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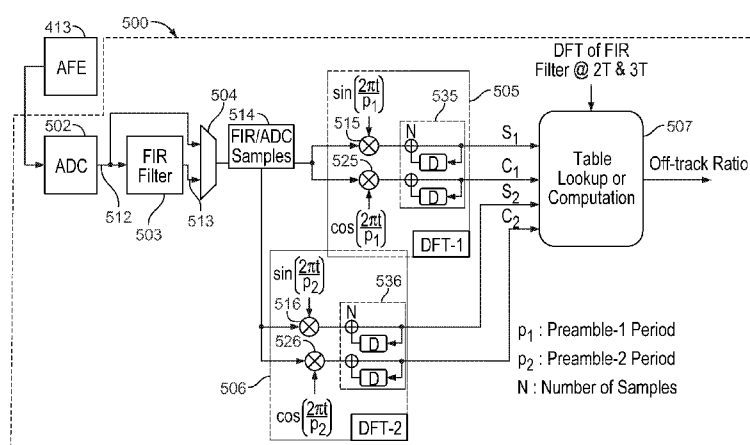


FIG. 5

(57) Abstract: A storage device includes read circuitry having a read head having a detector that outputs signals representing data from a first track and an adjacent track. The read head is subject to off-track excursions during which the read head detects signals from both the first track and an adjacent track. Data on each track includes a preamble including a repeating pattern. The repeating pattern in any first track is orthogonal to the repeating pattern in any track adjacent to the first track. The read circuitry also includes respective Discrete Fourier Transform circuits to identify components in the signals corresponding to respective frequencies characteristic of the repeating pattern on the first track and the repeating pattern on the second track, and computation circuitry to determine from the components a ratio by which the read head is off-track. Corresponding methods are provided for operating such a storage device and for reading data.

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METHOD AND APPARATUS FOR DETERMINING
READ-HEAD DEVIATION USING ORTHOGONAL PREAMBLES

Cross Reference to Related Application

[0001] This claims the benefit of copending, commonly-
5 assigned United States Provisional Patent Application
No. 62/024,251, filed July 14, 2014, and United States
Application No. 14/797,393, filed July 13, 2015, which
are hereby incorporated by reference herein in their
entirety.

10 Field of Use

[0002] This disclosure relates to data storage systems
of the type in which read and write heads move over the
surface of a storage medium. More particularly, this
disclosure relates to determining the degree of off-track
15 deviation of a read head, to improve read performance.

Background

[0003] The background description provided herein is
for the purpose of generally presenting the context of
the disclosure. Work of the inventors hereof, to the
20 extent the work is described in this background section,
as well as aspects of the description that may not
otherwise qualify as prior art at the time of filing, are
neither expressly nor impliedly admitted to be prior art
against the present disclosure.

25 **[0004]** In magnetic recording, as one example, reading
and writing are performed by one or more heads that move
relative to the surface of a storage medium. Many
magnetic disk drives, for example, include a plurality of
individual disks, or "platters," which may be two-

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sided -- i.e., each platter can store data on each of its two sides. Therefore, such a disk drive would have at least two heads for each platter. Indeed, for each platter, there is normally at least one write head and at least one separate read head, so that such a disk drive normally has at least four heads per platter.

[0005] In a common configuration, all of the heads in a given disk drive are mounted on arms attached to a common actuator that controls the radial position of the heads (an angular, tangential or circumferential component of motion is provided by the rotation of the platters relative to the heads). This is true whether there is one or many platters, and one or multiple heads per platter.

[0006] In order to control the radial position selected by the actuator, each surface of each platter has distributed upon it positional information referred to as "servo" data. The servo data are commonly distributed in spaced-apart servo "wedges" (generally spaced equiangularly) on the platter surface. By reading the servo data as each servo wedge passes under the read head, the disk drive controller can determine the precise radial and angular position of the head and can feed back that determination to control the position of the read head or the write head, depending on the required operation. Among the servo data are sync marks, which are used to determine angular position. Separate instances of the sync mark are provided at different radial positions -- i.e., for different tracks.

[0007] Data on adjacent tracks are generally independent of one another. However, as areal densities for magnetic data storage continue to increase, data tracks are being written in an overlapping or "shingled" fashion -- e.g., in "two-dimensional magnetic recording"

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(TDMR) -- and reading is performed using read heads or sensors having dimensions comparable to the track width. Therefore, it is important to know whether, and by how much, a read head is deviating from its nominal position relative to a track.

Summary

[0008] A method according to this disclosure, for operating a storage device having a storage medium, includes writing data to tracks on the storage medium, where data for each track including a preamble including a repeating pattern, and wherein the repeating pattern in any first track is orthogonal to the repeating pattern in any track adjacent to the first track. The method further includes detecting with a read head signals from both the first track and an adjacent track, and analyzing preamble output of the read head to determine a ratio by which the read head is off-track.

[0009] In a further implementation of that method, the analyzing includes applying a Discrete Fourier Transform to the preamble output of the read head.

[0010] According to another implementation, a method of reading data from a storage device having a storage medium to which data are written in tracks, where data on each track includes a preamble including a repeating pattern, and where the repeating pattern in any first track is orthogonal to the repeating pattern in any track adjacent to the first track, includes detecting the first track with a read head subject to off-track excursions during which the read head detects signals from both the first track and an adjacent track, and analyzing preamble output of the read head to determine a ratio by which the read head is off-track.

[0011] According to a further implementation of that method, the analyzing includes applying a Discrete

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Fourier Transform to the preamble output of the read head.

