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(54) **FINE ACTUATOR REACTION FORCE CANCELLATION FLEXIBLE SUSPENSION**

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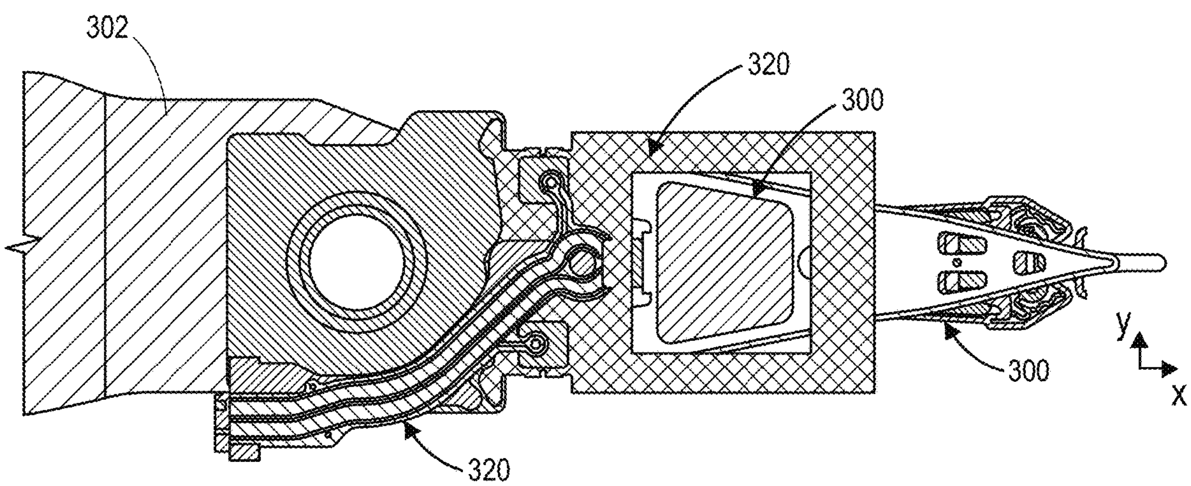
(57) **ABSTRACT**

A head stack assembly (HSA) for a hard disk drive includes a carriage from which multiple arms extend, where the arms include an outer arm at each end of the carriage and inner arms between the outer arms, such that each inner arm carries two suspension assemblies and each outer arm carries only one suspension assembly coupled with an inner side of the outer arm, with each suspension assembly including a corresponding fine actuator. The HSA further includes a counter-suspension assembly coupled to an outer side of each outer arm, where each counter-suspension assembly includes a structurally flexible dummy load beam having a mass distribution and a stiffness distribution configured to mitigate multiple structural dynamics modes of the operating suspension assembly coupled to the inner side of the outer arm.



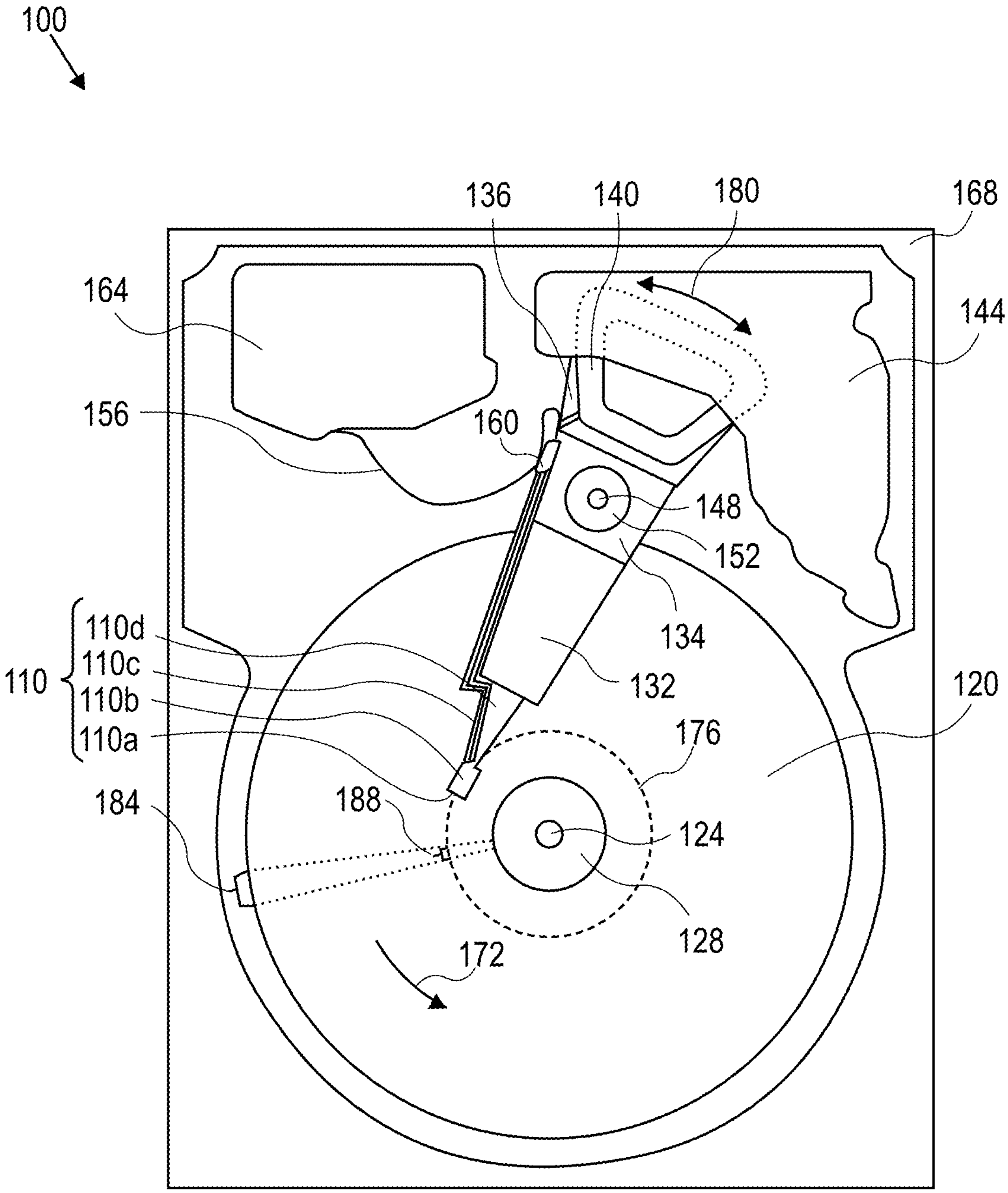

100
136
140
180
168
164
144
156
160
148
152
134
110d
110c
110
110b
110a
132
120
176
184
188
124
128
172

