(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
10 July 2025 (10.07.2025)

WIPO | PCT

(10) International Publication Number
WO 2025/147271 A1

(51) International Patent Classification:
E21B 44/02 (2006.01) *E21B 7/06* (2006.01)
E21B 47/01 (2006.01)

(21) International Application Number:
PCT/US2024/012216

(22) International Filing Date:
19 January 2024 (19.01.2024)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
18/404,420 04 January 2024 (04.01.2024) US

(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US).

(72) Inventors: **ZHANG, He**; 315 Jalan Ahmad Ibrahim, Singapore 639940 (SG). **PAN, Yi**; 16548 Donwick Dr., Conroe, Texas 77385-3506 (US). **TIAN, Kaixiao**; 315 Jalan Ahmad Ibrahim, Singapore 639940 (SG). **DAHAL, Jeevan**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US). **BHAIDASNA, Ketan C.**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US). **DARBE, Robert P.**; 3000 N. Sam Houston Parkway E., Houston, Texas 77032-3219 (US). **LANNING, Curtis**; 16548 Donwick Dr., Conroe, Texas 77385-3506 (US). **PLUNKETT, Kelley**; 16548 Donwick Dr., Conroe, Texas 77385-3506 (US). **CLARK, Kevin C.**; 16548 Donwick Dr., Conroe, Texas 77385-3506 (US).

(74) Agent: **COREY S. TUMEY**; P.O. Box 890226, Houston, Texas 77062-9998 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST,

(54) Title: USE OF BENDING MOMENT ON BIT MEASUREMENTS AND SIMULATIONS TO DETERMINE HEALTH CONDITION OF PUSH-THE-BIT ROTARY STEERABLE SYSTEMS AND ASSESS DIRECTIONAL DRILLING CAPABILITY

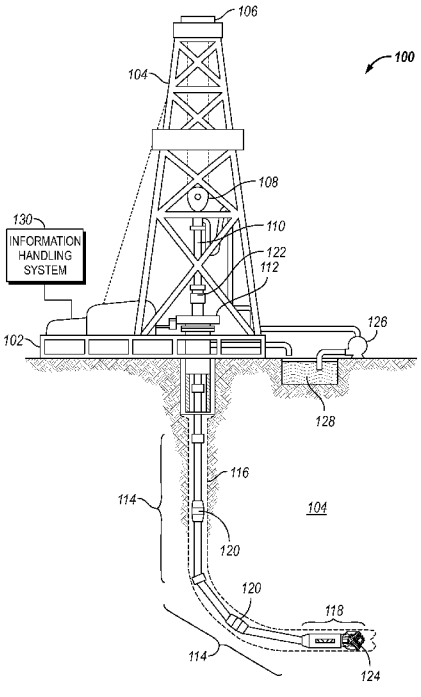


FIG. 1

(57) Abstract: A method and system for measuring health in a rotary steerable system (RSS). The method may include forming a bottom-hole assembly (BHA) model, taking a bending moment on bit (BOB) measurement from a sensor disposed in a BHA, and comparing the BOB measurement to the BHA model to determine if a steering actuator is malfunctioning, wherein the steering actuator is disposed on the BHA. The system may include at least one sensor disposed on the BHA, wherein the at least one sensor takes at least one bending moment on bit (BOB) measurement. Further, the system may include a plurality of steering actuators disposed on the BHA and an information handling system in communication with the BHA.

WO 2025/147271 A1

[Continued on next page]

SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

USE OF BENDING MOMENT ON BIT MEASUREMENTS AND SIMULATIONS TO DETERMINE HEALTH CONDITION OF PUSH-THE-BIT ROTARY STEERABLE SYSTEMS AND ASSESS DIRECTIONAL DRILLING CAPABILITY

BACKGROUND

[0001] Boreholes may be created for a variety of purposes, including for use as a fluid conduit to access subterranean deposits. A drilling operation may be utilized to construct one or more boreholes to access those subterranean deposits. During the construction of a borehole, it may be necessary to steer the drill bit along as desired path. Accordingly, one or more components on a drillstring may be used to steer the drill bit during drilling operations.

