (such as 186, 188, 190, 192), generating a second position error signal (such as 222) as a second selected combination of burst signals from the servo position fields and generating a third position error signal (such as 344) as a weighted sum of the first and second position error signals. The servo control circuit then controls the position of the head (such as 118) through the controlled application of current to the activator coil (such as 126) using the third position error signal.

It will be clear that the present invention is well adapted to attain the ends and advantages mentioned as well as those inherent therein. While a presently preferred embodiment has been described for purposes of this disclosure, numerous changes may be made which will readily suggest themselves to those skilled in the art and which are encompassed in the spirit of the invention disclosed and as defined in the appended claims.

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Claims

1. In a disc drive of the type including a rotatable disc, the disc having a surface upon which a plurality of tracks are defined by servo position fields, the disc drive further including a controllably positionable actuator adjacent the disc, the actuator having a head which provides servo burst signals in response to the relative position of the head to selected servo position fields, the disc drive further having control circuitry for applying current to a coil of the actuator to position the head relative to the disc, a method for controlling the position of the head relative to a selected track, characterized by:

(a) generating a first position error signal as a first combination of servo burst signals from selected servo position fields associated with the selected track;

(b) generating a second position error signal as a second combination of servo burst signals from selected servo position fields associated with the selected track;

(c) generating a third position error signal as a selected combination of the first and second position error signals, the third position error signal characterized as nominally linear with respect to the width of the selected track; and

(d) applying current to the coil in response to the third position error signal in order to position the head relative to the selected track.

2. The method of claim 1, wherein step (c) is further characterized by:

(c)(1) providing a weight value; and

(c)(2) using the weight value to generate the third position error signal as a weighted sum of the first and second position error signals.

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3. The method of claim 2, wherein step (c)(1) is further characterized by:

(c)(1)(a) selecting an initial value for the weight value;

(c)(1)(b) incrementing the initial value to obtain the weight value used in step (c)(2) by repetitively performing steps of:

(c)(1)(b)(i) positioning the head at a first position relative to the selected track;

(c)(1)(b)(ii) obtaining a first gain measurement at the first position;

(c)(1)(b)(iii) moving the head to a second position relative to the selected track;

(c)(1)(b)(iv) obtaining a second gain measurement at the second position; and

(c)(1)(b)(v) incrementing the initial value by a value proportional to the difference between the first and second gain measurements.

4. The method of claim 3, wherein the first position is over the center of the selected track.

5. The method of claim 3, wherein the second position is halfway between the center of the selected track and a selected track boundary of the selected track.

6. The method of claim 2, wherein step (c)(1) is further characterized by:

(c)(1)(a) moving the head to a selected position relative to the selected track;

(c)(1)(b) generating the first and second position error signals while the head is maintained over the selected position; and

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(c)(1)(c) determining the weight value from the first and second position error signals.

7. The method of claim 6, wherein the selected position comprises a position one-eighth of the track width away from a selected track boundary of the selected track.

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8. A disc drive, comprising:

a rotatable disc, the disc including a surface having servo position fields defining a plurality of nominally concentric tracks;

an actuator assembly adjacent the disc, the actuator including a head and an actuator coil, the head generating servo burst signals from selected servo position fields as the disc rotates adjacent the head; and

a servo control circuit, responsive to the servo burst signals, for positioning the head relative to the disc through the application of current to the actuator coil, the servo control circuit comprising a servo processor having associated programming to:

generate a first position error signal as a first combination of selected servo position fields associated with a selected track;

generate a second position error signal as a second combination of selected servo position fields associated with the selected track;

generate a third position error signal as a selected combination of the first and second position error signals, the third position error signal characterized as nominally linear with respect to the width of the selected track; and

generate a correction signal used to control the current applied to the actuator coil in response to the third position error signal.

9. The disc drive of claim 8, wherein the third position error signal comprises a weighted sum of the first and second position error signals, the weighted sum determined through the use of a weight value α, wherein the third position error signal is determined by summing the product of the first position error signal and the weight value α with the product of the second position error signal and a quantity equal to $(1-\alpha)$.