FIG. 1

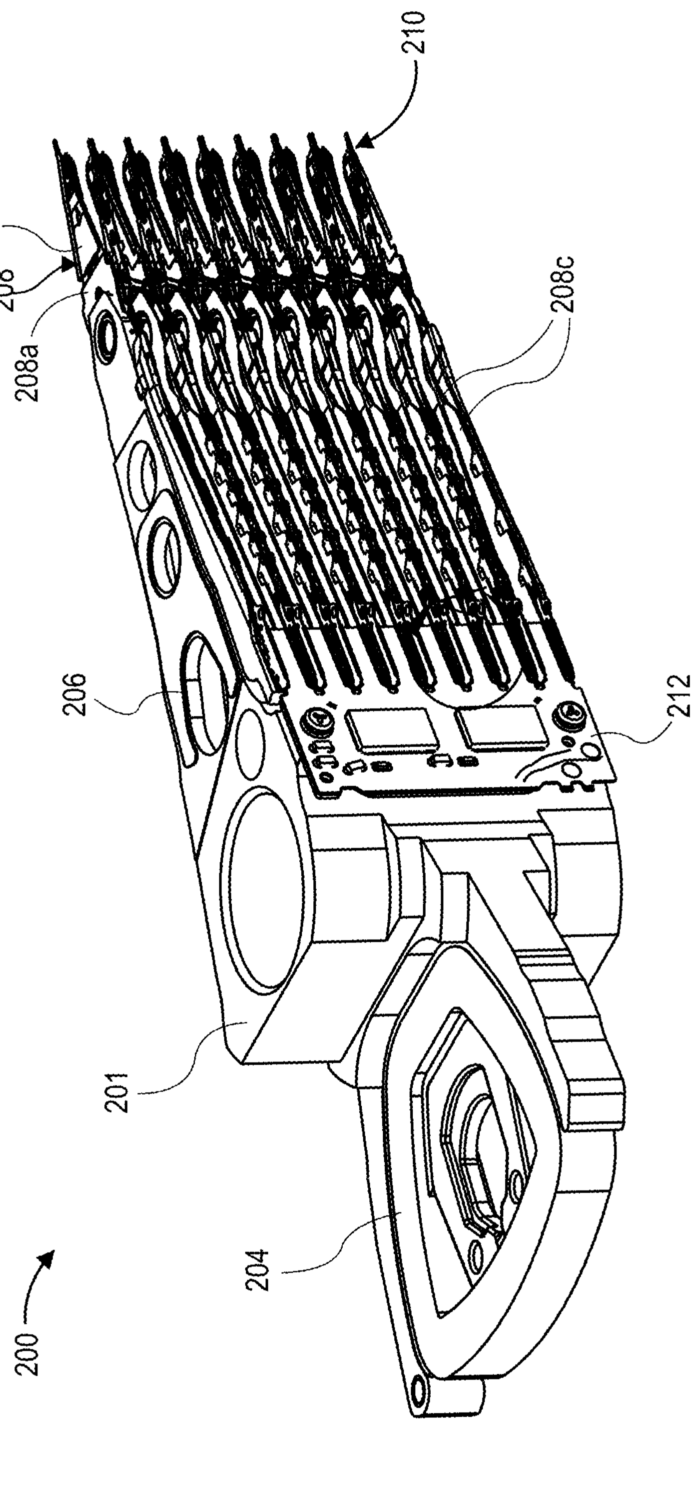


FIG. 2

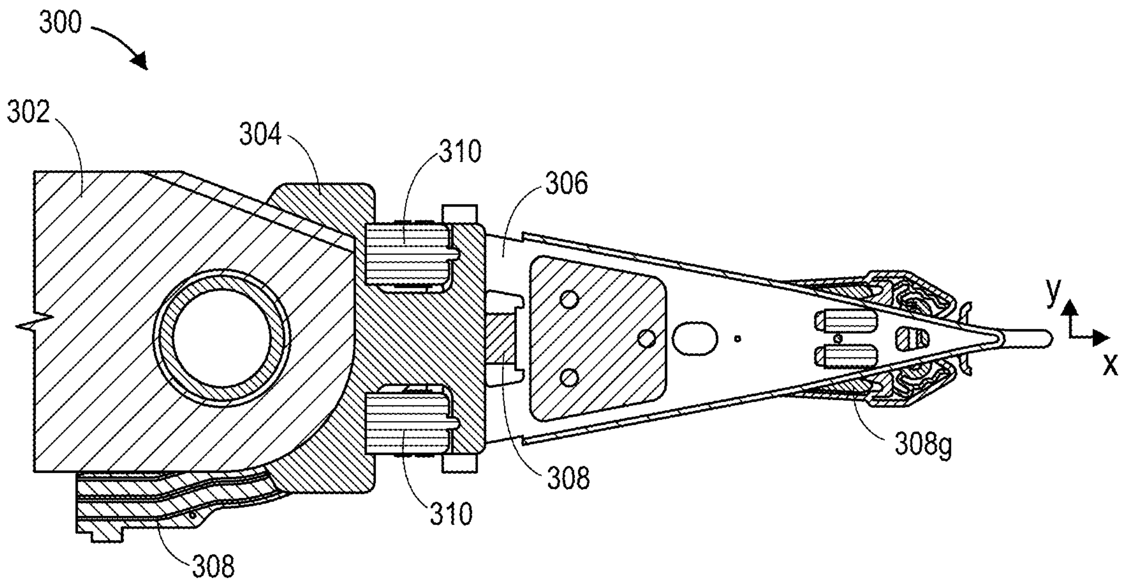

300
302
304
310
306
y
x
308g
308
310
308

FIG. 3A

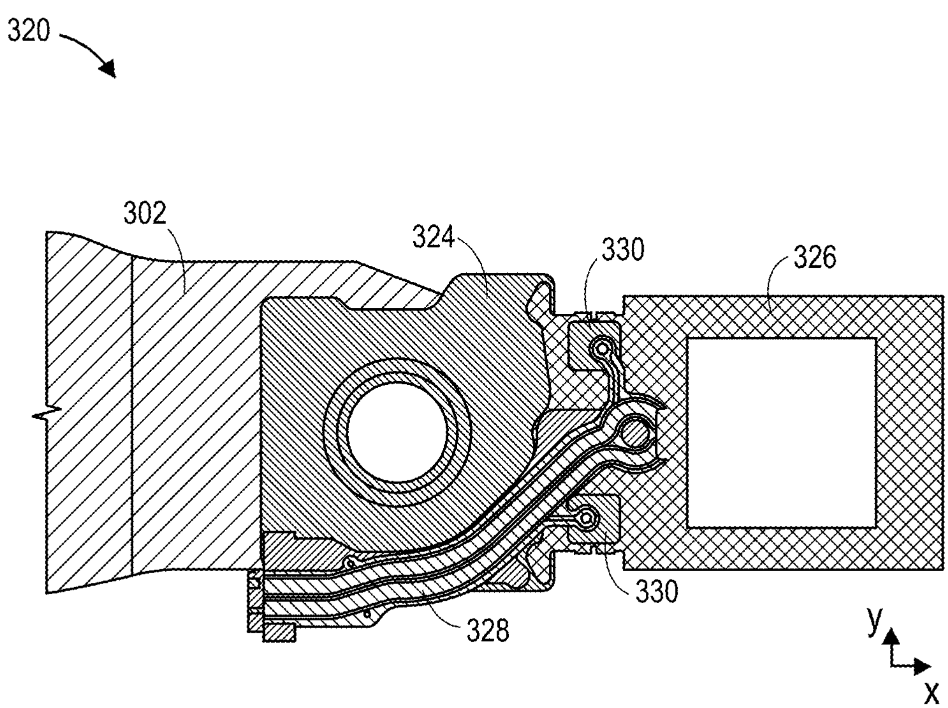

320
302
324
330
326
330
328
y
x

FIG. 3B

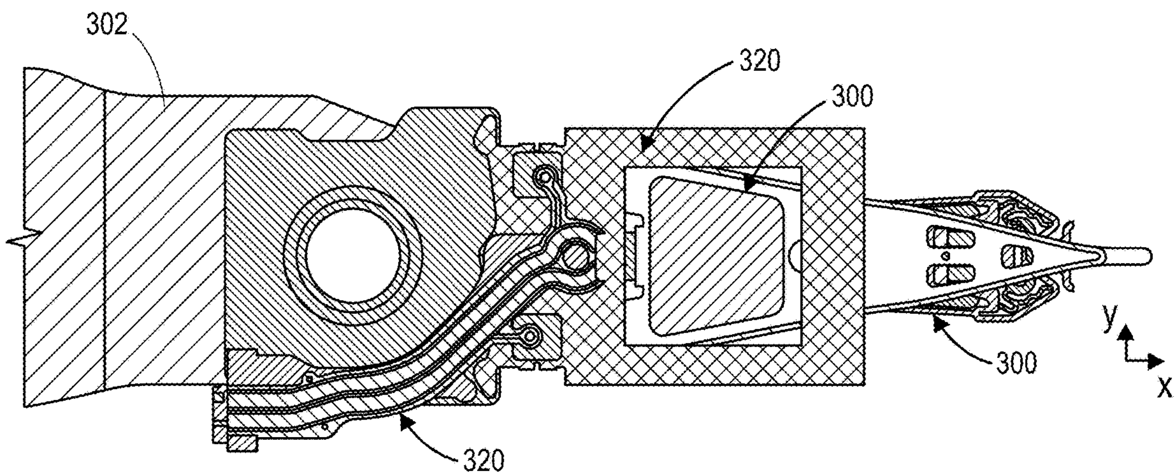


FIG. 3C

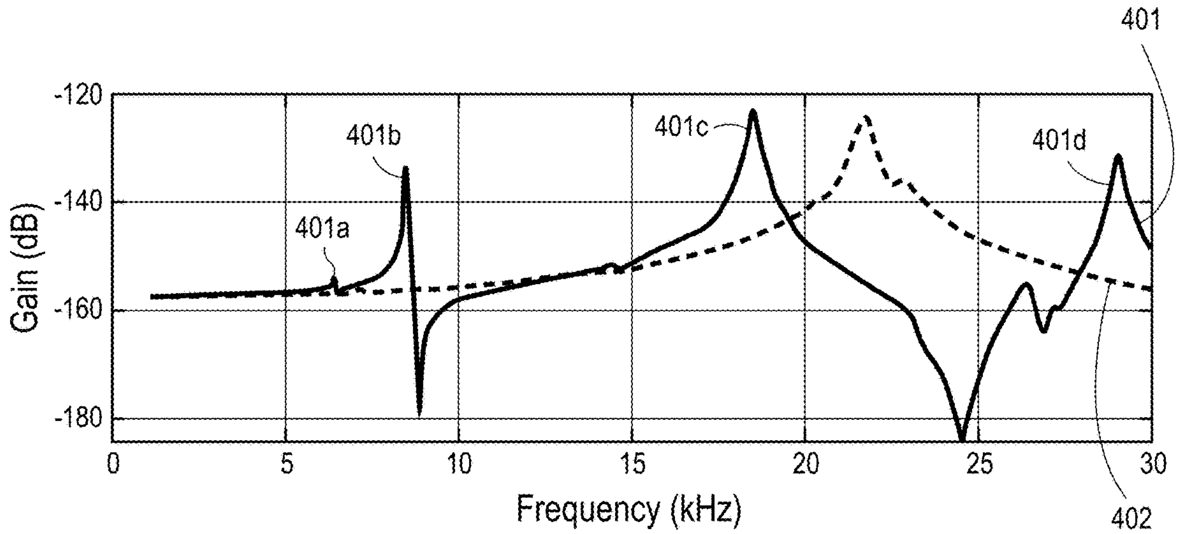

401
-120
-140
-160
-180
Gain (dB)
401a
401b
401c
401d
0
5
10
15
20
25
30
Frequency (kHz)
402

FIG. 4A

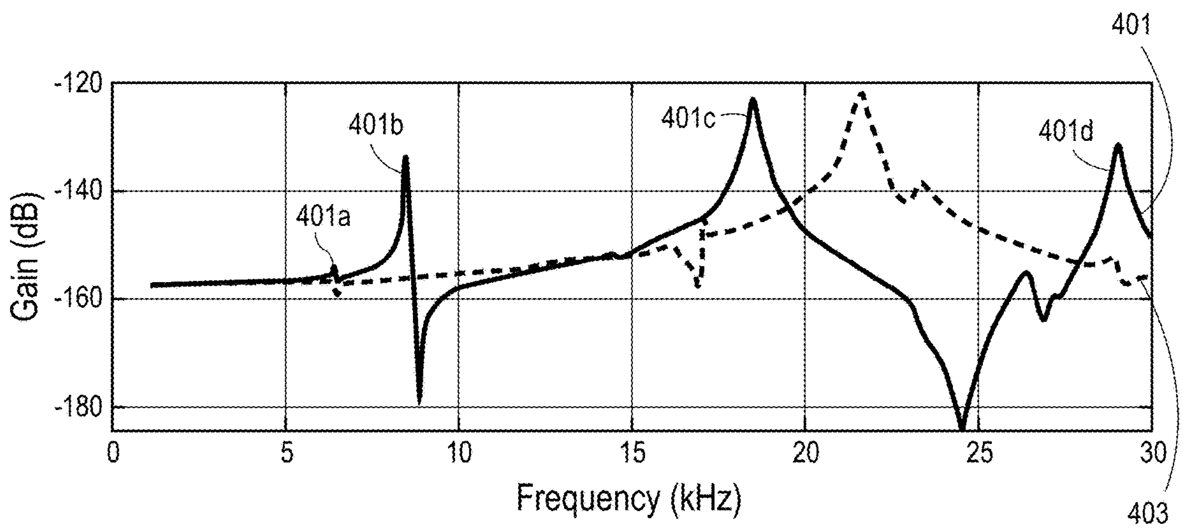

401
-120
-140
-160
-180
Gain (dB)
401a
401b
401c
401d
0
5
10
15
20
25
30
Frequency (kHz)
403