BRIEF DESCRIPTION OF DRAWINGS

[0002] These drawings illustrate certain aspects of some examples of the present disclosure and should not be used to limit or define the disclosure.

[0003] Figure 1 is a diagram of an example drilling environment.

[0004] Figure 2 is a diagram of an example bottom-hole assembly (BHA)with a rotary steerable system.

[0005] Figure 3 is a diagram of an example BHA with one or more steering actuators.

[0006] Figure 4 is a diagram of another example BHA with one or more steering actuators.

[0007] Figure 5 illustrates a schematic of an information handling system.

[0008] Figure 6 illustrates a schematic of a chip set.

[0009] Figure 7 illustrates a computing network.

[0010] Figure 8 illustrates a neural network.

[0011] Figure 9 illustrates a coordinate reference system *O-xyz* attached at a bit on the BHA.

[0012] Figure 10 illustrates a diagram of a beam element.

[0013] Figure 11 illustrates a geometrical relationship of a borehole centerline and definition of bit tilt in the inclination plane.

[0014] Figure 12 illustrates a geometrical relationship of the borehole centerline and definition of the bit tilt in the pseudo-azimuth plane.

[0015] Figure 13 illustrates an example of the violation of contact compatibility condition.

[0016] Figure 14 is a diagram of an example of a stationary valve.

[0017] Figure 15 is a diagram of another example of the stationary valve.

[0018] Figure 16A is a diagram showing one steering actuator that is activated.

[0019] Figure 16B is a diagram showing two steering actuators that are activated.

[0020] Figure 17 is a graph of force from a steering actuator as a function of overlapping angle.

[0021] Figure 18 is a diagram illustrating resultant moment and its orientation.

[0022] Figure 19A is a graph of bending moment on bit (BOB) between downhole measurements and simulation for a nutating mode.

[0023] Figure 19B is a graph of bending moment on bit (BOB) between downhole measurements and simulation for a geostationary mode.

[0024] Figure 20A illustrates a free body diagram of the BHA.

[0025] Figure 20B illustrates a free body diagram of the BHA with gravitational force measurements.

[0026] Figure 21 is a graph illustrating measured BOB compared to a finite element BHA model prediction of BOB.

[0027] Figure 22 is a graph of a nutating mode.

[0028] Figures 23-26 are graphs comparing malfunctioning steering actuators to operational steering actuators.

[0029] Figure 27 is a workflow to determine health of each steering actuator.

DETAILED DESCRIPTION

[0030] In general, this application discloses one or more embodiments for providing a rotary steerable system on a drillstring that is capable of more precise steering of a bottom-hole assembly (and a drill bit thereon) and determination of the health of rotary steerable system (RSS). In examples, a sensor disposed within a drill bit may be employed to measure the bending moment on bit (BOB) at a high sampling frequency of 1024 Hz, which may provide valuable insights into the functionality of RSS and the prediction of borehole trajectory only if the BOB data may be interpreted properly and accurately. Given that the BOB is a consequence of the bottom-hole assembly (BHA) lateral deflection, a finite element BHA model considering the RSS actuation force is developed to reproduce the downhole BOB measurements. The finite element BHA model disclosed herein may allow for better control of directional trajectory and effective diagnostic of downhole steering dysfunctions by use of the BHA model and downhole BOB data.

[0031] During drilling operations, lateral deflection of bottom-hole assembly (BHA) under the actuation force of push-the-bit rotary steerable systems (RSS) may be measured to determine drilled borehole trajectory smoothly tracking a predefined well path. In directional drilling, both bit side forces and bending moment on bit (BOB), determined by several factors including gravity,

borehole curvature, BHA configuration, bit tilt, contacts between BHA and borehole, and steering assembly force of a push-the-bit RSS, may govern the direction of the borehole propagation. In examples, steering assembly force may be actively controlled to affect the bit side force and BOB. Thus, monitoring the health of the push-the-bit RSS may be utilized to ensure that steering assembly forces are generated to regulate the bit side force and BOB for borehole direction steering.