- [0012] An implementation of a storage device according to this disclosure includes read circuitry having a read head having a detector that outputs signals representing data from a first track and an adjacent track, where the read head is subject to off-track excursions during which the read head detects signals from both the first track and an adjacent track, and where data on each track including a preamble including a repeating pattern, with the repeating pattern in any first track being orthogonal to the repeating pattern in any track adjacent to the first track. The read circuitry also includes respective Discrete Fourier Transform circuits to identify components in the signals corresponding to respective frequencies characteristic of the repeating pattern on the first track and the repeating pattern on the second track, and computation circuitry to determine from the components a ratio by which the read head is off-track.
- [0013] According to a further implementation of that storage device, the detector outputs analog signals, and the read circuitry further includes analog-to-digital converter circuitry that outputs samples of the analog signals for input to the respective Discrete Fourier Transform circuits.

Brief Description of the Drawings

- [0014] Further features of the disclosure, its nature and various advantages, will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

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[0015] FIG. 1 is a side elevational view of a portion of a disk drive with which the present disclosure may be used;

[0016] FIG. 2 is a plan view of the disk drive portion of FIG. 1, taken from line 2-2 of FIG. 1;

[0017] FIG. 3 is a schematic representation of an example of adjacent data tracks with an off-track read head;

[0018] FIG. 4 is a schematic representation of a controller for the drive of FIGS. 1 and 2;

[0019] FIG. 5 is a schematic representation of off-track detection circuitry that may be used in apparatus according to this disclosure;

[0020] FIG. 6 is a graph of Discrete Fourier Transform results in an implementation of a method according to this disclosure; and

[0021] FIG. 7 is a flow diagram of an implementation of an alternate method according to this disclosure.

Detailed Description

[0022] FIGS. 1 and 2 show an example of a disk drive 100 with which the present disclosure may be used. In this particular example, disk drive 100 has three platters 101, 102, 103, although any number of platters may be included in a disk drive with which the present disclosure may be used. As shown, each platter 101, 102, 103 has, on each of its upper and lower surfaces 111, 112, a coating 110 made from a material in which data can be stored, e.g., magnetically. The present disclosure also is relevant to a disk drive in which one or more platters includes coating 110 on only one of its surfaces, but such a disk drive would store less data in the same volume than a disk drive with two-sided platters. The platters 101-103 are mounted on a rotatable spindle 104. Motor 105 rotates spindle 104 to

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rotate platters 101-103 in the direction of arrow A (FIG. 2). Although motor 105 is shown connected directly to spindle 104, in some cases motor 105 may be located off-axis of spindle 104 and would be connected to spindle 104 through belts or gears (not shown).

5 [0023] Read/write head assembly 120 includes an actuator 121 that bears arms 122-125, one of which is disposed adjacent to each surface 111, 112 of a platter 101, 102, 103 that has a memory storage
10 coating 110. In this example, with heads on both surfaces of each of arms 123, 124, that amounts to four arms 122-125, but in the single-sided platter example discussed above, there would be only three arms. In other examples, the number of arms would increase or
15 decrease along with the number of platters.

[0024] Each arm 122-125 bears, at or near its end furthest from actuator 121, and on both its upper and lower surfaces in the case of arms 123, 124, a plurality of read heads/sensors and write heads. In this case, two
20 sensors 131, 132 are shown, and will be used to represent read sensors, although it would normally at least be expected that each set of one or more read sensors has a companion write head (not shown). It should be noted that FIGS. 1 and 2 are schematic only and not to scale.
25 For example, the spindle diameter may be larger by comparison to the disk diameter.

[0025] A motor 126, commonly referred to as a "voice-coil motor," rotates actuator 121 back and forth along the directions of arrow B (FIG. 2) to move the heads 131, 132 along the path indicated by dashed arrow 201,
30 although arms 122-125 normally cannot point directly at the center of the disk. The motion of actuator 121 thus changes both the radial and circumferential positions of heads 131, 132, but the circumferential positional change

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is relatively unimportant insofar as the platters are rotating. The motion of actuator 121 thus is used to control the radial position of heads 131, 132.

[0026] The location on surface 111 of platter 101 (the other surfaces are similar) of the aforementioned wedges is shown in FIG. 2. Each servo wedge 200 includes data identifying it by wedge, or sector, number (to give an angular, tangential or circumferential position) and by data representing, at each point along a radius of the platter, the distance from spindle 104, although sometimes some of this information is omitted from some of the wedges.

[0027] As noted above, as areal densities for magnetic data storage continue to increase, data tracks are being written in an overlapping or "shingled" fashion -- e.g., in "two-dimensional magnetic recording" (TDMR) -- and reading is being performed using read heads or sensors having dimensions comparable to the track width. Therefore, it is important to know whether, and by how much, a read head is deviating from its nominal position relative to a track. If an off-track condition is detected, system parameters can be optimized for better performance based on the amount by which the heads are off-track. For example, filter parameters, as well as the amount of gain for each head, can be adjusted based on the amount by which the heads are off-track.

[0028] In accordance with implementations of this disclosure, adjacent tracks may be written with orthogonal preambles -- i.e., preambles that are mutually exclusive, as described in copending, commonly-assigned United States Patent Application No. 14/563,578, filed December 8, 2014, which is hereby incorporated by reference herein in its entirety. Specifically, the preambles may be chosen to be a pair of periodic patterns

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such that the inner product of the two patterns in question, when represented as sequences of write current polarities $\{-1,1\}$, over a window chosen to contain an integer number of periods of both patterns, is zero. For example, a 2T pattern (110011001100...) may be written to the preambles on each even-numbered track, while a 3T pattern (111000111000111000...) may be written to the preambles on each odd-numbered track, although any pair of periods where one period is not a multiple of the other may be selected. There may be other patterns as well, such as a 4T pattern (111100001111000011110000...). Any pair of such orthogonal patterns may be used for adjacent tracks in accordance with this disclosure. These patterns may be described in terms of tones (i.e., sinusoidal signals at the fundamental frequencies of the respective patterns).