FIG. 4B

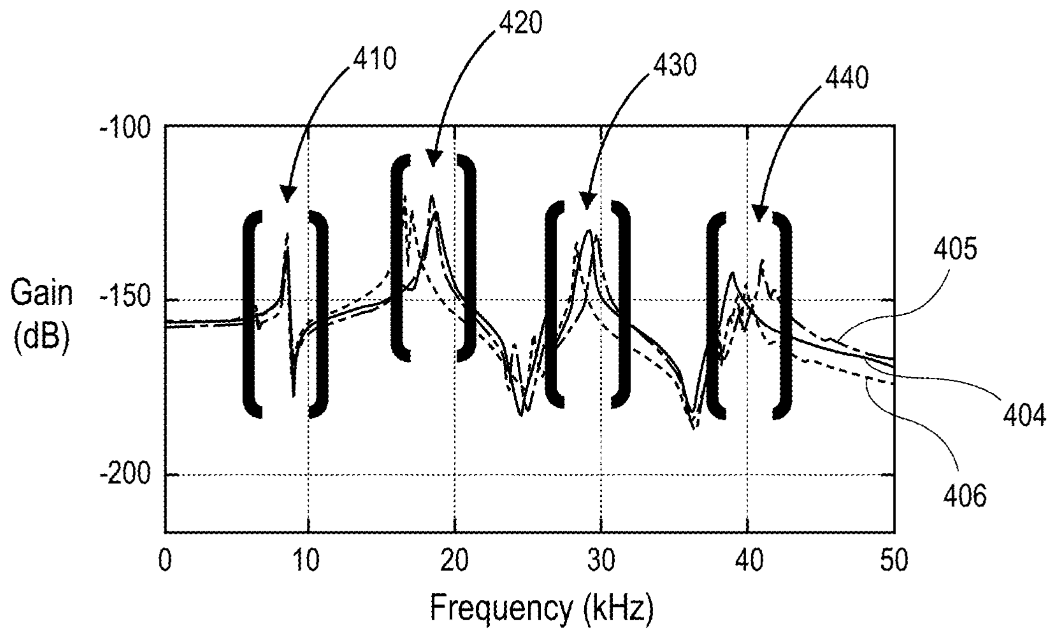

410
420
430
440
405
404
406
Gain (dB)
-100
-150
-200
0
10
20
30
40
50
Frequency (kHz)

FIG. 4C

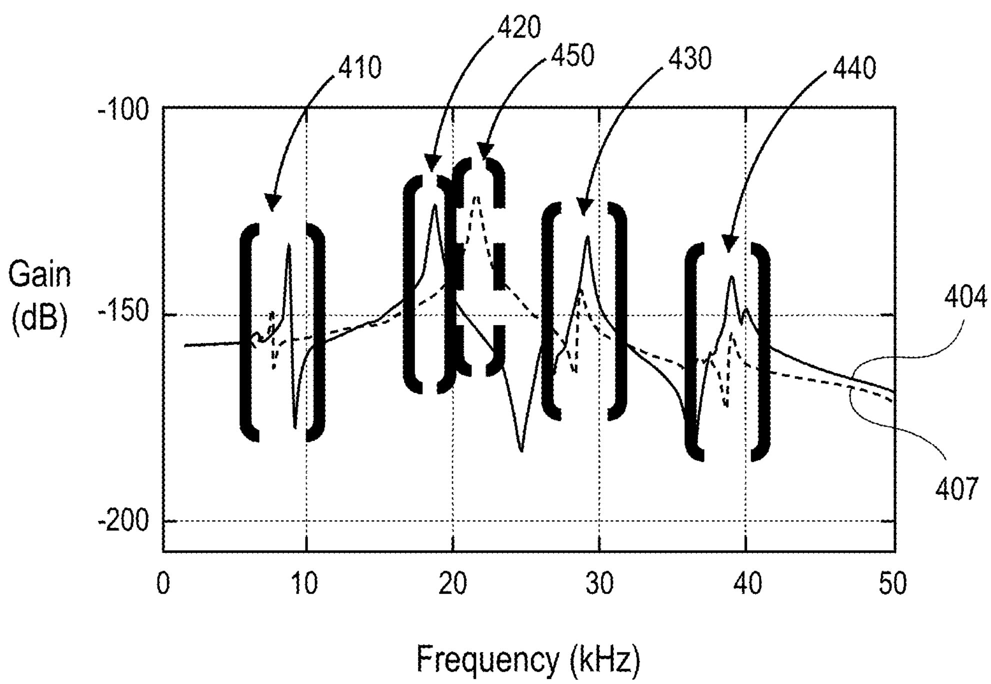

410
420
450
430
440
404
407
Gain (dB)
-100
-150
-200
0
10
20
30
40
50
Frequency (kHz)