[0032] A direct measurement of the bit side force, however, may not be accessible, whereas the downhole measurements of BOB may come from sensors within the BHA. Furthermore, there does not exist a simple relationship relating the steering assembly force to the bit force and BOB, which dictates to build a mathematical BHA model to output the bit side force and BOB for a controlled input of steering assembly force. The good agreement of measured and simulated BOB results provides additional information regarding the bit side force, which in conjunction with the BOB can be used to assess the directional capability of the RSS system under the constraints of existing borehole geometry and BHA configurations. Moreover, the health of the RSS system and the steering assembly force may be either determined from the downhole measured BOB using data analysis techniques including but not limited to machine learning, or from the simulation results with the proposed BHA model, which accounts for the influence of deficiency of steering assembly force on the BOB.

[0033] During directional drilling a predetermined well path may be determined based on curve and/or drilling laterally. While this process is traditionally accomplished by directional drillers with manual controls, techniques such as steering control and/or geo-steering may be applied to achieve partial or full automation, which may increase efficiency and reliability of the said operation. Irrespective of the automation level, determining direction along which the borehole propagates may be a variable to determine other aspects of the direction drilling operation. To evaluate the borehole propagating direction in real time, sensors installed in the BHA may be utilized to measure the borehole inclination and azimuth. Typically, such sensors are not in the proximity of the drill bit, thus the borehole propagating direction is approximated with the BHA direction measured at some distance away from the bit. Disclosed below are methods and systems to determine the borehole propagating direction at bit using the BOB measurements.

[0034] Figure 1 is a diagram of an example drilling environment. Drilling environment 100 may include drilling platform 102 that supports derrick 104 having a traveling block 108 for raising and lowering top drive 110 and drillstring 114. Top drive 110 supports and rotates drillstring 114 as it is lowered through wellhead 112. In turn, drill bit 124, located at the end of drillstring 114, may create borehole 116. Each of these components is described below.

[0035] Platform 102 is a structure which may be used to support one or more other components of drilling environment 100 (e.g., derrick 104). Platform 102 may be designed and constructed from suitable materials (e.g., concrete) which are able to withstand the forces applied by other components (e.g., the weight and counterforces experienced by derrick 104). In any embodiment, platform 102 may be constructed to provide a uniform surface for drilling operations in drilling environment 100.

[0036] Derrick 104 is a structure which may support, contain, and/or otherwise facilitate the operation of one or more pieces of the drilling equipment. In any embodiment, derrick 104 may support crown block 106, traveling block 108, and/or any part connected to (and including) drillstring 114. Derrick 104 may be constructed from any suitable materials (e.g., steel) to provide the strength necessary to support those components.

[0037] Crown block 106 is one or more simple machine(s) which may be rigidly affixed to derrick 104 and include a set of pulleys (e.g., a "block"), threaded (e.g., "reeved") with a drilling line (e.g., a steel cable), to provide mechanical advantage. Crown block 106 may be disposed vertically above traveling block 108, where traveling block 108 is threaded with the same drilling line.

[0038] Traveling block 108 is one or more simple machine(s) which may be movably affixed to derrick 104 and include a set of pulleys, threaded with a drilling line, to provide mechanical advantage. Traveling block 108 may be disposed vertically below crown block 106, where crown block 106 is threaded with the same drilling line. In any embodiment, traveling block 108 may be mechanically coupled to drillstring 114 (e.g., via top drive 110) and allow for drillstring 114 (and/or any component thereof) to be lifted from (and out of) borehole 116. Both crown block 106 and traveling block 108 may use a series of parallel pulleys (e.g., in a "block and tackle" arrangement) to achieve significant mechanical advantage, allowing for the drillstring to handle greater loads (compared to a configuration that uses non-parallel tension). Traveling block 108 may move vertically (e.g., up, down) within derrick 104 via the extension and retraction of the drilling line.

[0039] Top drive 110 is a machine which may be configured to rotate drillstring 114. Top drive 110 may be affixed to traveling block 108 and configured to move vertically within derrick 104 (e.g., along with traveling block 108). In any embodiment, the rotation of drillstring 114 (caused by top drive 110) may cause drillstring 114 to form borehole 116. Top drive may use one or more motor(s) and gearing mechanism(s) to cause rotations of drillstring 114. In any embodiment, a rotatory table (not shown) and a "Kelly" drive (not shown) may be used in addition to, or instead of, top drive 110.