[0029] A pair of tracks 301, 302 with orthogonal preambles 311, 312 as described above is shown in FIG. 3. Although tracks 301, 302 are shown as being straight, in the case of a rotating medium such as a disk drive platter, tracks 301, 302 actually would be curved. FIG. 3 also shows a read head 300 which is in an off-track condition; although read head 300 nominally should be aligned with track 301, read head 300 as shown is mainly over track 301, but is partially over track 302 as well. The portions of tracks 301, 302 that are shown would be outside the servo wedges 200 --i.e., preambles 311, 312 are interspersed among the user data outside the servo wedges 200 (e.g., at the beginnings of at least some data packets). Normally, each preamble is followed by one of sync marks 321, 322. However, in some cases, extra preambles may be inserted without sync marks.

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[0030] Read head 300 is connected to a read channel 401 of a hard drive controller 400 (FIG. 4). In addition, an unseen write head is connected to a write channel 402 of hard drive controller 400. Hard drive controller 400 also includes a processor 410 and memory 411, as well as a connection 412 to a host processor (not shown). Memory 411 may be used to store the position error signal (PES) data that indicates the track position offsets. A servo control loop in hard drive controller 400 uses the PES data to keep read head 300 (as well as the unseen write head) on track.

[0031] In accordance with an implementation of this disclosure, read channel 401 of hard drive controller 400 also includes Discrete Fourier Transform (DFT) circuitry 500, shown in more detail in FIG. 5, to determine the amount by which read head 300 is off-track. Read channel 401 will include, as is well known, an analog front end (AFE) 413 that will output mainly sinusoidal signals. In an example where the orthogonal preambles 311, 312 of the two tracks 301, 302 include, respectively, a 2T tone and a 3T tone, the sinusoidal signal derived by AFE 413 from the 2T tone will have a period of 4T (1100), while the sinusoidal signal derived from the 3T tone will have a period of 6T (111000). If other tones are used, they will have corresponding periods.

[0032] The two sinusoidal signals from AFE 413 are input to analog-to-digital converter (ADC) 502 to provide digitized ADC samples 512. Digitized ADC samples 512 are then filtered by finite-impulse-response (FIR) filter 503 to provided FIR samples 513. A multiplexer 504 selects either digitized ADC samples 512, or FIR samples 513.

[0033] First, as described above, the tones correspond to sinusoidal signals at frequencies determined by the

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respective patterns. For some tones (e.g., 3T and 4T), the DFT process may reveal a fundamental tone and additional harmonics. Once the harmonics are identified, the portion of each signal attributable to the
5 fundamental frequency of each tone can be determined.

[0034] Multiplexer output samples 514 are input to Discrete Fourier Transform circuit 505 operating at the first (e.g., 2T) frequency and to Discrete Fourier Transform circuit 506 operating at the second (e.g., 3T)
10 frequency. In Discrete Fourier Transform (DFT) circuits 505, 506, p_1 is the period of the first frequency, p_2 is the period of the second frequency, and N is the number of samples to be accumulated. Each DFT circuit has a multiplier 515 or 516 that convolves each
15 of N samples with $\sin(2\pi t/p_1)$ or $\sin(2\pi t/p_2)$, respectively, and a multiplier 525 or 526 that convolves each of the N samples with $\cos(2\pi t/p_1)$ or $\cos(2\pi t/p_2)$, respectively. Respective accumulators 535, 536 accumulate the multiplication results over all samples.

[0035] Discrete Fourier Transform circuit 505 outputs signals s_1 and c_1 , representing the sine and cosine of the contribution of the first tone to the output of read head 300, while Discrete Fourier Transform circuit 506
25 outputs signals s_2 and c_2 , representing the sine and cosine of the contribution of the second tone to the output of read head 300. These signals s_1 , c_1 , s_2 , c_2 can be used in computation block 507 (discussed below) to determine a ratio representing how much of read head 300 is over track 301 and how much of read head 300 is over
30 track 302.

[0036] FIG. 6 shows the DFT results for 2T and 3T tones for an example in which the FIR filter equalizes the channel to the target response of [4,7,1,0,0]. As can be seen, each of the 2T tones 601 (all tones are

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fundamental) has a magnitude $A_{2T}=21.540659228538015$. The 3T tone has both fundamental (602) and harmonic (612) components; the fundamental component 602 of the 3T tone has a magnitude $A_{3T}=26.263620804789610$.

5 **[0037]** Returning to FIG. 5, block 507 can compute the magnitudes of the contributions to the samples 514 by the fundamental components of each of the 2T (all components are fundamental) and 3T tones, which may be represented as m_{2T} and m_{3T} . For an N -point DFT:

$$10 \quad m_{2T} = \frac{2}{N} \cdot \sqrt{s_1^2 + c_1^2} \quad m_{3T} = \frac{2}{N} \cdot \sqrt{s_2^2 + c_2^2}$$

The desired off-track ratio r may then be computed as follows:

$$r = (m_{2T}/A_{2T}) / (m_{3T}/A_{3T})$$

[0038] The DFT computations in block 507 can be performed by suitable arithmetic circuits (e.g., arithmetic logic units (ALUs)) that perform the arithmetic and trigonometric functions needed. Alternatively, however, block 507 could be implemented as one or more look-up tables with pre-computed results, where the values of s_1 , c_1 , s_2 , c_2 are used as addresses into the look-up table to extract the correct results.