FIG. 4D

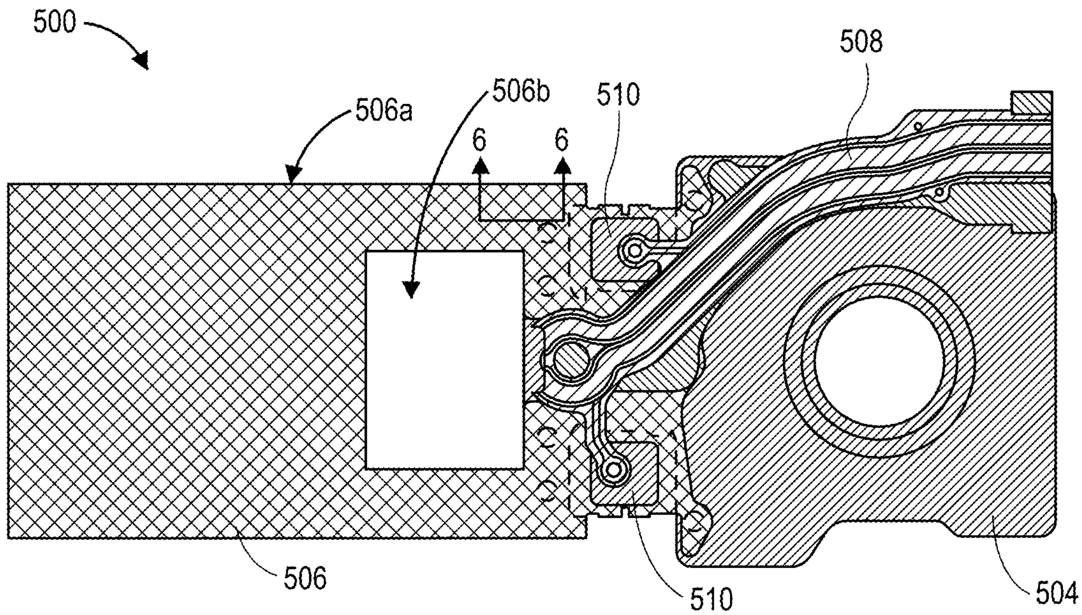

500
506a
506b
6
6
510
508
506
510
504

FIG. 5A

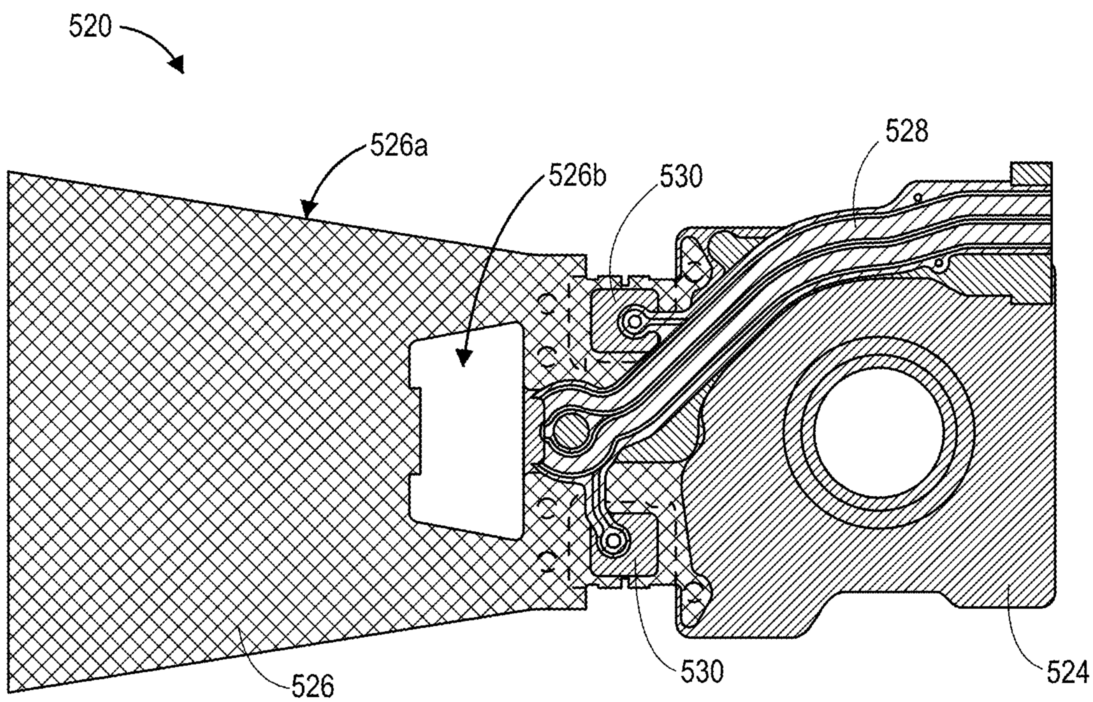

520
526a
526b
530
528
526
530
524

FIG. 5B

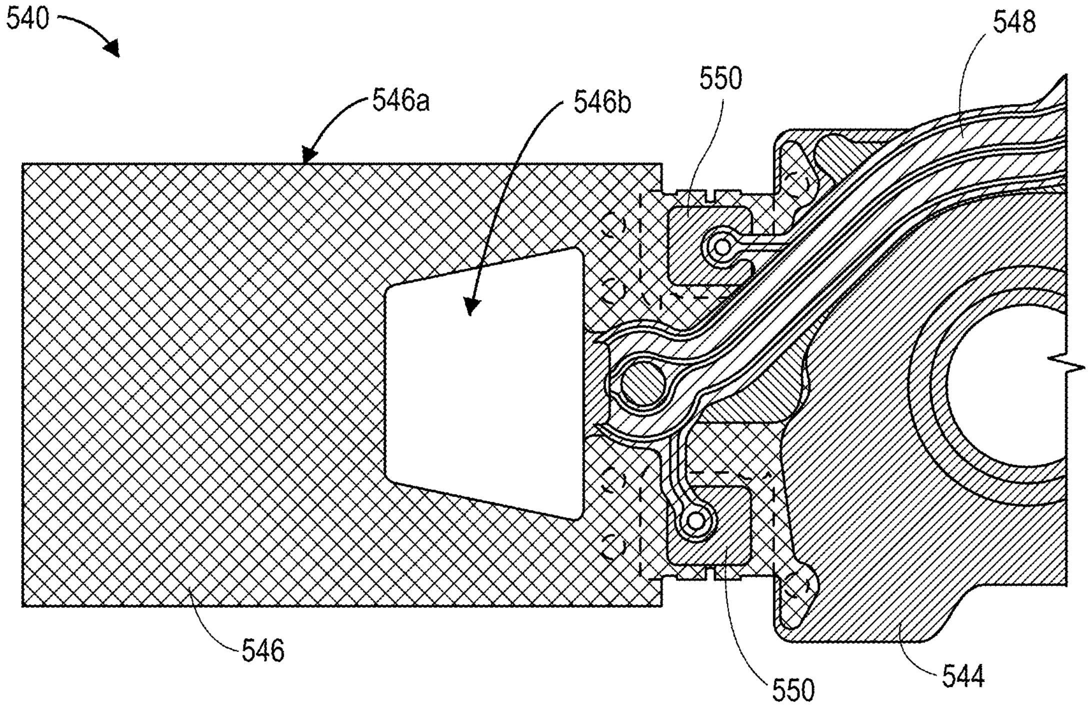

540
546a
546b
550
548
546
550
544

FIG. 5C

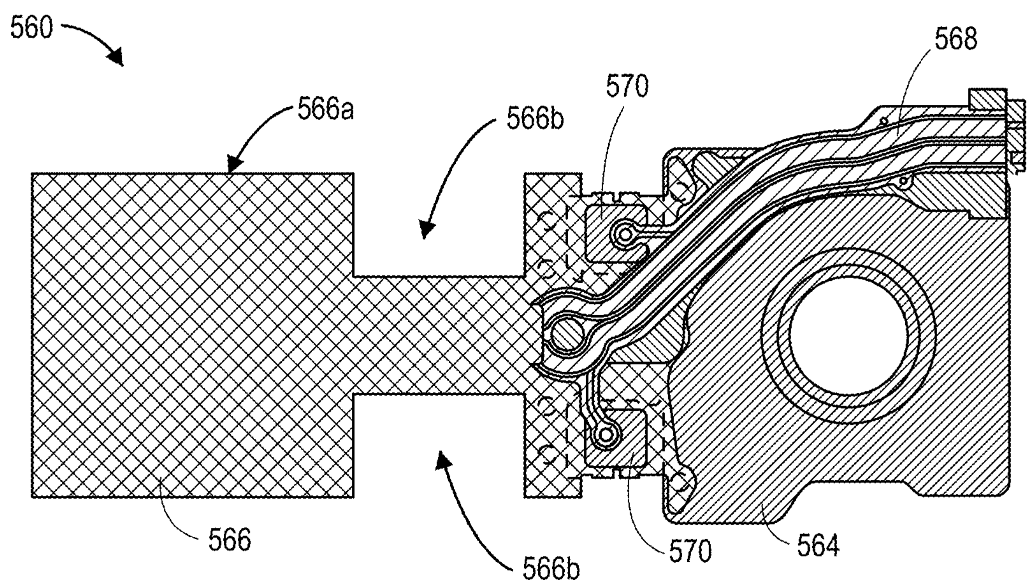

560
566a
566b
570
568
566
566b
570
564

FIG. 5D

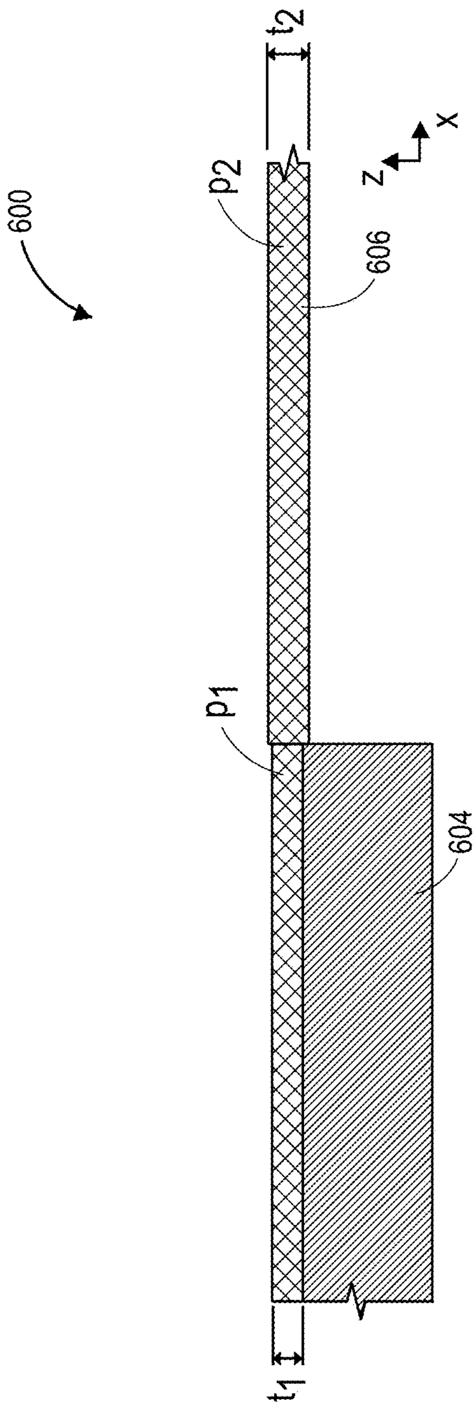


FIG. 6

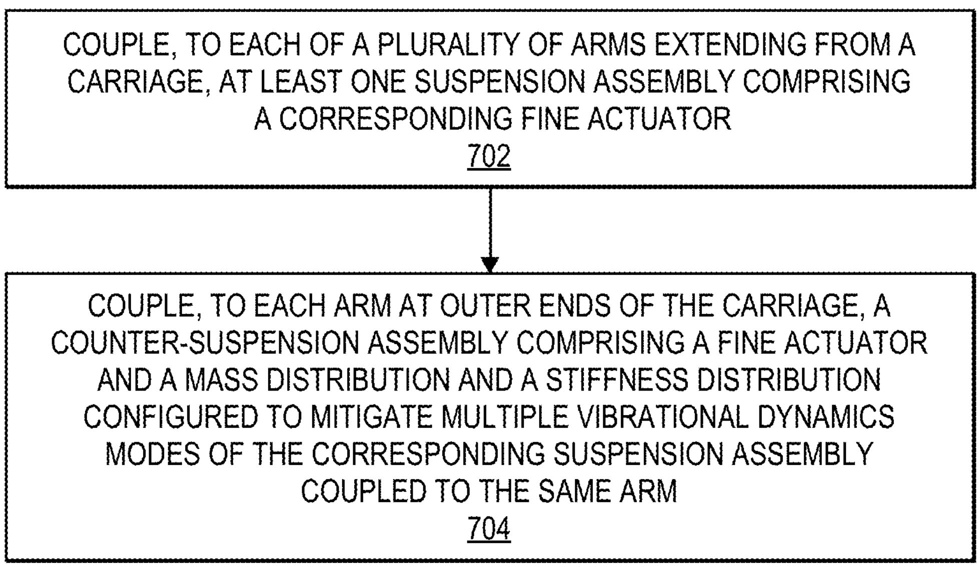

COUPLE, TO EACH OF A PLURALITY OF ARMS EXTENDING FROM A CARRIAGE, AT LEAST ONE SUSPENSION ASSEMBLY COMPRISING A CORRESPONDING FINE ACTUATOR
702
COUPLE, TO EACH ARM AT OUTER ENDS OF THE CARRIAGE, A COUNTER-SUSPENSION ASSEMBLY COMPRISING A FINE ACTUATOR AND A MASS DISTRIBUTION AND A STIFFNESS DISTRIBUTION CONFIGURED TO MITIGATE MULTIPLE VIBRATIONAL DYNAMICS MODES OF THE CORRESPONDING SUSPENSION ASSEMBLY COUPLED TO THE SAME ARM
704

FIG. 7

FINE ACTUATOR REACTION FORCE CANCELLATION FLEXIBLE SUSPENSION

FIELD OF EMBODIMENTS

[0001] Embodiments of the invention may relate generally to a hard disk drive and particularly to a flexible suspension assembly for fine actuator reaction force cancellation.

BACKGROUND

[0002] A hard disk drive (HDD) is a non-volatile storage device that is housed in a protective enclosure and stores digitally encoded data on one or more circular disks having magnetic surfaces. When an HDD is in operation, each magnetic-recording disk is rapidly rotated by a spindle system. Data is read from and written to a magnetic-recording disk using a read-write head (or "transducer") that is positioned over a specific location of a disk by an actuator. A read-write head makes use of magnetic fields to write data to and read data from the surface of a magnetic-recording disk. A write head works by using the current flowing through its coil to produce a magnetic field. Electrical pulses are sent to the write head, with different patterns of positive and negative currents. The current in the coil of the write head produces a localized magnetic field across the gap between the head and the magnetic disk, which in turn magnetizes a small area on the recording medium.

[0003] An HDD includes at least one head gimbal assembly (HGA) that generally includes a suspension assembly and a corresponding head slider mounted thereon and which houses the read/write transducer (or "head"). Each slider is attached to the free end of the suspension assembly that is cantilevered from the rigid arm of an actuator. Several actuator arms may be combined to form a single movable unit, a head stack assembly (HSA), typically having a rotary pivotal bearing system. The suspension assembly of a conventional HDD typically includes a relatively stiff load beam with a mount plate at its base end, which attaches to the actuator arm, and whose free end mounts a flexure (or "gimbal" or "gimbal flexure") that carries the slider and its read-write head. Positioned between the mount plate and the functional end of the load beam is effectively a "hinge" that is compliant in the vertical bending direction (normal to the disk surface). The hinge enables the load beam to suspend and load the slider and the read-write head toward the spinning disk surface. It is then the function of the flexure to provide gimbaled support for the slider so that the slider can pitch and roll (i.e., can gimbal) in order to adjust its orientation.