[0040] Wellhead 112 is a machine which may include one or more pipes, caps, and/or valves to provide pressure control for contents within borehole 116 (e.g., when fluidly connected to a well (not shown)). In any embodiment, during drilling, wellhead 112 may be equipped with a blowout preventer (not shown) to prevent the flow of higher-pressure fluids (in borehole 116) from escaping to the surface in an uncontrolled manner. Wellhead 112 may be equipped with other ports and/or sensors to monitor pressures within borehole 116 and/or otherwise facilitate drilling operations.

[0041] Drillstring 114 is a machine which may be used to form borehole 116 and/or gather data from borehole 116 and the surrounding geology. Drillstring 114 may include one or more drillpipe(s), one or more repeater(s) 120, and bottom-hole assembly 118. Drillstring 114 may rotate (e.g., via top drive 110) to form and deepen borehole 116 (e.g., via drill bit 124) and/or via one or more motor(s) attached to drillstring 114.

[0042] Borehole 116 is a hole in the ground which may be formed by drillstring 114 (and one or more components thereof). Borehole 116 may be partially or fully lined with casing to protect the surrounding ground from the contents of borehole 116, and conversely, to protect borehole 116 from the surrounding ground.

[0043] Bottom-hole assembly 118 is a machine which may be equipped with one or more tools for creating, providing structure, and maintaining borehole 116, as well as one or more tools for measuring the surrounding environment (e.g., measurement while drilling (MWD), logging while drilling (LWD)). In any embodiment, bottom-hole assembly 118 may be disposed at (or near) the end of drillstring 114 (e.g., in the most "downhole" portion of borehole 116).

[0044] Non-limiting examples of tools that may be included in bottom-hole assembly 118 include a drill bit (e.g., drill bit 124), casing tools (e.g., a shifting tool), a plugging tool, a mud motor, a drill collar (thick-walled steel pipes that provide weight and rigidity to aid the drilling process), actuators (and pistons attached thereto), a rotary steerable system, and any measurement tool (e.g., sensors, probes, particle generators, etc.).

[0045] Further, bottom-hole assembly 118 may include a telemetry sub to maintain a communications link with the surface (e.g., with information handling system 130). Such telemetry communications may be used for (i) transferring tool measurement data from bottom-hole assembly 118 to surface receivers, and/or (ii) receiving commands (from the surface) to bottom-hole assembly 118 (e.g., for use of one or more tool(s) in bottom-hole assembly 118).

[0046] As illustrated, the information handling system 130 may comprise any instrumentality or aggregate of instrumentalities operable to compute, estimate, classify, process, transmit, broadcast, receive, retrieve, originate, switch, store, display, manifest, detect, record, reproduce,

handle, or utilize any form of information, intelligence, or data for business, scientific, control, or other purposes. For example, an information handling system 130 may be a personal computer, a network storage device, or any other suitable device and may vary in size, shape, performance, functionality, and price.

[0047] Information handling system 130 may include a processing unit (e.g., microprocessor, central processing unit, etc.) that may process drilling data from rotary steerable system (RSS) 242, discussed below, by executing software or instructions obtained from a local non-transitory computer readable media (e.g., optical disks, magnetic disks). The non-transitory computer readable media may store software or instructions of the methods described herein. Non-transitory computer readable media may include any instrumentality or aggregation of instrumentalities that may retain data and/or instructions for a period of time. Non-transitory computer readable media may include, for example, storage media such as a direct access storage device (e.g., a hard disk drive or floppy disk drive), a sequential access storage device (e.g., a tape disk drive), compact disk, CD-ROM, DVD, RAM, ROM, electrically erasable programmable read-only memory (EEPROM), and/or flash memory; as well as communications media such wires, optical fibers, microwaves, radio waves, and other electromagnetic and/or optical carriers; and/or any combination of the foregoing. Information handling system 130 may also include input device(s) (e.g., keyboard, mouse, touchpad, etc.) and output device(s) (e.g., monitor, printer, etc.). The input device(s) and output device(s) provide a user interface that enables an operator to interact with RSS 242, discussed below, and/or software executed by a processing unit. For example, information handling system 130 may enable an operator to select analysis options, view collected log data, view analysis results, and/or perform other tasks.