[0039] As one example, a look-up table implementation can be configured as a two-stage operation. In a first stage, m_{2T} and m_{3T} can be derived from a look-up table using s_1 , c_1 , s_2 , c_2 as inputs. Because the expressions for m_{2T} and m_{3T} are the same (see above), this stage can be further streamlined by using the same look-up table for both the m_{2T} calculation and the m_{3T} calculation. This can be done either with a dual-port look-up table, or by time-division multiplexing a single-port look-up table, although the latter option would be slower. Or two separate look-up tables can be used, one of which determines m_{2T} from s_1 , c_1 , and the other of which

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determines m_{3T} from s_2 , c_2 . Either way, the second stage can use the m_{2T} and m_{3T} results as addresses into another look-up table that provides the value of the ratio r . Alternatively, a single look-up table can be used to
5 derive r directly from s_1 , c_1 , s_2 , c_2 , but because different combinations of s_1 , c_1 , s_2 , c_2 may yield the same value of r , such an alternative may be less efficient because it may require a larger look-up table.

[0040] Once the ratio r has been computed based on
10 reading signals from preambles 311, 312, then as is well-known, r can be used when reading user data to determine how much of the read signals are attributable to each of data payloads 331, 332, and thereby to determine those data payloads 331, 332.

15 **[0041]** A method 700 of operating a storage device according to this disclosure is diagrammed in FIG. 7. In a method including writing data, at 701, data are written to tracks on the storage medium, including a preamble for each track, where the preamble for any track is
20 orthogonal to the preamble for any adjacent track. At 702, the read head is positioned over a target track to be read. At 703, read head signals are detected. As noted above, the read head signals are likely to contain contributions from both the target track and an adjacent
25 track. At 704, preamble output of the read head is analyzed, as described above, to determine a ratio by which the read head is off-track. At 705, the ratio is used to identify and read data from target track. At 706, it is determined whether there are any additional
30 tracks to be read. If there are additional tracks to be read, method 700 returns to 702 to read those tracks. If at 706 there are no additional tracks to be read, method 700 ends. Note that a method of reading tracks

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that have previously been written would begin at 702 rather than at 701, as indicated by dashed line 707.

[0042] It will be understood that the foregoing is only illustrative of the principles of the invention, and
5 that the invention can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation, and the present invention is limited only by the claims which follow.

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WHAT IS CLAIMED IS:

1. A method of operating a storage device having a storage medium, the method comprising:

5 writing data to tracks on the storage medium,
data for each track including a preamble including a repeating pattern, wherein the repeating pattern in any first track is orthogonal to the repeating pattern in any track adjacent to the first track;

10 detecting with a read head signals from both
the first track and an adjacent track;

analyzing preamble output of the read head to determine a ratio by which the read head is off-track.

2. The method of claim 1 wherein the analyzing comprises applying a Discrete Fourier Transform to the
15 preamble output of the read head.

3. The method of claim 2 further comprising filtering the preamble output of the read head prior to the applying.

4. The method of claim 2 wherein the applying
20 comprises applying a separate Discrete Fourier Transform for a frequency corresponding to the repeating pattern on the first track and a frequency corresponding to the repeating pattern on the adjacent track.

5. The method of claim 4 wherein the analyzing
25 comprises deriving a detected magnitude and a fundamental frequency magnitude for each frequency from outputs of the Discrete Fourier Transforms.

6. The method of claim 5 further comprising:
identifying fundamental and harmonic components
30 prior to the deriving; and

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performing the deriving on only the fundamental components.

7. A method of reading data from a storage device having a storage medium to which data are written in tracks, with data on each track including a preamble including a repeating pattern, wherein the repeating pattern in any first track is orthogonal to the repeating pattern in any track adjacent to the first track, the method comprising:

detecting the first track with a read head subject to off-track excursions during which the read head detects signals from both the first track and an adjacent track;

analyzing preamble output of the read head to determine a ratio by which the read head is off-track.

8. The method of claim 7 wherein the analyzing comprises applying a Discrete Fourier Transform to the preamble output of the read head.

9. The method of claim 8 further comprising filtering the preamble output of the read head prior to the applying.

10. The method of claim 8 wherein the applying comprises applying a separate Discrete Fourier Transform for a frequency corresponding to the repeating pattern on the first track and a frequency corresponding to the repeating pattern on the adjacent track.

11. The method of claim 10 wherein the analyzing comprises deriving a detected magnitude and a fundamental frequency magnitude for each frequency from outputs of the Discrete Fourier Transforms.

12. The method of claim 11 further comprising:

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identifying fundamental and harmonic components prior to the deriving; and performing the deriving on only the fundamental components.

- 5 13. A storage device comprising:
 read circuitry including:
 a read head having a detector that outputs
 signals representing data from a first track and an adjacent
 track, the read head being subject to off-track excursions
10 during which the read head detects signals from both the first
 track and an adjacent track, data on each track including a
 preamble including a repeating pattern, wherein the repeating
 pattern in any first track is orthogonal to the repeating
 pattern in any track adjacent to the first track;
15 respective Discrete Fourier Transform circuits
 to identify components in the signals corresponding to
 respective frequencies characteristic of the repeating pattern
 on the first track and the repeating pattern on the second
 track; and
20 computation circuitry to determine from the
 components a ratio by which the read head is off-track.

14. The storage device of claim 13 wherein:
 the detector outputs analog signals; and
 the read circuitry further comprises analog-to-
25 digital converter circuitry that outputs samples of the analog
 signals for input to the respective Discrete Fourier Transform
 circuits.

15. The storage device of claim 14 further
 comprising filter circuitry between the analog-to-digital
30 converter circuitry and the respective Discrete Fourier
 Transform circuits.