[0004] Increasing areal density (a measure of the quantity of information bits that can be stored on a given area of disk surface) has led to the necessary development and implementation of secondary and even tertiary actuators (generally, "fine actuators") for improved head positioning through relatively fine positioning, in addition to a primary voice coil motor (VCM) actuator which provides relatively coarse positioning. Some HDDs employ milli- or micro-actuator designs to provide second and/or third stage actuation of the recording head to enable more accurate positioning of the head relative to the recording tracks. Milli-actuators may be broadly classified as actuators that move the entire front end of the suspension: e.g., load beam, flexure and slider, and are typically used as second stage actuators. Micro-actuators (or "microactuators") may be broadly classified as actuators that move (e.g., rotate) only the slider, moving it relative to the suspension and load beam, or move only the read-write element relative to the slider body. A microactuator may be used solely in conjunction with a first stage actuator (e.g., VCM), or in conjunction with a first stage actuator and a second stage actuator (e.g., milli-actuator) for more accurate head positioning. Unless otherwise indicated, the terms "microactuator", "milli-actuator", "secondary actuator", "tertiary actuator", "dual stage actuator", "fine actuator" and the like, if used herein, refer generally to a relatively fine-positioning actuator (e.g., technically, either secondary or tertiary) used in conjunction with a primary relatively coarse-positioning actuator, such as a VCM actuator in the context of an HDD. Piezoelectric (PZT) based and capacitive micro-machined transducers are two types of fine-actuators that have been developed for use with HDD sliders.

[0005] Any approaches that may be described in this section are approaches that could be pursued, but not necessarily approaches that have been previously conceived or pursued. Therefore, unless otherwise indicated, it should not be assumed that any of the approaches described in this section qualify as prior art merely by virtue of their inclusion in this section.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Embodiments are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

[0007] FIG. **1** is a plan view illustrating a hard disk drive, according to an embodiment;

[0008] FIG. **2** is a perspective view illustrating an actuator assembly, according to an embodiment;

[0009] FIG. **3**A is a plan view illustrating a hard disk drive suspension assembly coupled to an arm on the inner side, according to an embodiment;

[0010] FIG. **3**B is a plan view illustrating a hard disk drive counter-suspension assembly coupled to an arm on the outer side, according to an embodiment;

[0011] FIG. **3**C is a plan view illustrating the suspension assembly of FIG. **3**A and the counter-suspension assembly of FIG. **3**B mounted on the shared arm, according to an embodiment;

[0012] FIG. **4**A is a graph illustrating example frequency response functions, including for a single conventional and mirrored suspension assemblies on shared arm, according to an embodiment;

[0013] FIG. **4**B is a graph illustrating example frequency response functions, including for a single conventional and with a counter-suspension assembly on shared arm, according to an embodiment;

[0014] FIG. **4**C is a graph illustrating example frequency response functions, including for single conventional and counter-suspension assemblies, according to an embodiment;

[0015] FIG. **4**D is a graph illustrating example frequency response functions, including for a single conventional and with a counter-suspension assembly on shared arm, according to an embodiment;

[0016] FIG. **5**A is a plan view illustrating a first example counter-suspension assembly, according to an embodiment;

[0017] FIG. **5**B is a plan view illustrating a second example counter-suspension assembly, according to an embodiment;

[0018] FIG. **5**C is a plan view illustrating a third example counter-suspension assembly, according to an embodiment;

[0019] FIG. **5**D is a plan view illustrating a fourth example counter-suspension assembly, according to an embodiment;

[0020] FIG. **6** is a cross-sectional side view illustrating an example counter-suspension assembly having non-uniform thickness, according to an embodiment; and

[0021] FIG. **7** is a flow diagram illustrating a method of manufacturing a head stack assembly (HSA), according to an embodiment.

DETAILED DESCRIPTION

[0022] Generally, approaches to fine actuator reaction force cancellation for a suspension assembly of a head-gimbal assembly (HGA) for a hard disk drive (HDD) are described. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the embodiments of the invention described herein. It will be apparent, however, that the embodiments of the invention described herein may be practiced without these specific details. In other instances, well-known structures and devices may be shown in block diagram form in order to avoid unnecessarily obscuring the embodiments of the invention described herein.

Introduction

Terminology

[0023] References herein to “an embodiment”, “one embodiment”, and the like, are intended to mean that the particular feature, structure, or characteristic being described is included in at least one embodiment of the invention. However, instances of such phrases do not necessarily all refer to the same embodiment,

[0024] The term “substantially” will be understood to describe a feature that is largely or nearly structured, configured, dimensioned, etc., but with which manufacturing tolerances and the like may in practice result in a situation in which the structure, configuration, dimension, etc. is not always or necessarily precisely as stated. For example, describing a structure as “substantially vertical” would assign that term its plain meaning, such that the sidewall is vertical for all practical purposes but may not be precisely at 90 degrees throughout.

[0025] While terms such as “optimal”, “optimize”, “minimal”, “minimize”, “maximal”, “maximize”, and the like may not have certain values associated therewith, if such terms are used herein the intent is that one of ordinary skill in the art would understand such terms to include affecting a value, parameter, metric, and the like in a beneficial direction consistent with the totality of this disclosure. For example, describing a value of something as “minimal” does not require that the value actually be equal to some theoretical minimum (e.g., zero), but should be understood in a practical sense in that a corresponding goal would be to move the value in a beneficial direction toward a theoretical minimum.

Context

[0026] FIG. **2** is a perspective view illustrating an actuator assembly, according to an embodiment. Actuator assembly **200** comprises a carriage **201** (see, e.g., carriage **134** of FIG. **1**) rotatably coupled with a central pivot shaft (not shown here; see, e.g., pivot shaft **148** of FIG. **1**) by way of a pivot bearing assembly (not shown here; see, e.g., pivot bearing assembly **152** of FIG. **1**), and rotationally driven by a voice coil motor (VCM), of which a voice coil **204** is illustrated here. Actuator assembly **200** further comprises multiple actuator arms **206** (see, e.g., arm **132** of FIG. **1**), to each of which is coupled a suspension assembly **208** (see, e.g., lead suspension **110***c* of FIG. **1**) housing a read-write head **210** (see, e.g., read-write head **110***a* of FIG. **1**), and typically comprising a swaged baseplate **208***a*, a load beam **208***b* (see, e.g., load beam **110***d* of FIG. **1**), and a suspension tail **208***c*. Each suspension assembly **208** is electrically connected with a flexible printed circuit (FPC) **212** coupled with the carriage **201**, by way of suspension tail **208***c*.

[0027] Recall that fine actuators were developed and implemented for improved head positioning through relatively fine positioning, in addition to a primary voice coil motor (VCM) actuator which provides relatively coarse positioning. A hard disk drive (HDD) head stack assembly (HSA) typically contains multiple arms. The top and bottom arms of the HSA, also referred to as outer arms, carry only one suspension with a head to read/write (R/W) data on a media surface. By contrast, the inner arms of the HSA carry two suspensions on each arm, i.e., one suspension with an up-facing head to R/W on the bottom media surface of an above disk and the other suspension with a down-facing head to R/W data on the top media surface of an adjacent below disk. For suspensions integrated with PZT actuators, it is often beneficial to fine-drive the up and down facing suspensions in opposite directions (out-of-phase) so that the reaction forces induced on the common arm are cancelled. This leads to better performance with less resonance peaks in the fine actuator transfer function (TF). A TF, also referred to as a Frequency Response Function (FRF), is used to express the dynamic characteristics of a structure in frequency domain with peaks at its resonant frequencies and gains of those peaks related to the damping for those resonances and how external forces are applied. This cancellation is effective for inner arms carrying two suspensions as the reaction forces from the two suspension fine actuators are of the same amplitude but out of phase and, therefore, cancel each other. However, there is no opposing suspension to fine-drive for reaction force cancellation for the outer arms carrying only one suspension.

[0028] Due to the absence of reaction force cancellation on the outer arms, when the fine actuators on all suspensions are driven in parallel, the reaction forces from outer arms responsively create extra resonance peaks for inner heads. One solution is to use a demultiplexer (“demux”) to fine-drive inner arm heads separately from outer arm heads, at least one approach to which is described in U.S. Pat. No. 11,482,254, the entire content of which is incorporated by reference for all purposes as if fully set forth herein. Such demux control circuitry decouples inner arm heads from outer arm heads to achieve significantly effective reaction force cancellation for the inner arm heads, resulting in a better TF. However, fine actuator TF of outer heads is still not as good as fine actuator TF of inner heads due to the absence of reaction force cancellation in that context.

Flexible Counter-Suspension Assembly

[0029] To address the foregoing challenges associated with the performance of the outer heads, as may manifest in the expression of a corresponding FRF, according to an embodiment a balancing (e.g., "counter") fine actuator on a counter-suspension (e.g., "dummy" suspension) assembly may be implemented on the outer arms to cancel the reaction force for the single "real" suspension on such arm. The balancing fine actuator is operated out-of-phase with the suspension fine actuator on the same arm, and the structural dynamics of the corresponding counter-suspension is "tuned", e.g., judiciously configured as a flexible structure/component, to match key suspension resonance frequencies and to achieve optimal reaction force cancellation similar to or approaching that of the inner arms with two suspensions.

[0030] FIG. **3**A is a plan view illustrating a hard disk drive suspension assembly coupled to an arm on the inner side, according to an embodiment. As depicted, suspension assembly **300** is coupled to the inner surface (lower surface in this top view) of an arm **302**. Suspension assembly **300** comprises a mount plate **304**, which is typically swaged to the arm **302**, to which is connected a load beam **306** which is coupled with a flexure **308** generally running the length of the suspension assembly **300** and ending at a distal gimballing portion **308***g* (or "gimbal" or "gimbal flexure") which carries a slider and its read-write head (not visible here; see, e.g., slider **110***b* and read-write head **110***a* of FIG. **1**). Suspension assembly **300** further comprises a fine actuator **310**, here referred to as a milliactuator as it is configured to move the load beam **306**. Fine actuator **310** is generally positioned between and coupled with mount plate **304** and load beam **306**. For purposes of this description, suspension assembly **300** is considered a "real" or working or operational suspension.

