

ADJUSTING TRACK DENSITY AND BIT DENSITY TO PROVIDE LIMITED EXCESS CAPACITY IN A STORAGE DEVICE

FIELD OF THE INVENTION

5 This invention relates to areal density in data storage devices and particularly to assigning different areal densities to different recording surfaces of a multi-surface hard disc drive.

BACKGROUND OF THE INVENTION

 Areal data density represents the quantity of data (e.g., number of bits)
10 that may be recorded in a given area of a recording surface. In a disc drive, areal density is a function of the track density, which is the number of tracks per inch (TPI) across the radius of the disc surface, and recording or bit density, which is the number of bits per inch (BPI) recorded along a track.

 In the past, the track density was the same for all surfaces of the disc
15 drive. The magnetic heads were manufactured to specifications based on the track density. Specifically, the widths of the read and write portions of the head were designed to not extend to an adjacent track and thus had to be smaller than or equal to the track width associated with the track density.

 Like all manufacturing processes, the process for forming a head is
20 susceptible to slight variations that result in heads with nonuniform widths. As the track density increase, these slight variations will cause a greater percentage of heads to fail initial testing because they are unable to meet the track density specification. This increase in failure rate increases manufacturing time and cost.

25 The present invention provides a solution to this and other problems, and offers other advantages over the prior art.

SUMMARY OF THE INVENTION

 A method sets bit densities and track densities for a plurality of heads in a data storage device. The method includes determining an initial bit density

value and an initial track density for each head. An initial total capacity for the storage device is determined based on the initial track densities and the initial bit densities. A desired capacity for the storage device is selected and the initial total capacity and the desired capacity are compared. One of either a bit density
5 or track density is then adjusted so that the data storage device has an adjusted capacity that provides some excess capacity over the desired capacity where the excess capacity is less than any excess capacity that was present between the initial capacity and the desired capacity. A data storage device formed through this method is also provided.

10 Other features and benefits that characterize the present invention will be apparent upon reading the following detailed description and review of the associated drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

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

FIG. 2 is a flow diagram of a process of determining initial bit density and track density settings for a plurality of heads.

20 FIG. 3 is a flow diagram of a process for adjusting storage density values.

FIG. 4 is a flow diagram of a process for determining if the drive's performance requires that the drive's capacity be changed.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

25 FIG. 1 is a perspective view of a disc drive 100 in which the present invention is useful. Disc drive 100 includes a housing with a base 102 and a top cover (not shown). Disc drive 100 further includes a disc pack 106, which is mounted on a spindle motor (not shown), by a disc clamp 108. Disc pack 106 includes a plurality of individual discs 107, which are mounted for co-rotation

about central axis 109. Each disc surface has an associated disc head-slider 110 that is mounted to disc drive 100 for communication with the confronting disc surface. Head-slider 110 includes a slider structure arranged to fly above the associated disc surface of an individual disc of disc pack 106, and a transducing
5 head 111 arranged to write data to, and read data from, concentric tracks on the confronting disc surface. The concentric tracks are, in effect, parallel to each other at different radii on the disc. In the example shown in FIG. 1, head-sliders 110 are supported by suspensions 112 which are in turn attached to track accessing arms 114 of an actuator 116. Actuator 116 is driven by a voice coil
10 motor (VCM) 118 to rotate the actuator, and its attached heads 110, about a pivot shaft 120. Rotation of actuator 116 moves the heads along an arcuate path 122 to position the heads over a desired data track between a disc inner diameter 124 and a disc outer diameter 126. Voice coil motor 118 is driven by servo electronics included on circuit board 130 based on signals generated by the heads
15 of head-sliders 110 and a host computer (not shown). Read and write electronics are also included on circuit board 130 to supply signals to the host computer based on data read from disc pack 106 by the read heads of head-sliders 110, and to supply write signals to the write head of head-sliders 110 to write data to the discs. The present invention is implemented in the software or firmware
20 programming of a controller on circuit board 130.

FIGS. 2, 3 and 4 provide flow diagrams that describe a method of setting storage density values such as track density and bit density for various heads in a disc drive under one embodiment of the present invention. In particular, FIG. 2 describes a process for determining initial track density and bit density settings
25 for the various heads, FIG. 3 describes a process for adjusting those settings to achieve a desired capacity for the disc drive while improving margins, and FIG. 4 describes a process for determining if the drive's performance with the track density and bit density adjustments will require the drive capacity to be changed.