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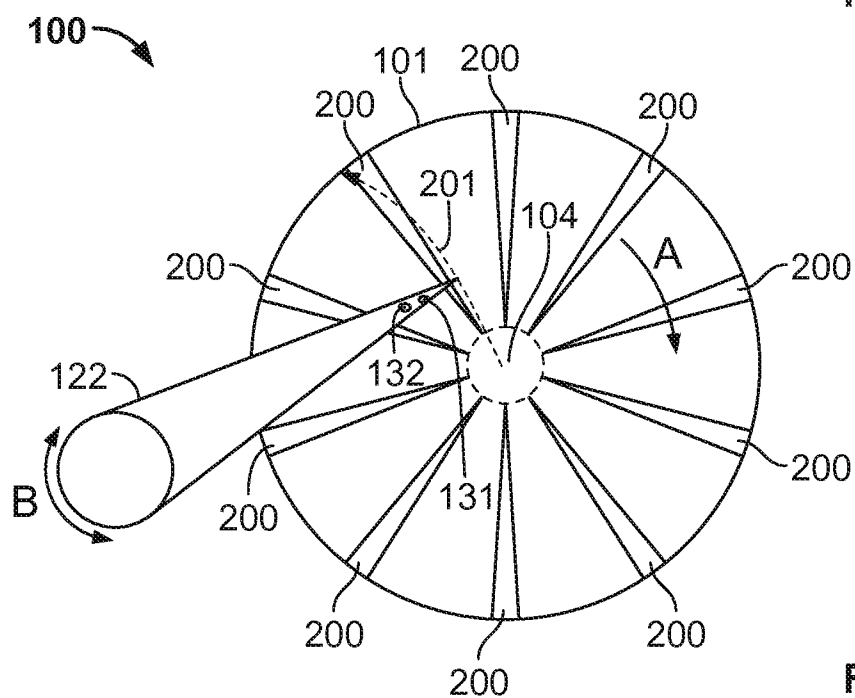
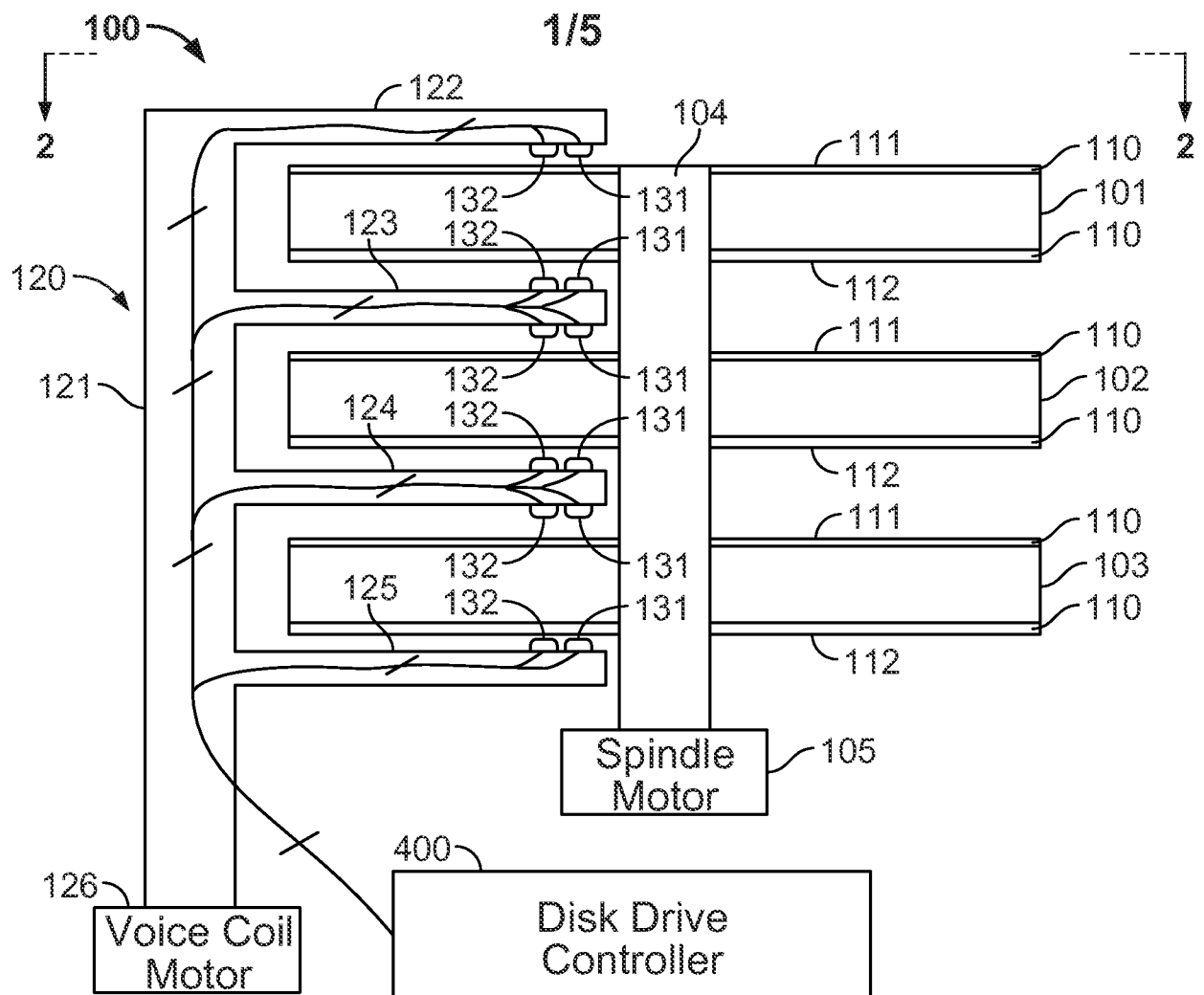
16. The storage device of claim 15 wherein the filter circuitry comprises a finite impulse response filter.

17. The storage device of claim 14 wherein the computation circuitry derives a detected magnitude and a
5 fundamental frequency magnitude for each frequency from outputs of the Discrete Fourier Transform circuits.

18. The storage device of claim 17 wherein:
the computation circuitry comprises a look-up
table; and
10 the outputs of the Discrete Fourier Transform circuits are addresses into the look-up table.

19. The storage device of claim 18 further comprising filter circuitry on outputs of the analog-to-digital converter circuitry; wherein:
15 the computation circuitry operates also on output from the filter circuitry.