[0031] FIG. **4**A is a graph illustrating example frequency response functions, including for a single conventional and mirrored suspension assemblies on shared arm, according to an embodiment. In this example, the solid function (or signal) **401** represents the FRF of the read-write node on the suspension assembly **300** (with a head) mounted on an arm (see, e.g., arm **302** of FIG. **3**A), e.g., characterizing the head off-track response to the voltage input of fine actuator **310**, without any balancing or counter-suspension on the opposing side of the shared arm (see, e.g., FIG. **3**A). As non-limiting examples for context for the approaches, techniques, embodiments described herein, depicted here by function **401** are a series of peaks: (a) a torsion mode **401***a* around about 6.4 kHz, (b) a whole arm (flat) sway mode **401***b* around about 8.5 kHz, (c) an end arm (twisting) sway mode **401***c* around about 18.5 kHz, and (d) a twisting sway mode **401***d* around about 29 kHz. These peaks are discussed in more detail hereafter with reference to a corresponding counter-suspension assembly. Here, the dashed function (or signal) **402** represents the FRF of the read-write node on the suspension assembly **300** with a mirrored suspension assembly (with a head) installed on the opposing side of the shared arm, responsive to the common voltage input to respective fine actuators such as fine actuator **310** on both suspensions on the shared arm.

[0032] FIG. **3**B is a plan view illustrating a hard disk drive counter-suspension assembly coupled to an arm on the outer side, according to an embodiment. As depicted, counter-suspension assembly **320** is coupled to the outer surface (upper surface in this top view) of an arm **302**. Counter-suspension assembly **320** comprises a mount plate **324**, which is typically swaged to the arm **302**, to which is connected a load beam **326** which is coupled with a flexure **328**. Here, flexure **328** only runs to the load beam **326** near fine actuator **330**, and does not end at a distal gimballing portion as this counter-suspension **320** does not carry a slider or read-write head. As mentioned, counter-suspension assembly **320** further comprises a balancing fine actuator **330**, here referred to as a milliactuator as it is configured to move the load beam **326**. Balancing fine actuator **330** is generally positioned between and coupled with mount plate **324** and load beam **326**. For purposes of this description, counter-suspension assembly **320** may be considered or referred to as a "dummy" suspension.

[0033] FIG. **3**C is a plan view illustrating the suspension assembly of FIG. **3**A and the counter-suspension assembly of FIG. **3**B mounted on a shared arm, according to an embodiment. Refer to the respective FIGS. **3**A-**3**B for descriptions of the constituent components of suspension assembly **300** and counter-suspension assembly **320**. FIG. **4**B is a graph illustrating example frequency response functions, including for a single conventional and with a counter-suspension assembly on shared arm, according to an embodiment. In this example, the solid function (or signal) **401** again represents the FRF of the read-write node on the suspension assembly **300** mounted on an arm (see, e.g., arm **302** of FIG. **3**A) and responsive to the voltage input of fine actuator **310**. Here, the dashed function (or signal) **403** represents the FRF of the read-write node on the suspension assembly **300** with the counter-suspension assembly **320** mounted on the opposing side of the shared arm (e.g., arm **302** of FIG. **3**C), and responsive to the common voltage of fine actuator **310** and balancing fine actuator **330** (FIG. **3**B). The control voltage to fine actuator **310** of suspension assembly **300** on the outer arm **302** is also applied to the fine actuator **330** of the counter-suspension assembly **320** on the same arm **302**. The fine actuator **330** of the counter-suspension assembly **320** is designed to move the counter-suspension assembly **320** in the opposite direction with respect to the fine actuator **310** of the suspension assembly **300** on the same arm **302** so that their reaction forces on the arm are in opposite directions. Therefore, such opposing reaction forces are effectively cancelled when the counter-suspension is designed to match a real suspension (e.g., with head) dynamics. It is noteworthy that multiple structural modes of (inner) suspension assembly **300** are effectively mitigated or cancelled with the use of a (outer) counter-suspension assembly **320**, e.g., as depicted, the whole arm (flat) sway mode **401***b*, end arm (twisting) sway **401***c*, twisting sway **401***d*. Whereas signal **401** indicates three major peaks (e.g., **401***b*-**401***d*) to 30 kHz, signal **403** indicates only the one major peak to 30 kHz, e.g., at around 22 kHz.

[0034] Comparing the example signal **403** (FIG. **4**B) representing the FRF of the read-write node on the suspension assembly **300** with the counter-suspension assembly **320** on the opposing side of the shared arm, with the signal **402** (FIG. **4**A) representing the FRF of the read-write node on the suspension assembly **300** with a mirrored suspension assembly on the opposing side of the shared arm, it is visually apparent that signal **403** relatively closely matches with signal **402**. Albeit, counter-suspension assembly **320** may be further optimized to more closely match the two structural dynamics functions, as the graphs of FIGS. **4**A-**4**B here simply serve non-limiting explanatory purposes. The point is that a counter-suspension (or "balancing" suspension) assembly such as counter-suspension assembly **320** can be judiciously configured as a flexible structure/component (i.e., "tuned"), in conjunction with a balancing fine actuator such as balancing fine actuator **330** operating out-of-phase with the suspension fine actuator **310** on the same arm **302**, such that the structural dynamics of the counter-suspension assembly **320** substantially matches key resonance frequencies of the corresponding suspension assembly **300**, to achieve optimal reaction force cancellation/mitigation of multiple modes similar to or approaching that of the inner arms with two suspensions. Furthermore, the cost to manufacture a counter-suspension assembly such as counter-suspension assembly **320** may be significantly less than a mirrored suspension assembly, at least in part due to the absence of a relatively costly read-write head and gimbal flexure.

[0035] FIG. **4**C is a graph illustrating example frequency response functions, including for single conventional and counter-suspension assemblies, according to an embodiment. Here the illustrated frequency range is expanded beyond 30 kHz to show a fourth peak **440** around 40 kHz. In this example, the solid function (or signal) **404** represents the FRF corresponding to a single conventional suspension assembly (with a head) mounted on an arm and responsive to the voltage input of a fine actuator (see, e.g., fine actuator **310** of FIG. **3**A), the alternating dashed function (or signal) **405** represents the FRF corresponding to a single trapezoidal counter-suspension assembly (no head) mounted on an arm and responsive to the voltage input of a corresponding fine actuator (see, e.g., fine actuator **330** of FIG. **3**B), and the fine dashed function (or signal) **406** represents the FRF corresponding to a single rectangular counter-suspension assembly (no head) mounted on an arm and responsive to the voltage input of a fine actuator such as fine actuator **330**. FIG. **4**C shows that there are four highlighted (i.e., bracketed) peaks **410**, **420**, **430**, and **440** corresponding to the structural dynamics of each respective single suspension assembly, each occurring roughly around the same frequency as the other suspension assemblies.

[0036] FIG. **4**D is a graph illustrating example frequency response functions, including for a single conventional and with a counter-suspension assembly on shared arm, according to an embodiment. Here too the illustrated frequency range is expanded beyond 30 kHz. In this example, the solid function (or signal) **404** again represents the FRF corresponding to a single conventional suspension assembly mounted on an arm and responsive to the voltage input of fine actuator **310**, while the fine dashed function (or signal) **407** represents the FRF corresponding to a conventional suspension assembly and a rectangular counter-suspension assembly mounted on the shared arm and responsive to the voltage input of respective fine actuators (e.g., including a balancing fine counter-actuator such as fine actuator **330** of FIG. **3**B). FIG. **4**D illustrates that while there are the aforementioned four major peaks **410**, **420**, **430**, and **440** to 40 kHz corresponding to the structural dynamics of a single conventional suspension assembly, the example signal **407** representing the FRF corresponding to conventional suspension assembly **300** with a counter-suspension assembly **320** on the opposing side of the shared arm **302** results in only one major peak **450**.

Example Dummy Load Beam Structures

[0037] In practice, the precise structural configuration of a counter-suspension assembly (e.g., counter-suspension assembly **320** of FIG. **3**B) may vary from implementation to implementation, based largely on the structural dynamics of the corresponding suspension assembly that is the target of such counter-balancing. Noteworthy structural attributes that may or should be considered, according to one or more embodiments, is the distribution of mass and/or the distribution of stiffness within a given "dummy" load beam (e.g., load beam **326** of FIG. **3**B). As such, counter-suspension assembly **320** may be configured as a flexible structure rather than as a simple rigid body mass (which does not or only negligibly deforms under physics forces) designed as an equivalent mass to be driven by a dummy fine actuator as the mass of an opposing HGA being targeted. Consequently, counter-suspension assembly **320** may be designed to counter or mitigate multiple structural modes of the corresponding suspension assembly **300** (FIG. **3**A) under the fine actuator **310** (FIG. **3**A) forces, rather than only a single (e.g., low frequency) structural mode/peak. Thus, multiple dummy load beam structural configurations were modeled and analyzed, and are presented as follows as non-limiting example configurations that may be optimized for mode mitigation/cancellation by substantially matching key modes of a "real" operating suspension assembly.

[0038] FIG. **5**A is a plan view illustrating a first example counter-suspension assembly, according to an embodiment. Counter-suspension assembly **500** is coupled to the outer surface of an arm (not shown here; see, e.g., arm **302** of FIG. **3**B). Counter-suspension assembly **500** comprises a mount plate **504**, to which is connected a rectangular load beam **506** which is coupled with a flexure **508**. Here also, flexure **508** only runs to the load beam **506** near a fine actuator **510** because counter-suspension assembly **500** does not carry a slider or read-write head. For purposes of this description, counter-suspension assembly **500** may be considered or referred to as a "dummy" suspension including a "dummy" load beam **506**. With a rectangular structural main body ***506a*** like that of counter-suspension assembly **500**, further comprising a rectangular cut-out ***506b*** from the main body ***506a***, optimization techniques considered include but are not limited to various adjustments to the length of the main body ***506a*** in the longitudinal direction (x-direction, along the long axis of main body ***506a***) as well as various adjustments to the length of the cut-out ***506b*** in the longitudinal direction. Likewise, various adjustments to the width of the main body ***506a*** in the lateral direction (y-direction, along the short axis of the main body ***506a***) and/or the cut-out ***506b*** may also be applied in optimizing a counter-suspension assembly such as counter-suspension assembly **500** to match key modes of a corresponding operating suspension assembly for mode cancellation/mitigation purposes.