[0048] Non-limiting examples of techniques for transferring tool measurement data (to the surface) include mud pulse telemetry and through-wall acoustic signaling. For through-wall acoustic signaling, one or more repeater(s) 120 may detect, amplify, and re-transmit signals from bottom-hole assembly 118 to the surface (e.g., to information handling system 130), and conversely, from the surface (e.g., from information handling system 130) to bottom-hole assembly 118.

[0049] Repeater 120 is a device which may be used to receive and send signals from one component of drilling environment 100 to another component of drilling environment 100. As a non-limiting example, repeater 120 may be used to receive a signal from a tool on bottom-hole assembly 118 and send that signal to information handling system 130. Two or more repeaters 120 may be used together, in series, such that a signal to/from bottom-hole assembly 118 may be relayed through two or more repeaters 120 before reaching its destination.

[0050] Transducer 122 is a device which may be configured to convert non-digital data (e.g., vibrations, other analog data) into a digital form suitable for information handling system 130. As a non-limiting example, one or more transducer(s) 122 may convert signals between mechanical and electrical forms, enabling information handling system 130 to receive the signals from a telemetry sub, on bottom-hole assembly 118, and conversely, transmit a downlink signal to the telemetry sub on bottom-hole assembly 118. In any embodiment, transducer 122 may be located at the surface and/or any part of drillstring 114 (e.g., as part of bottom-hole assembly 118).

[0051] Drill bit 124 is a machine which may be used to cut through, scrape, and/or crush (i.e., break apart) materials in the ground (e.g., rocks, dirt, clay, etc.). Drill bit 124 may be disposed at the frontmost point of drillstring 114 and bottom-hole assembly 118. In any embodiment, drill bit 124 may include one or more cutting edges (e.g., hardened metal points, surfaces, blades, protrusions, etc.) to form a geometry which aids in breaking ground materials loose and further crushing that material into smaller sizes. In any embodiment, drill bit 124 may be rotated and forced into (i.e., pushed against) the ground material to cause the cutting, scraping, and crushing action. The rotations of drill bit 124 may be caused by top drive 110 and/or one or more motor(s) located on drillstring 114 (e.g., on bottom-hole assembly 118).

[0052] Pump 126 is a machine that may be used to circulate drilling fluid 128 from a reservoir, through a feed pipe, to derrick 104, to the interior of drillstring 114, out through drill bit 124 (through orifices, not shown), back upward through borehole 116 (around drillstring 114), and back into the reservoir. In any embodiment, any suitable pump 126 may be used (e.g., centrifugal, gear, etc.) which is powered by any source (e.g., electricity, combustible fuel, etc.).

[0053] Drilling fluid 128 is a liquid which may be pumped through drillstring 114 and borehole 116 to collect drill cuttings, debris, and/or other ground material from the end of borehole 116 (e.g., the volume most recently hollowed by drill bit 124). Further, drilling fluid 128 may provide conductive cooling to drill bit 124 (and/or bottom-hole assembly 118). In any embodiment, drilling fluid 128 may be circulated via pump 126 and filtered to remove unwanted debris.

[0054] Information handling system 130 is a computing system which may be operatively connected to drillstring 114 (and/or other various components of the drilling environment). In any embodiment, information handling system 130 may utilize any suitable form of wired and/or wireless communication to send and/or receive data to and/or from other components of drilling environment 100. In any embodiment, information handling system 130 may receive a digital telemetry signal, demodulate the signal, display data (e.g., via a visual output device), and/or store the data. In any embodiment, information handling system 130 may send a signal (with data) to

one or more components of drilling environment 100 (e.g., to control one or more tools on bottom-hole assembly 118).

[0055] Figure 2 is a diagram of an example bottom-hole assembly. Bottom-hole assembly 118 may include a rotary steerable system 242 to control drilling direction 240 of drill bit 124. Each of these components is described below.

[0056] Drilling direction 240 is the direction in which drill bit 124 (and/or bottom-hole assembly 118) is oriented to create borehole 116. Drilling direction 240 may be changed via rotary steerable system 242, using one or more steering actuator(s) 246.