In step 200 of FIG. 2, the track density for each head in the drive is determined. This can be determined by measuring the actual width of the read and write elements on each head or by writing test tracks with each head and measuring the width of the written track. The track density for each head is initially set independently of the track density of the other heads in the disc drive. At step 202, the total track density for the disc drive is determined by adding the individual track densities from each of the heads in the drive.

In step 204, the bit density of each head is determined. This can be accomplished by writing a series of test tracks to the disc and reading the data back. Each test track is written and read using a different bit density. After the tracks are read, the number of errors in the read data is determined and the highest bit density to provide an acceptable number of errors is set as the maximum bit density for the head. To provide a margin of safety, a bit density that is less than the maximum bit density is selected for the head. For instance, under one embodiment, the selected bit density is 10 kilobytes per inch less than the maximum bit density. At step 206, the bit densities for the different heads are added together to form a total bit density for the drive.

After the individual and total track densities and bit densities have been determined, the process of FIG. 2 selects a nominal track densities and bit densities for the drive at step 208. These nominal values are determined based on the desired capacity for the drive.

At step 210, the total capacity of the current drive is determined from the individual track densities determined in step 200 and the individual bit densities determined in step 204. Under one embodiment, this total capacity associated with each head is calculated as:

$$\sum_{i=0}^{TCount} 2\pi \cdot \left(r_{ID} + \frac{r_{OD} - r_{ID}}{TD} i \right) \cdot BD \quad \text{EQ.1}$$

where

$$TCount = (r_{OD} - r_{ID}) \cdot TD \quad \text{EQ.2}$$

and where TD is the track density for the head, BD is the bit density for the head, r_{OD} is the radius at the outer diameter of the disc associated with the head, r_{ID} is the radius at the inner diameter of the disc, and i provides a track count
5 from track 0 to the maximum track count given by Equation 2. To determine the total capacity for the drive, the individual capacities associated with each head are added together.

Once the total capacity for the drive and the required capacity for the drive have been determined, embodiments of the present invention try to adjust
10 the track density and/or bit density of one or more heads to form an adjusted capacity. In particular, the track densities and/or bit densities are adjusted so that there is excess capacity between the adjusted capacity and the required capacity. In addition, if the initial total capacity of the drive provides excess capacity over the required capacity, the track densities and/or bit densities are
15 adjusted to reduce that excess as much as possible while keeping the adjusted capacity above the required capacity. By reducing this excess capacity, embodiments of the present invention improve the margins between the maximum track densities and bit densities for the heads and the track densities and bit densities at which they are operated.

20 The process of adjusting the track density and bit density for the heads begins at step 300 of FIG. 3. In step 300, the total capacity is compared to the required capacity. If the total capacity is less than the required capacity, the process continues at step 302 where the total bit density for the drive is increased. Under one embodiment, this is accomplished by selecting to increase
25 the bit density of the head with the lowest current bit density. In other embodiments, this is achieved by increasing the bit density of the head that has the highest track density. By selecting this head, this embodiment of the

invention maximizes the affects of raising the bit density by increasing the drive's total capacity as much as possible.

After the bit density has been increased and the total capacity recalculated, the adjusted total capacity is compared to the required capacity at
5 step 304. If the adjusted capacity is still less than the required capacity, the total track density of the drive is increased at step 306 and the total capacity of the drive is recalculated.

Under one embodiment, the increase in track density is achieved by increasing the track density of the head with the lowest track density. In other
10 embodiments, the increase in total track density is achieved by increasing the track density of the head with the highest bit density so as to maximize the gain in total capacity.

After the total track density has been increased and the capacity of the drive has been recalculated, the new capacity is compared to the required
15 capacity at step 308. If the new capacity is still below the required capacity, the process returns to step 302 to increase the total bit density again. Steps 302, 304, 306, and 308 are repeated until the total capacity of the drive exceeds the required capacity at either step 304 or step 308.

Under some embodiments of the invention, when steps 302 and 306 are
20 repeated, an effort is made to not increase the bit density or track density of a head twice. This helps to limit the extent to which each head is pushed beyond its initial measured values for track density and bit density.

When the total capacity of the drive reaches or exceeds the required capacity at step 304 or 308, the process of adjusting the bit densities and track
25 densities for the drive ends at step 310.

Note that although FIG. 3 shows the bit density being adjusted before the track density in each iteration of steps 302, 304, 306, and 308, in other embodiments the track density is adjusted before the bit density.