[0039] FIG. **5**B is a plan view illustrating a second example counter-suspension assembly, according to an embodiment. Counter-suspension assembly **520** is coupled to the outer surface of an arm (not shown here; see, e.g., arm **302** of FIG. **3**B). Counter-suspension assembly **520** comprises a mount plate **524**, to which is connected a trapezoidal load beam **526** which is coupled with a flexure **528**. Here also, flexure **528** only runs to the load beam **526** near a fine actuator **530** because counter-suspension assembly **520** does not carry a slider or read-write head. For purposes of this description, counter-suspension assembly **520** may be considered or referred to as a "dummy" suspension including a "dummy" load beam **526**. With a trapezoidal structural main body **526***a* like that of counter-suspension assembly **520**, further comprising a largely trapezoidal cut-out **526***b* from the main body **526***a*, optimization techniques considered include but are not limited to various adjustments to the length of the main body **526***a* in the longitudinal direction (x-direction, along the long axis of main body **526***a*) as well as various adjustments to the length of the cut-out **526***b* in the longitudinal direction. Likewise, various adjustments to the width of the main body **526***a* in the lateral direction (y-direction, along the short axis of main body **526***a*), the relationship between the bases and legs of main body **506***a*, the width of the cut-out **526***b*, and/or the relationship between the bases and legs of the cut-out **526***b* may also be applied in optimizing a counter-suspension assembly such as counter-suspension assembly **520** to match key modes of a corresponding operating suspension assembly for mode cancellation/mitigation purposes.

[0040] FIG. **5**C is a plan view illustrating a third example counter-suspension assembly, according to an embodiment. Counter-suspension assembly **540** is coupled to the outer surface of an arm (not shown here; see, e.g., arm **302** of FIG. **3**B). Counter-suspension assembly **540** comprises a mount plate **544**, to which is connected a rectangular load beam **546** which is coupled with a flexure **548**. Here also, flexure **548** only runs to the load beam **546** near a fine actuator **550** because counter-suspension assembly **540** does not carry a slider or read-write head. For purposes of this description, counter-suspension assembly **540** may be considered or referred to as a "dummy" suspension including a "dummy" load beam **546**. With a rectangular structural main body **546***a* like that of counter-suspension assembly **540**, further comprising a trapezoidal cut-out **546***b* from the main body **546***a*, optimization techniques considered include but are not limited to various adjustments to the length of the main body **546***a* in the longitudinal direction (x-direction, along the long axis of main body **546***a*) as well as various adjustments to the length of the cut-out **546***b* in the longitudinal direction. Likewise, various adjustments to the width of the main body **546***a* in the lateral direction (y-direction, along the short axis of main body **546***a*), and/or the relationship between the bases and legs of the cut-out **546***b* may also be applied in optimizing a counter-suspension assembly such as counter-suspension assembly **540** to match key modes of a corresponding operating suspension assembly for mode cancellation/mitigation purposes.

[0041] FIG. **5**D is a plan view illustrating a fourth example counter-suspension assembly, according to an embodiment. Counter-suspension assembly **560** is coupled to the outer surface of an arm (not shown here; see, e.g., arm **302** of FIG. **3**B). Counter-suspension assembly **560** comprises a mount plate **564**, to which is connected a rectangular load beam **566** which is coupled with a flexure **568**. Here also, flexure **568** only runs to the load beam **566** near a fine actuator **570** because counter-suspension assembly **560** does not carry a slider or read-write head. For purposes of this description, counter-suspension assembly **560** may be considered or referred to as a "dummy" suspension including a "dummy" load beam **566**. With a rectangular structural main body **556***a* like that of counter-suspension assembly **560**, further comprising a cut-away **566***b* from at least one lateral side of the main body **566***a*, optimization techniques considered include but are not limited to various adjustments to the length of the main body **566***a* in the longitudinal direction (x-direction, along the long axis of main body **566***a*) as well as various adjustments to the length of the cut-away(s) **566***b* in the longitudinal direction. Likewise, various adjustments to the width of the main body **566***a* in the lateral direction (y-direction, along the short axis of main body **566***a*) and/or the cut-away(s) **566***b* may also be applied in optimizing a counter-suspension assembly such as counter-suspension assembly **560** to match key modes of a corresponding operating suspension assembly for mode cancellation/mitigation purposes.

[0042] FIG. **6** is a cross-sectional side view illustrating an example counter-suspension assembly having non-uniform thickness, according to an embodiment. Reference is made to FIG. **5**A for location of cross-section **6**-**6**. Counter-suspension assembly **600** is coupled to the outer surface of an arm (not shown here). Counter-suspension assembly **600** comprises a mount plate **604**, which is typically swaged to the arm, to which is connected a load beam **606**. Counter-suspension assembly **600** further comprises a fine actuator (not visible here), here referred to as a milliactuator as it is configured to move the load beam **606**. For purposes of this description, counter-suspension assembly **600** may be considered or referred to as a "dummy" suspension. According to at least the embodiment illustrated here, counter-suspension assembly **600** comprises the load beam **606** comprising a non-uniform thickness. According to a related embodiment, counter-suspension assembly **600** comprises the load beam **606** which comprises a first thickness t_1 at a first portion p_1 structurally interfacing with the mount plate **604** and a different second thickness t_2 at a second portion p_2 extending away from the mount plate **604**. This embodiment illustrates that in addition to varying the configuration of structural features (e.g., main body, cut-out, cut-away) and shapes (e.g., rectangular, trapezoidal) in the x-direction (longitudinal) and y-direction (lateral) as described in reference to FIGS. **5**A-**5**D, the thickness of the load beam **606** may additionally and alternatively be varied in the height (z-direction) for optimizing a counter-suspension assembly such as counter-suspension assembly **600** to match key modes of a corresponding operating suspension assembly for mode cancellation/mitigation purposes. For purposes of example, the first thickness t_1 at the first portion p_1 of load beam **606** structurally interfacing with the mount plate **604** is thinner than the second thickness t_2 at the second portion p_2 of the load beam **606** extending away from the mount plate **604**. However, the location at which the load beam **606** may transition from one thickness to another, as well as the number of different thicknesses and thickness transitions, may vary from implementation to implementation, based largely on the structural dynamics of the corresponding suspension assembly that is the target of the multiple mode counter-balancing. In FIG. **6**, the second portion p_2 of the load beam **606** is thickened compared to first portion p_1 from both top and bottom surfaces (e.g., in both up and down directions). Alternatively, the second portion p_2 of the load beam **606** may be thickened only in from the top or the bottom surface relative to p_1 (e.g., in either the up or down direction), such as for ease of manufacturing.

Method of Manufacturing a Head Gimbal Assembly

[0043] FIG. **7** is a flow diagram illustrating a method of manufacturing a head stack assembly (HSA), according to an embodiment. A head stack assembly (HSA) assembled, manufactured, produced according to the method of FIG. **7** is designed, configured, intended for implementation into a hard disk drive (HDD) (see, e.g., HDD **100** of FIG. **1**).

[0044] At block **702**, couple, to each of a plurality of arms extending from a carriage, at least one suspension assembly comprising a corresponding fine actuator. For example, a suspension assembly such as suspension assembly **300** (FIGS. **3**A, **3**C) comprising a corresponding fine actuator **310** is coupled to each of a plurality of arms **302** (FIGS. **3**A, **3**C) extending from a carriage (see, e.g., carriage **201** of FIG. **2**).

[0045] At block **704**, couple, to each arm at outer ends of the carriage, a counter-suspension assembly comprising a fine actuator and a mass distribution and a stiffness distribution configured to mitigate multiple structural dynamics modes of the corresponding suspension assembly coupled to the same arm. For example, a counter-suspension assembly such as counter-suspension assembly **320** (FIGS. **3**B-**3**C), **500** (FIG. **5**A), **520** (FIG. **5**B), **540** (FIG. **5**C), **560** (FIG. **5**D), comprising a corresponding fine actuator **330** (FIG. **3**B), **510** (FIG. **5**A), **530** (FIG. **5**B), **550** (FIG. **5**C), **570** (FIG. **5**D), is coupled to each of a plurality of arms **302** (FIGS. **3**A-**3**C).

[0046] In view of the embodiments described herein, a counter-suspension (or "balancing" suspension) assembly can be judiciously configured as a flexible structure/component (i.e., "tuned"), in conjunction with a balancing fine actuator operating out-of-phase with the corresponding "real" suspension fine actuator on the same arm, such that the structural dynamics of the counter-suspension assembly substantially matches multiple key resonance frequencies of the corresponding suspension assembly to achieve optimal reaction force cancellation/mitigation of multiple structural dynamics modes. The cost to manufacture a counter-suspension assembly may be significantly less than a mirrored suspension assembly, at least in part due to the absence of a relatively costly read-write head and gimbal flexure.

Physical Description of an Illustrative Operating Context

[0047] Embodiments may be used in the context of a digital data storage device (DSD) such as a hard disk drive (HDD). Thus, in accordance with an embodiment, a plan view illustrating a conventional HDD **100** is shown in FIG. **1** to aid in describing how a conventional HDD typically operates.

[0048] FIG. **1** illustrates the functional arrangement of components of the HDD **100** including a slider **110***b* that includes a magnetic read-write head **110***a*. Collectively, slider **110***b* and head **110***a* may be referred to as a head slider. The HDD **100** includes at least one head gimbal assembly (HGA) **110** including the head slider, a lead suspension **110***c* attached to the head slider typically via a flexure, and a load beam **110***d* attached to the lead suspension **110***c*. The HDD **100** also includes at least one recording medium **120** rotatably mounted on a spindle **124** and a drive motor (not visible) attached to the spindle **124** for rotating the medium **120**. The read-write head **110***a*, which may also be referred to as a transducer, includes a write element and a read element for respectively writing and reading information stored on the medium **120** of the HDD **100**. The medium **120** or a plurality of disk media may be affixed to the spindle **124** with a disk clamp **128**.

[0049] The HDD **100** further includes an arm **132** attached to the HGA **110**, a carriage **134**, a voice-coil motor (VCM) that includes an armature **136** including a voice coil **140** attached to the carriage **134** and a stator **144** including a voice-coil magnet (not visible). The armature **136** of the VCM is attached to the carriage **134** and is configured to move the arm **132** and the HGA **110** to access portions of the medium **120**, all collectively mounted on a pivot shaft **148** with an interposed pivot bearing assembly **152**. In the case of an HDD having multiple disks, the carriage **134** may be referred to as an "E-block," or comb, because the carriage is arranged to carry a ganged array of arms that gives it the appearance of a comb.