[0057] Rotary steerable system (RSS) 242 is a mechanism which may control drilling direction 240. In any embodiment, RSS 242 may be coupled to one or more components of drillstring 114 via bottom-hole assembly 118. RSS 242 may function by utilizing one or more steering actuator(s) 246 to push against the side(s) of borehole 116 to cause changes in the orientation of drill bit 124 (and/or bottom-hole assembly 118). When steering actuator(s) 246 press against the walls of borehole 116, bottom-hole assembly 118 is subjected to a counteracting force which may cause a torque that pivots drill bit 124 away from an existing drilling direction 240 to a new drilling direction 240 (e.g., a "push-the-bit" system for directional drilling).

[0058] In any embodiment, RSS 242 may function while bottom-hole assembly 118 is rotating. To cause the deflection of drilling direction 240 in a (relatively) consistent direction, steering actuator(s) 246 may be extended only while facing the appropriate direction. That is, as all steering actuator(s) 246 are rotating with bottom-hole assembly 118, steering actuator(s) 246 may be extended only for the portion of time in which they are facing the direction opposite the current drilling direction 240. Thus, steering actuator(s) 246 may be repeatedly extended and retracted—as bottom-hole assembly 118 rotates—to effectuate a change to the drilling direction 240.

[0059] As a non-limiting example, for simplicity, consider a two-dimensional environment where bottom-hole assembly 118 has a drilling direction 240 due "rightward". Then, to avoid an obstacle, for a drill bit 124 to change to a slightly "downward" (but still mostly rightward) drilling direction 240. To cause this change, steering actuator(s) 246 that face "upward" (i.e., the direction opposite downward) are extended to push drill bit 124 downward. Once the drilling direction 240 is achieved, steering actuator(s) 246 remain retracted as no further change in drilling direction 240 is needed.

[0060] Steering controller 243 is a mechanism which may control the operation of one or more steering actuator(s) 246 to achieve the change in drilling direction 240. Steering controller 243 may be a computing device (e.g., like information handling system 130) which includes a processor, memory, storage, interface device(s), etc. Steering controller 243 may utilize electronics

for controlling steering actuator(s) 246 (e.g., via electrical actuation) and/or via mechanical mechanisms for controlling steering actuator(s) 246 (e.g., via hydraulic actuation). Steering controller 243 may control the timing of the extension and retraction of steering actuator(s) 246—as bottom-hole assembly 118 rotates—such that drill bit 124 is deflected to a chosen drilling direction 240.

[0061] Actuator row 244 is an arrangement of two or more steering actuators 246 disposed circumferentially around bottom-hole assembly 118, in a plane that is substantially orthogonal (i.e., perpendicular) to drilling direction 240. In any embodiment, steering actuator(s) 246 in actuator row 244 may be disposed uniformly around a circumference of bottom-hole assembly 118. As a non-limiting example, RSS 242 may include a plurality of actuator rows 244 and/or steering actuators 246. Each actuator row 244 may comprise three or more steering actuators 246. Within a single actuator row 244, the three steering actuators 246 may be disposed about 60° apart from each other on bottom-hole assembly 118.

[0062] Figure 3 is a diagram of an example bottom-hole assembly (BHA) 118. BHA 118 may comprise drill bit 124, one or more steering actuator(s) 246, configured for actuator movement 249 during rotation 248. In the example of FIGURE 3, steering actuator(s) 246 are in the form of pistons which have a linear actuator movement 249 orthogonal to the curved surface of bottom-hole assembly 118. Similar to the example shown in FIGURE 2, in any embodiment, there may be any number of actuator row(s) 244 with any number of steering actuator(s) 246 disposed at a radial offset from each other around a circumference of bottom-hole assembly 118.

[0063] Figure 4 is a diagram of an example BHA 118. BHA 118 may include drill bit 124, one or more steering actuator(s) 246, configured for actuator movement 249 during rotation 248. In the example of Figure 4, steering actuator(s) 246 are in the form of hinged pads which have an actuator movement 249 that pivots away from the surface of bottom-hole assembly 118. As shown in the example of Figure 4, in any embodiment, there may be any number of actuator row(s) 244 with any number of steering actuator(s) 246 which are arranged at a radial offset from each other around a circumference of bottom-hole assembly 118.