Returning to step 300, if the initial total capacity of the drive exceeds the required capacity, a series of steps are performed to reduce the bit density and/or the track density of one or more of the heads. By reducing these values, the present invention improves the margin between the head's maximum bit density and maximum track density and the head's operating bit density and operating track density.

The process of reducing these storage densities begins at step 312, where the total bit density for the drive is reduced by reducing the bit density of one of the heads. Under one embodiment, this is achieved by reducing the bit density of the head with the highest bit density. In other embodiments, this is achieved by reducing the bit density of the head with the lowest track density in order to minimize the impact on drive capacity. After the total bit density is reduced, an adjusted capacity for the drive is calculated using the new bit densities.

At step 314, the adjusted capacity is compared to the required capacity to see if the reduction in bit density caused too much of a decrease in capacity. If the new capacity is still above the required capacity, the process continues at step 316, where the total track density for the drive is reduced and the capacity of the drive is recalculated.

Under one embodiment, the reduction in track density is achieved by reducing the track density of the head with the highest track density. In other embodiments, the head with the lowest bit density value has its track density reduced in order to limit the drop in total capacity caused by the reduction in track density.

After the total track density has been reduced and the adjusted capacity has been recalculated, the adjusted capacity is compared to the required capacity at step 318. If the adjusted capacity is still above the required capacity at step 318, the process returns to step 312 to once again reduce the bit density of the drive.

Steps 312, 314, 316, and 318 are repeated as long as the adjusted capacity remains above the required capacity. Under some embodiments, an effort is made to spread the reduction in bit density and track density across as many heads as possible. As such, these embodiments reduce a storage density value for
5 each head once before reducing a storage density value of any head twice.

If the adjusted capacity drops below the required capacity at either step 314 or step 318, the process of FIG. 3 restores the bit density and track density settings to their previous state at step 320. Thus, if the total capacity is below the required capacity at step 314, the last reduction in bit density performed at
10 step 314 is reversed. Similarly, if the total capacity is below the required capacity at step 318, the last reduction in track density is reversed. After step 320, the process of adjusting track density and bit density ends at step 310.

Note that although the bit density was decreased before the track density in FIG. 3, in other embodiments, the track density is decreased before the bit
15 density.

After the track density and bit density adjustments are complete, the drive is tested at step 400 of FIG. 4 to see if the drive operates properly with the new bit density and track density settings. This testing can include testing for any number of characteristics such as Off-Track Capabilities (OTC), Track Mis-
20 Registration (MTR) including Write-To-Read Tolerance and Write-to-Write Tolerance, and data error rates.

After testing, the results of the tests are examined at step 402 to determine if the drive should be deconfigured to a lower capacity. If the results of the test indicate that the drive performs within specification at step 402, the
25 remainder of the certification process is performed at step 404.

However, if the drive does not meet specification with the current bit density and track density settings, the drive is deconfigured by selecting a new required capacity for the drive at step 406. For example, if the initial desired

capacity was 20 Gigabytes, a failing drive could be deconfigured to be a 15 Gigabyte drive.

After the new required capacity has been determined, the process of FIG. 3 for adjusting bit density and track density is repeated for the new required capacity as shown by step 408. Under some embodiments, the adjusted settings for the bit densities and track densities that were produced before deconfiguration are used as the starting bit densities and track densities when the process of FIG. 3 is repeated. In other embodiments, the bit densities and track densities are reset to the initial values they had before the adjustment process of FIG. 3.

The process of FIG. 3 for adjusting bit density and track density can be used on any combination of total bit density and total track density for a drive. In particular, the process of FIG. 3 can be used regardless of whether the total bit density and/or total track density is above or below a nominal track density and nominal bit density determined for the desired capacity of the drive.

For example, table 1 below shows the changes in total track density and total bit density for a drive that had a total track density and a total bit density that were above the nominal track density and nominal bit density, respectively.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	7	2	YES
1st adjustment	6	2	YES
2nd adjustment	6	1	YES
3rd adjustment	5	1	YES
4th adjustment	5	0	YES
5th adjustment	4	0	YES
6th adjustment	4	-1	YES

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
7th adjustment	3	-1	YES
8th adjustment	3	-2	YES
9th adjustment	2	-2	NO

Table 1

In Table 1, excess bit density is the difference between the total bit density and the nominal bit density and excess track density is the difference between the total track density and the nominal track density. After the ninth
5 adjustment, the capacity has dropped below the required capacity. Because of this, the bit density and track density settings produced by the eighth adjustment are used as the final bit density and track density settings.