[0050] An assembly comprising a head gimbal assembly (e.g., HGA **110**) including a flexure to which the head slider is coupled, an actuator arm (e.g., arm **132**) and/or load beam to which the flexure is coupled, and an actuator (e.g., the VCM) to which the actuator arm is coupled, may be collectively referred to as a head-stack assembly (HSA). An HSA may, however, include more or fewer components than those described. For example, an HSA may refer to an assembly that further includes electrical interconnection components. Generally, an HSA is the assembly configured to move the head slider to access portions of the medium **120** for read and write operations.

[0051] With further reference to FIG. **1**, electrical signals (e.g., current to the voice coil **140** of the VCM) comprising a write signal to and a read signal from the head **110***a*, are transmitted by a flexible cable assembly (FCA) **156** (or "flex cable", or "flexible printed circuit" (FPC)). Interconnection between the flex cable **156** and the head **110***a* may include an arm-electronics (AE) module **160**, which may have an on-board pre-amplifier for the read signal, as well as other read-channel and write-channel electronic components. The AE module **160** may be attached to the carriage **134** as shown. The flex cable **156** may be coupled to an electrical-connector block **164**, which provides electrical communication, in some configurations, through an electrical feed-through provided by an HDD housing **168**. The HDD housing **168** (or "enclosure base" or "baseplate" or simply "base"), in conjunction with an HDD cover, provides a semi-sealed (or hermetically sealed, in some configurations) protective enclosure for the information storage components of the HDD **100**.

[0052] Other electronic components, including a disk controller and servo electronics including a digital-signal processor (DSP), provide electrical signals to the drive motor, the voice coil **140** of the VCM and the head **110***a* of the HGA **110**. The electrical signal provided to the drive motor enables the drive motor to spin providing a torque to the spindle **124** which is in turn transmitted to the medium **120** that is affixed to the spindle **124**. As a result, the medium **120** spins in a direction **172**. The spinning medium **120** creates a cushion of air that acts as an air-bearing on which the air-bearing surface (ABS) of the slider **110***b* rides so that the slider **110***b* flies above the surface of the medium **120** without making contact with a thin magnetic-recording layer in which information is recorded. Similarly in an HDD in which a lighter-than-air gas is utilized, such as helium for a non-limiting example, the spinning medium **120** creates a cushion of gas that acts as a gas or fluid bearing on which the slider **110***b* rides.

[0053] The electrical signal provided to the voice coil **140** of the VCM enables the head **110***a* of the HGA **110** to access a track **176** on which information is recorded. Thus, the armature **136** of the VCM swings through an arc **180**, which enables the head **110***a* of the HGA **110** to access various tracks on the medium **120**. Information is stored on the medium **120** in a plurality of radially nested tracks arranged in sectors on the medium **120**, such as sector **184**. Correspondingly, each track is composed of a plurality of sectored track portions (or "track sector") such as sectored track portion **188**. Each sectored track portion **188** may include recorded information, and a header containing error correction code information and a servo-burst-signal pattern, such as an ABCD-servo-burst-signal pattern, which is information that identifies the track **176**. In accessing the track **176**, the read element of the head **110***a* of the HGA **110** reads the servo-burst-signal pattern, which provides a position-error-signal (PES) to the servo electronics, which controls the electrical signal provided to the voice coil **140** of the VCM, thereby enabling the head **110***a* to follow the track **176**. Upon finding the track **176** and identifying a particular sectored track portion **188**, the head **110***a* either reads information from the track **176** or writes information to the track **176** depending on instructions received by the disk controller from an external agent, for example, a microprocessor of a computer system.

[0054] An HDD's electronic architecture comprises numerous electronic components for performing their respective functions for operation of an HDD, such as a hard disk controller (HDC), an interface controller, an arm electronics module, a data channel, a motor driver, a servo processor, buffer memory, etc. Two or more of such components may be combined on a single integrated circuit board referred to as a "system on a chip" (SOC). Several, if not all, of such electronic components are typically arranged on a printed circuit board that is coupled to the bottom side of an HDD, such as to HDD housing **168**.

[0055] References herein to a hard disk drive, such as HDD **100** illustrated and described in reference to FIG. **1**, may encompass an information storage device that is at times referred to as a "hybrid drive". A hybrid drive refers generally to a storage device having functionality of both a traditional HDD (see, e.g., HDD **100**) combined with solid-state storage device (SSD) using non-volatile memory, such as flash or other solid-state (e.g., integrated circuits) memory, which is electrically erasable and programmable. As operation, management and control of the different types of storage media typically differ, the solid-state portion of a hybrid drive may include its own corresponding controller functionality, which may be integrated into a single controller along with the HDD functionality. A hybrid drive may be architected and configured to operate and to utilize the solid-state portion in a number of ways, such as, for non-limiting examples, by using the solid-state memory as cache memory, for storing frequently-accessed data, for storing I/O intensive data, and the like. Further, a hybrid drive may be architected and configured essentially as two storage devices in a single enclosure, i.e., a traditional HDD and an SSD, with either one or multiple interfaces for host connection.

Extensions and Alternatives

[0056] In the foregoing description, embodiments of the invention have been described with reference to numerous specific details that may vary from implementation to implementation. Therefore, various modifications and changes may be made thereto without departing from the broader spirit and scope of the embodiments. Thus, the sole and exclusive indicator of what is the invention, and is intended by the applicants to be the invention, is the set of claims that issue from this application, in the specific form in which such claims issue, including any subsequent correction. Any definitions expressly set forth herein for terms contained in such claims shall govern the meaning of such terms as used in the claims. Hence, no limitation, element, property, feature, advantage or attribute that is not expressly recited in a claim should limit the scope of such claim in any way. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

[0057] In addition, in this description certain process steps may be set forth in a particular order, and alphabetic and alphanumeric labels may be used to identify certain steps. Unless specifically stated in the description, embodiments are not necessarily limited to any particular order of carrying out such steps. In particular, the labels are used merely for convenient identification of steps, and are not intended to specify or require a particular order of carrying out such steps.

What is claimed is:

1. A hard disk drive (HDD) comprising:

a disk stack comprising a plurality of disk media rotatably mounted on a spindle;

a plurality of head sliders each housing a read-write transducer configured to read from and to write to a disk medium of the plurality of disk media;

a first-stage actuator configured for moving the plurality of head sliders to access portions of the plurality of disk media; and

a head stack assembly (HSA) coupled with the actuator, the HSA comprising:

a carriage coupled with the actuator,

a plurality of arms coupled to the carriage, the plurality of arms including an outer arm at each end of the disk stack and one or more inner arms between the outer arms, wherein each inner arm carries two suspension assemblies and each outer arm carries one suspension assembly, each suspension assembly comprising a corresponding fine actuator configured for moving a corresponding head slider of the plurality of head sliders to access portions of the corresponding disk medium, and

a counter-suspension assembly coupled to a side of at least one outer arm opposing the corresponding suspension assembly, the counter-suspension assembly having a mass distribution and a stiffness distribution configured to counter multiple structural dynamics modes of the corresponding suspension assembly.

2. The HDD of claim **1**, wherein the counter-suspension assembly comprises a fine actuator configured for moving a corresponding counter-load beam having a mass distribution and a stiffness distribution configured to counter the multiple structural dynamics modes of the corresponding suspension assembly.

3. The HDD of claim **2**, wherein the counter-load beam comprises a cut-out from a main body of the counter-load beam.

4. The HDD of claim **2**, wherein the counter-load beam is configured as a flexible structure.

5. The HDD of claim **4**, wherein the counter-load beam comprises a cut-out from a main body of the counter-load beam.

6. The HDD of claim **2**, wherein a control voltage of the fine actuator of each counter-suspension assembly is configured to drive the counter-load beam in an opposing direction from the corresponding suspension assembly.

7. The HDD of claim **1**, wherein the counter-suspension assembly comprises a counter-load beam having a rectangular main body and a cut-out through the main body.

8. The HDD of claim **1**, wherein the counter-suspension assembly comprises a counter-load beam having a trapezoidal main body and a cut-out through the main body.

9. The HDD of claim **1**, wherein the counter-suspension assembly comprises a counter-load beam having a non-uniform thickness.

10. The HDD of claim **9**, wherein:

the counter-suspension assembly further comprises a base plate coupled with the outer arm and to which the counter-load beam is coupled, and

the counter-load beam comprises a first thickness at a first portion structurally interfacing with the base plate and a different second thickness at a second portion extending away from the base plate.

11. A hard disk drive (HDD) head stack assembly (HSA) comprising:

means for carrying a plurality of arms;

a plurality of arms coupled to the means for carrying, the plurality of arms including an outer arm at each end of the means for carrying and one or more inner arms between the outer arms, wherein each inner arm carries two suspension assemblies and each outer arm carries one suspension assembly coupled with an inner side of the outer arm, each suspension assembly comprising a corresponding fine actuator; and

a counter-suspension assembly coupled to an outer side of each outer arm, each counter-suspension assembly having a mass distribution and a stiffness distribution configured to mitigate multiple structural dynamics modes of the suspension assembly coupled to the inner side of the outer arm.

12. The HSA of claim **11**, wherein the counter-suspension assembly comprises a fine actuator configured for moving a corresponding counter-load beam having a mass distribution and a stiffness distribution configured to mitigate the multiple structural dynamics modes of the suspension assembly coupled to the inner side of the outer arm.

13. The HSA of claim **12**, wherein the counter-load beam is a flexible structure.

14. The HSA of claim **12**, wherein a control voltage of the fine actuator of each counter-suspension assembly is configured to drive the counter-load beam in an opposing direction from the corresponding suspension assembly.

15. The HSA of claim **11**, wherein the counter-suspension assembly comprises a counter-load beam having a rectangular main body and a cut-out through the main body.

16. The HSA of claim **11**, wherein the counter-suspension assembly comprises a counter-load beam having a trapezoidal main body and a cut-out through the main body.

17. The HSA of claim **11**, wherein the counter-suspension assembly comprises a counter-load beam having a rectangular main body and a cut-away from each lateral side of the main body.

18. The HSA of claim **11**, wherein the counter-suspension assembly comprises a counter-load beam having a non-uniform thickness.

19. A hard disk drive comprising the HSA of claim **11**.

20. A method of manufacturing a head stack assembly (HSA), the method comprising:

coupling, to each of a plurality of arms extending from a carriage, at least one suspension assembly comprising a corresponding fine actuator; and

coupling, to each arm at outer ends of the carriage, a counter-suspension assembly comprising a fine actuator and a mass distribution and a stiffness distribution configured to mitigate multiple structural dynamics modes of the corresponding suspension assembly coupled to the same arm.

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