[0064] Figure 5 further illustrates an example information handling system 130 which may be employed to perform various steps, methods, and techniques disclosed herein. Persons of ordinary skill in the art will readily appreciate that other system examples are possible. As illustrated, information handling system 130 includes a processing unit (CPU or processor) 502 and a system bus 504 that couples various system components including system memory 506 such as read only memory (ROM) 508 and random-access memory (RAM) 510 to processor 502. Processors disclosed herein may all be forms of this processor 502. Information handling system 130 may

include a cache 512 of high-speed memory connected directly with, in close proximity to, or integrated as part of processor 502. Information handling system 130 copies data from memory 506 and/or storage device 514 to cache 512 for quick access by processor 502. In this way, cache 512 provides a performance boost that avoids processor 502 delays while waiting for data. These and other modules may control or be configured to control processor 502 to perform various operations or actions. Other system memory 506 may be available for use as well. Memory 506 may include multiple different types of memory with different performance characteristics. It may be appreciated that the disclosure may operate on information handling system 130 with more than one processor 502 or on a group or cluster of computing devices networked together to provide greater processing capability. Processor 502 may include any general-purpose processor and a hardware module or software module, such as first module 516, second module 518, and third module 520 stored in storage device 514, configured to control processor 502 as well as a special-purpose processor where software instructions are incorporated into processor 502. Processor 502 may be a self-contained computing system, containing multiple cores or processors, a bus, memory controller, cache, etc. A multi-core processor may be symmetric or asymmetric. Processor 502 may include multiple processors, such as a system having multiple, physically separate processors in different sockets, or a system having multiple processor cores on a single physical chip. Similarly, processor 502 may include multiple distributed processors located in multiple separate computing devices but working together such as via a communications network. Multiple processors or processor cores may share resources such as memory 506 or cache 512 or may operate using independent resources. Processor 502 may include one or more state machines, an application specific integrated circuit (ASIC), or a programmable gate array (PGA) including a field PGA (FPGA).

[0065] Each individual component discussed above may be coupled to system bus 504, which may connect each and every individual component to each other. System bus 504 may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. A basic input/output (BIOS) stored in ROM 508 or the like, may provide the basic routine that helps to transfer information between elements within information handling system 130, such as during start-up. Information handling system 130 further includes storage devices 514 or computer-readable storage media such as a hard disk drive, a magnetic disk drive, an optical disk drive, tape drive, solid-state drive, RAM drive, removable storage devices, a redundant array of inexpensive disks (RAID), hybrid storage device, or the like. Storage device 514 may include software modules 516, 518, and 520 for controlling processor 502. Information handling system 130 may include other hardware or

software modules. Storage device 514 is connected to the system bus 504 by a drive interface. The drives and the associated computer-readable storage devices provide nonvolatile storage of computer-readable instructions, data structures, program modules and other data for information handling system 130. In one aspect, a hardware module that performs a particular function includes the software component stored in a tangible computer-readable storage device in connection with hardware components, such as processor 502, system bus 504, and so forth, to carry out a particular function. In another aspect, the system may use a processor and computer-readable storage device to store instructions which, when executed by the processor, cause the processor to perform operations, a method or other specific actions. The basic components and appropriate variations may be modified depending on the type of device, such as whether information handling system 130 is a small, handheld computing device, a desktop computer, or a computer server. When processor 502 executes instructions to perform "operations", processor 502 may perform the operations directly and/or facilitate, direct, or cooperate with another device or component to perform the operations.

[0066] As illustrated, information handling system 130 employs storage device 514, which may be a hard disk or other types of computer-readable storage devices which may store data that are accessible by a computer, such as magnetic cassettes, flash memory cards, digital versatile disks (DVDs), cartridges, random access memories (RAMs) 510, read only memory (ROM) 508, a cable containing a bit stream and the like, may also be used in the exemplary operating environment. Tangible computer-readable storage media, computer-readable storage devices, or computer-readable memory devices, expressly exclude media such as transitory waves, energy, carrier signals, electromagnetic waves, and signals per se.