The process of FIG. 3 can also be used if the track density and bit density values provide a capacity that is greater than the required capacity but one of
10 these values is below their nominal values. For example, table 2 shows the affects of adjustment on a drive that initially exceeds drive capacity but has an initial bit density value that is below the nominal bit density value.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	-1	6	YES
1st adjustment	-2	6	YES
2nd adjustment	-2	5	YES
3rd adjustment	-3	5	YES
4th adjustment	-3	4	YES
5th adjustment	-4	4	YES
6th adjustment	-4	3	NO

Table 2

Similarly, Table 3 shows the affects of adjustment on a drive that exceeds capacity but has an initial track density value that is below the nominal value.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	5	-1	YES
1st adjustment	4	-1	YES
2nd adjustment	4	-2	YES
3rd adjustment	3	-2	YES
4th adjustment	3	-3	NO

Table 3

The process of FIG. 3 can also be used when the drive is below capacity because the track density, the bit density or both are below their nominal values. For example, table 4 shows the affects of adjustment when the bit density is below the nominal value and the drive is below the capacity requirement.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	-7	4	NO
1st adjustment	-6	4	NO
2nd adjustment	-6	5	NO
3rd adjustment	-5	5	YES

Table 4

Note that in table 4 the bit density and track density for the drive are increased until the drive meets the required capacity after the third adjustment.

Similarly, table 5 shows the affects of adjustment on a drive that does not meet the capacity requirements and that has an initial track density that is below the nominal value.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	2	-6	NO
1st adjustment	3	-6	NO
2nd adjustment	3	-5	NO
3rd adjustment	4	-5	NO
4th adjustment	4	-4	NO
5th adjustment	5	-4	NO
6th adjustment	5	-3	YES

Table 5

Lastly, table 6 shows the affects of adjusting bit density and track density in a drive that does not meet the capacity requirement and that has a bit density value and a track density value that are less the nominal values.

	Excess bit density	Excess track density	Total Capacity > = Required Capacity
Initial Setting	-2	-4	NO
1st adjustment	-1	-4	NO
2nd adjustment	-1	-3	NO
3rd adjustment	0	-3	NO
4th adjustment	0	-2	NO
5th adjustment	1	-2	NO
6th adjustment	1	-1	YES

Table 6

In summary, the present invention provides a method of setting bit densities and track densities for a plurality of heads 111 in a data storage

device 100. The method includes a step 204 of determining an initial bit density value for each head 111 and a step 200 of determining an initial track density for each head 111. An initial total capacity for the storage device 100 is determined at a step 210 based on the initial track densities and the initial bit densities. A
5 desired capacity for the storage device is selected at a step 208 and the initial total capacity and the desired capacity are compared at a step 300. One of either a bit density or track density is then adjusted 302, 306, 312, 316, 320, so that the data storage device 100 has an adjusted capacity that provides some excess capacity over the desired capacity where the excess capacity is less than any excess
10 capacity that was present between the initial capacity and the desired capacity.

A data storage device 100 is also provided that includes a plurality of heads 111 and a controller 130 for controlling the position of the heads and the rate at which the head reads to or writes from a surface. The position of the head 111 and the read/write rates are determined based in part on track densities
15 and bit densities that together form storage densities. The storage densities are formed through a process that begins by selecting (step 208) a desired capacity for the storage device. Initial storage densities are then selected (steps 200 and 204), before a total initial capacity for the storage device is determined (step 210). At least one of the storage densities is changed (steps 302, 306, 312, 316, 320) to
20 form an adjusted capacity that has an excess capacity beyond the desired capacity, where the excess capacity is less than any excess capacity between the total initial capacity and the desired capacity.

It is to be understood that even though numerous characteristics and advantages of various embodiments of the invention have been set forth in the
25 foregoing description, together with details of the structure and function of various embodiments of the invention, this disclosure is illustrative only, and changes may be made in detail, especially in matters of structure and arrangement of parts within the principles of the present invention to the full

extent indicated by the broad general meaning of the terms in which the appended claims are expressed. For example, the particular elements may vary depending on the particular application for the variable track density technique while maintaining substantially the same functionality without
5 departing from the scope and spirit of the present invention. In addition, although the preferred embodiment described herein is directed to a technique for optimizing track density for an embedded servo disc drive system, it will be appreciated by those skilled in the art that the teachings of the present invention can be applied to other systems, such as dedicated servo disc drive
10 systems employing servo information on a dedicated servo surface, to optical disc drive systems and to systems whose servo controls do not rely on information recorded on the movable storage medium, such as tape drive systems, without departing from the scope and spirit of the present invention.