20. The storage device of claim 19 wherein the filter circuitry comprises finite impulse response filter circuitry.



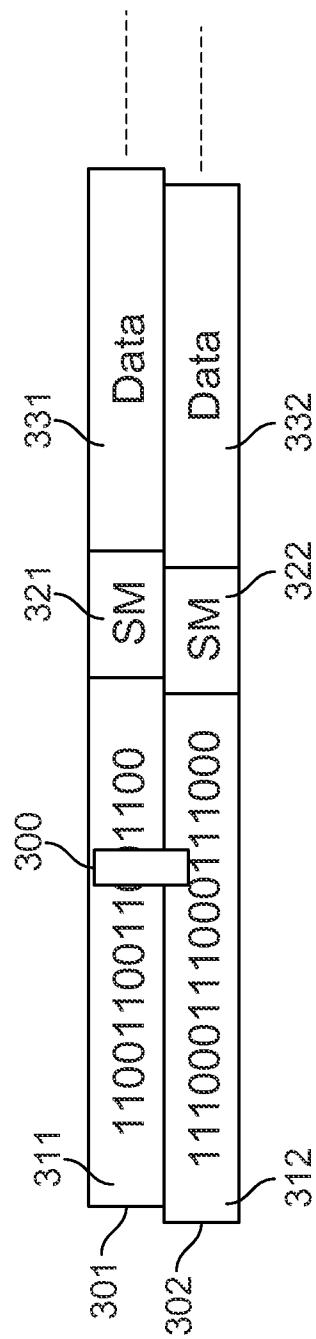


FIG. 3

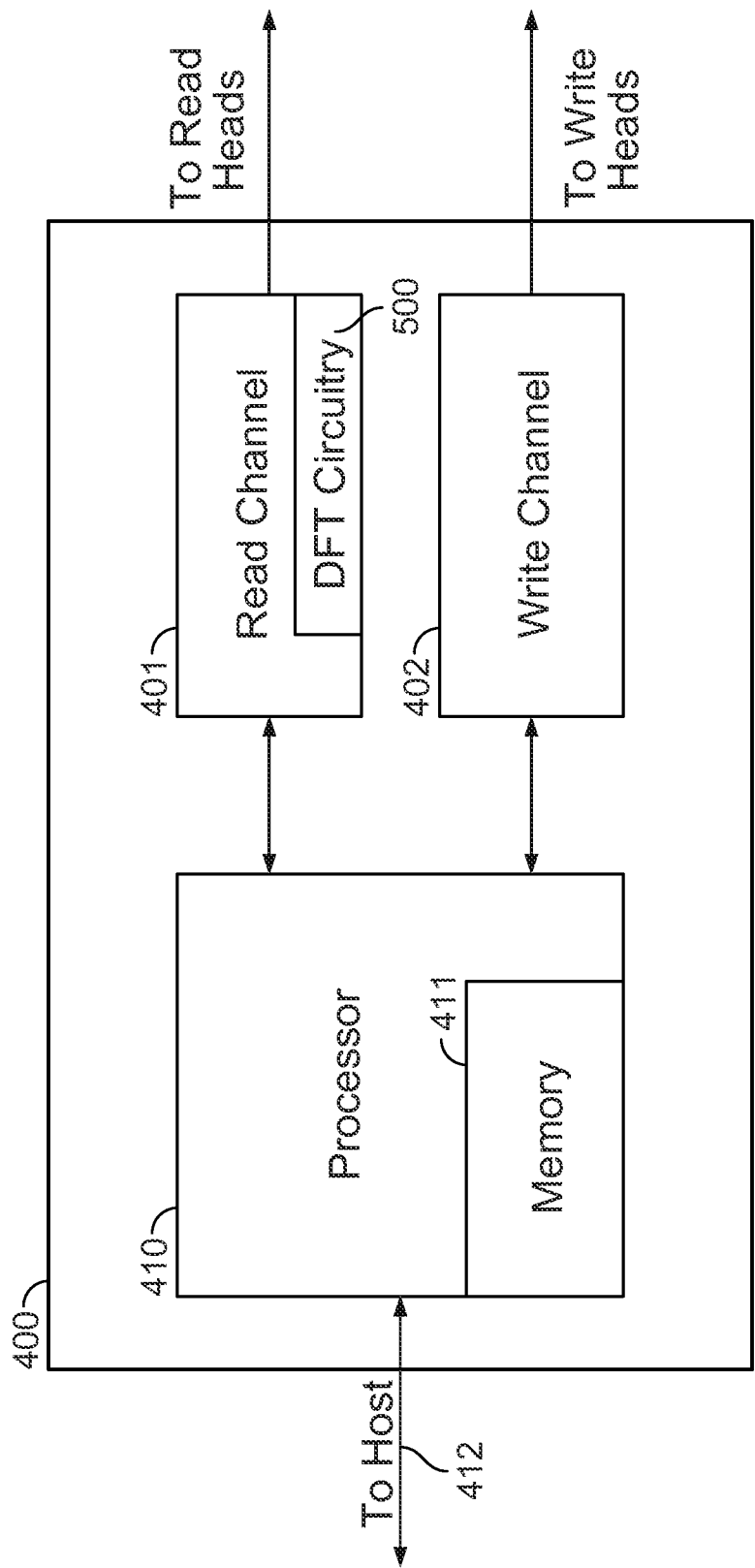


FIG. 4

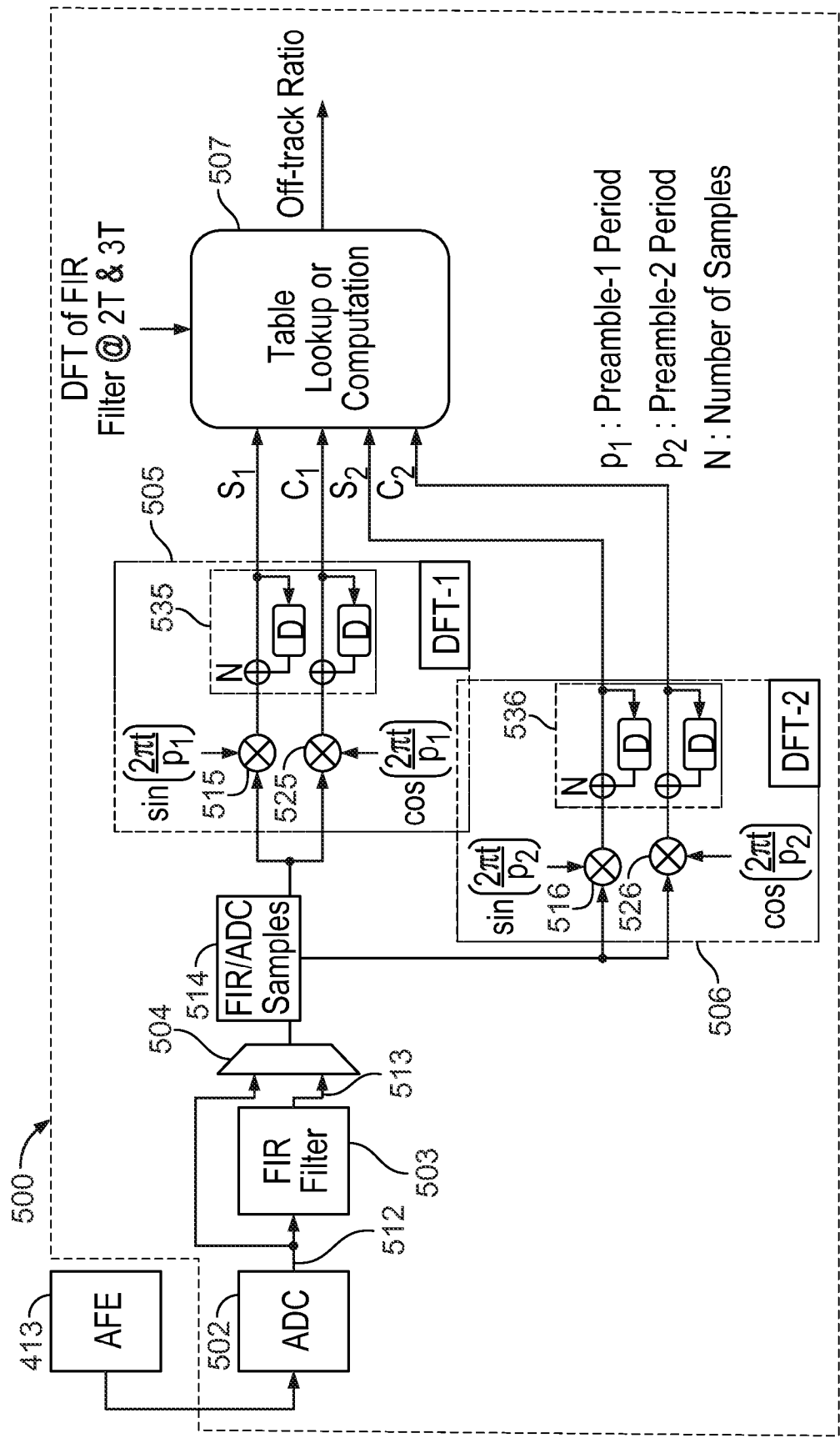


FIG. 5

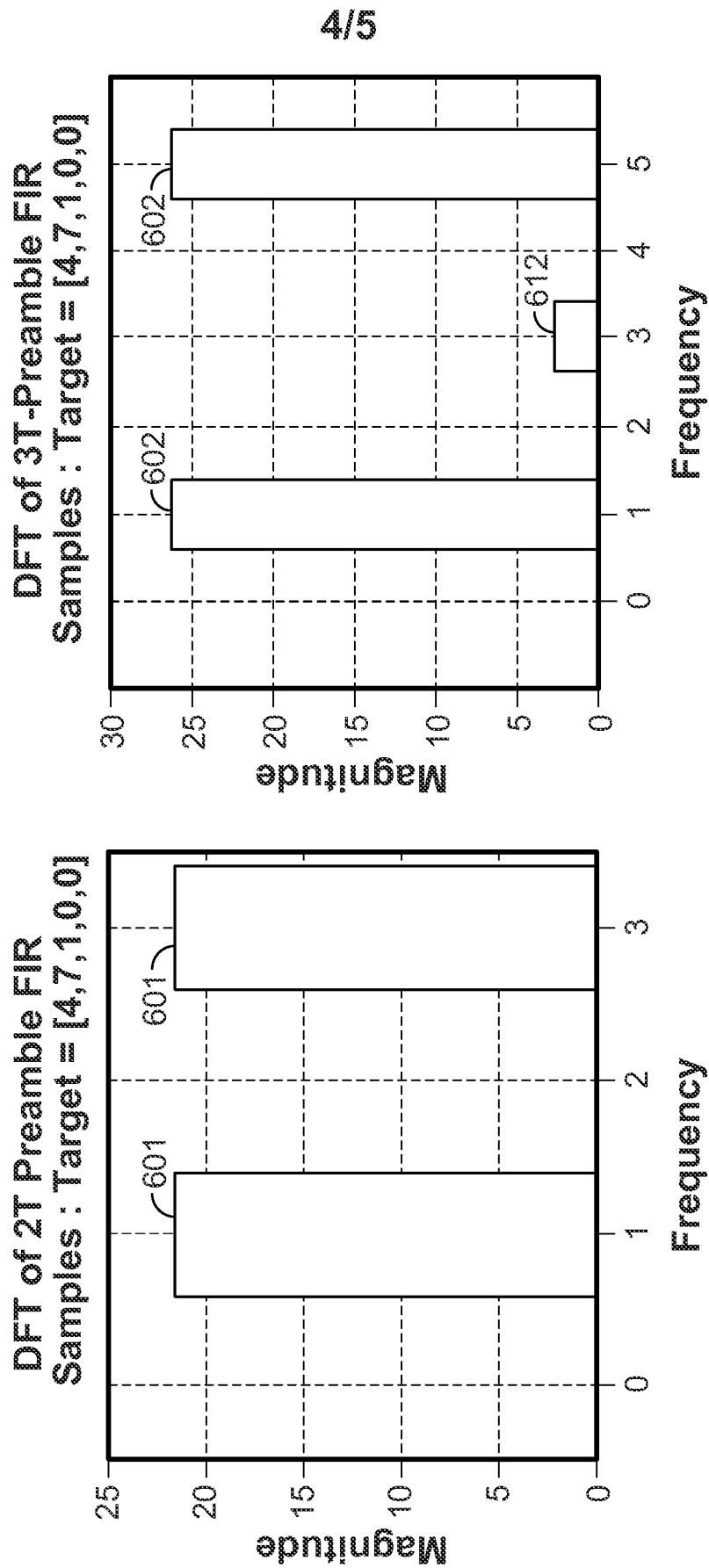


FIG. 6

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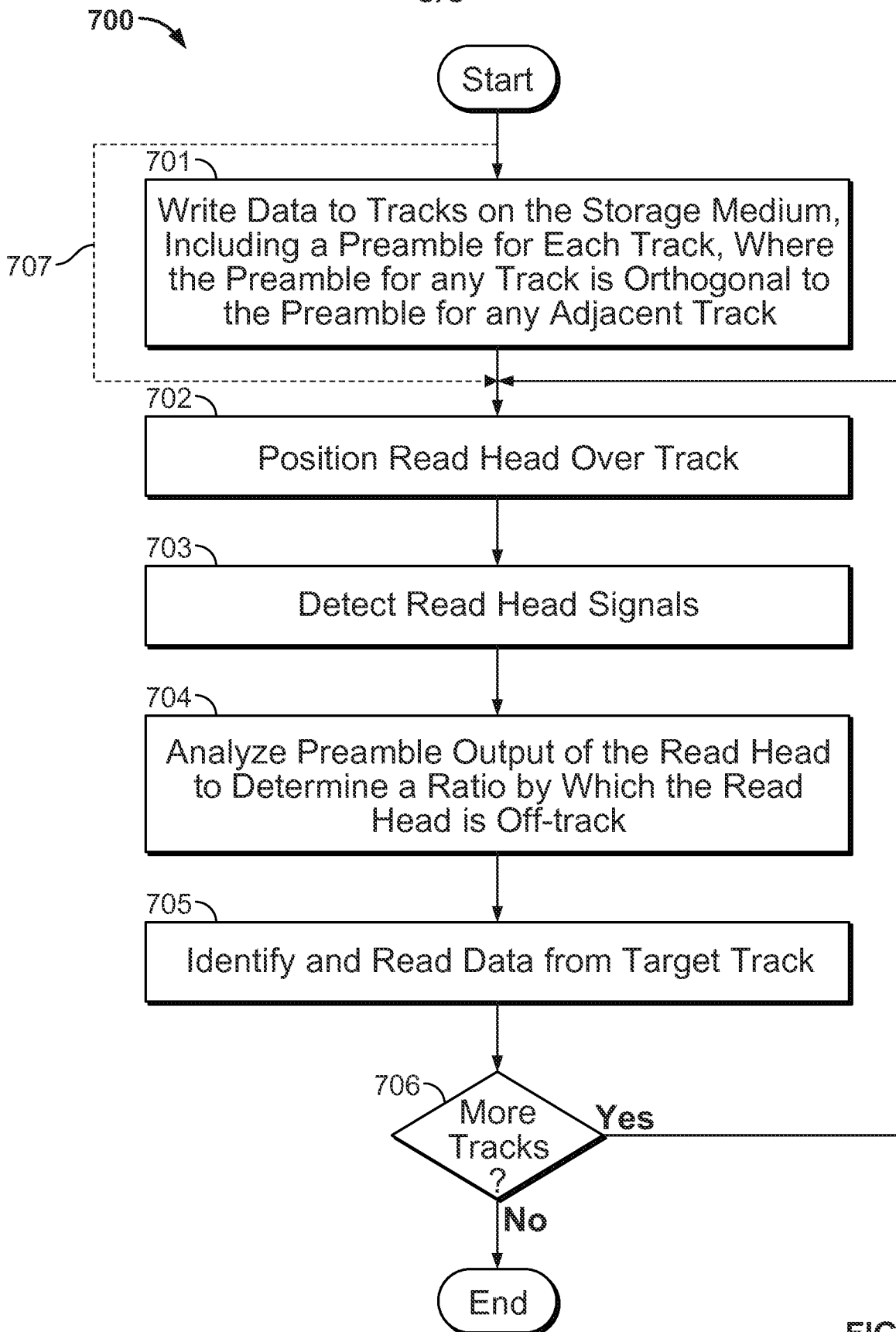


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/040157

A. CLASSIFICATION OF SUBJECT MATTER

INV. G11B20/10 G11B20/12 G11B20/14 G11B5/012 G11B5/09
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ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G11B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 342 734 B1 (PATAPOUTIAN ARA [US] ET AL) 11 March 2008 (2008-03-11) the whole document	1-3,7-9, 13-16
X	US 2011/149432 A1 (COKER JONATHAN DARREL [US] ET AL) 23 June 2011 (2011-06-23) the whole document	1,7
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Information on patent family members

International application No

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