WHAT IS CLAIMED IS:

1. A method of setting track densities and bit densities for a plurality of heads in a data storage device, the method comprising:
 - (a) determining a separate initial bit density for each head;
 - 5 (b) determining a separate initial track density for each head;
 - (c) calculating an initial total capacity for the data storage device based on all of the initial bit densities and all of the initial track densities;
 - (d) selecting a total desired capacity for the drive; and
 - 10 (e) adjusting one of either a bit density or a track density of one of the heads so that the data storage device has an adjusted capacity that provides some excess capacity over the desired capacity, the excess capacity being less than any excess capacity that was present between the initial capacity and the desired capacity.
- 15 2. The method of claim 1 wherein adjusting step (e) comprises increasing a bit density.
3. The method of claim 1 wherein adjusting step (e) comprises increasing
20 a track density.
4. The method of claim 1 wherein adjusting step (e) comprises:
 - (e)(i) decreasing one of either a bit density or a track density of one of the heads; and
 - 25 (e)(ii) checking to see if the adjusted capacity is less than the desired capacity.
5. The method of claim 4 wherein adjusting step (e) further comprises:



- (e)(iii) repeating decreasing step (e)(i) and checking step (e)(ii) until the adjusted capacity is less than the desired capacity; and
- (e)(iv) reversing the last decrease provided by decreasing step (e)(i) so that the adjusted capacity provides excess capacity.

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6. The method of claim 5 wherein repeating step (e)(iii) comprises alternately decreasing a bit density and a track density with each repetition of decreasing step (e)(i).

10 7. The method of claim 5 wherein repeating step (e)(iii) comprises decreasing one of either a bit density or a track density for a different head with each repetition of decreasing step (e)(i).

8. The method of claim 1 further comprising:

15 (f) evaluating the performance of the storage device while using the bit densities and track densities associated with the adjusted capacity.

9. The method of claim 8 further comprising:

20 (g) deconfiguring the storage device by setting a lowered desired capacity for the drive and repeating steps (a), (b), (c), and (e) using the lowered desired capacity.

10. A data storage device for storing data on one of a plurality of storage surfaces, the storage device comprising:

a plurality of heads, each head capable of reading from and writing to a storage surface at a head-specific bit density and a head-specific track density; and



5 a controller for controlling the position of the heads based in part on
the track density for each head and for controlling the rates at
which the heads write to and read from the storage surfaces
based in part on the bit density for each head, the track
densities and bit densities together forming storage densities
that are formed through a processes comprising:
selecting a desired capacity for the storage device;
determining initial storage densities for each head, the initial
storage densities comprising an initial bit density and an
10 initial track density for each head;
determining a total initial capacity for the storage device based
on the initial storage densities;
changing at least one density in the initial storage densities to
produce an adjusted capacity, the adjusted capacity
15 providing an excess capacity beyond the desired
capacity, the excess capacity being less than any excess
capacity present between the total initial capacity and
the desired capacity.

20 11. The data storage device of claim 10 wherein changing at least one
density in the initial storage rates comprises increasing a bit density for a head.

12. The data storage device of claim 10 wherein changing at least one
density in the initial storage densities comprises increasing a track density for
25 a head.

13. The data storage device of claim 10 wherein changing at least one
density in the initial storage densities comprises reducing a density.



14. The data storage device of claim 10 wherein changing at least one density further comprises:

reducing a storage density to form a set of adjusted storage densities;

5 determining an adjusted capacity based on the adjusted storage densities;

comparing the adjusted capacity to the desired capacity; and

10 if the adjusted capacity is less than the desired capacity reversing the last decrease in the storage densities and recalculating the adjusted capacity.

15 15. The data storage device of claim 14 wherein the steps of reducing a storage density, determining an adjusted capacity, and comparing the adjusted capacity to the desired capacity are repeated until the adjusted capacity is less than the desired capacity.

20 16. The data storage device of claim 15 wherein each step of reducing a storage density involves reducing a different storage density from the storage densities that were previously reduced.

17. The data storage device of claim 10 wherein the process for forming the storage densities further comprises:

testing the storage device while using the storage densities;

determining that the storage device fails testing;

25 deconfiguring the storage device by selecting a lower desired capacity for the storage device; and

repeating the step of adjusting the storage densities based on the lower desired capacity.



18. A method of producing a data storage device for storing data, the method comprising:

- 5 selecting initial storage densities for a plurality of heads on the storage device; and
- storage density adjustment steps for adjusting the storage densities of the storage device.