[0067] To enable user interaction with information handling system 130, an input device 522 represents any number of input mechanisms, such as a microphone for speech, a touch-sensitive screen for gesture or graphical input, keyboard, mouse, motion input, speech and so forth. Additionally, input device 522 may receive one or more measurements from bottom-hole assembly 118 (e.g., referring to Figure 1), discussed above. An output device 524 may also be one or more of a number of output mechanisms known to those of skill in the art. In some instances, multimodal systems enable a user to provide multiple types of input to communicate with information handling system 130. Communications interface 526 generally governs and manages the user input and system output. There is no restriction on operating on any particular hardware arrangement and therefore the basic hardware depicted may easily be substituted for improved hardware or firmware arrangements as they are developed.

[0068] As illustrated, each individual component described above is depicted and disclosed as individual functional blocks. The functions these blocks represent may be provided through the use of either shared or dedicated hardware, including, but not limited to, hardware capable of executing software and hardware, such as a processor 502, that is purpose-built to operate as an equivalent to software executing on a general purpose processor. For example, the functions of one or more processors presented in Figure 5 may be provided by a single shared processor or multiple processors. (Use of the term "processor" should not be construed to refer exclusively to hardware capable of executing software.) Illustrative embodiments may include microprocessor and/or digital signal processor (DSP) hardware, read-only memory (ROM) 508 for storing software performing the operations described below, and random-access memory (RAM) 510 for storing results. Very large-scale integration (VLSI) hardware embodiments, as well as custom VLSI circuitry in combination with a general-purpose DSP circuit, may also be provided.

[0069] Figure 6 illustrates an example information handling system 130 having a chipset architecture that may be used in executing the described method and generating and displaying a graphical user interface (GUI). Information handling system 130 is an example of computer hardware, software, and firmware that may be used to implement the disclosed technology. Information handling system 130 may include a processor 502, representative of any number of physically and/or logically distinct resources capable of executing software, firmware, and hardware configured to perform identified computations. Processor 502 may communicate with a chipset 600 that may control input to and output from processor 502. In this example, chipset 600 outputs information to output device 524, such as a display, and may read and write information to storage device 514, which may include, for example, magnetic media, and solid-state media. Chipset 600 may also read data from and write data to RAM 510. A bridge 602 for interfacing with a variety of user interface components 604 may be provided for interfacing with chipset 600. Such user interface components 604 may include a keyboard, a microphone, touch detection and processing circuitry, a pointing device, such as a mouse, and so on. In general, inputs to information handling system 130 may come from any of a variety of sources, machine generated and/or human generated.

[0070] Chipset 600 may also interface with one or more communication interfaces 526 that may have different physical interfaces. Such communication interfaces may include interfaces for wired and wireless local area networks, for broadband wireless networks, as well as personal area networks. Some applications of the methods for generating, displaying, and using the GUI disclosed herein may include receiving ordered datasets over the physical interface or be generated by the machine itself by processor 502 analyzing data stored in storage device 514 or RAM 510.

Further, information handling system 130 receives inputs from a user via user interface components 604 and executes appropriate functions, such as browsing functions by interpreting these inputs using processor 502.

[0071] In examples, information handling system 130 may also include tangible and/or non-transitory computer-readable storage devices for carrying or having computer-executable instructions or data structures stored thereon. Such tangible computer-readable storage devices may be any available device that may be accessed by a general purpose or special purpose computer, including the functional design of any special purpose processor as described above. By way of example, and not limitation, such tangible computer-readable devices may include RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other device which may be used to carry or store program code in the form of computer-executable instructions, data structures, or processor chip design. When information or instructions are provided via a network, or another communications connection (either hardwired, wireless, or combination thereof), to a computer, the computer properly views the connection as a computer-readable medium. Thus, any such connection is properly termed a computer-readable medium. Combinations of the above should also be included within the scope of the computer-readable storage devices.

[0072] Computer-executable instructions include, for example, instructions and data which cause a general-purpose computer, special purpose computer, or special purpose processing device to perform a certain function or group of functions. Computer-executable instructions also include program modules that are executed by computers in stand-alone or network environments. Generally, program modules include routines, programs, components, data structures, objects, and the functions inherent in the design of special-purpose processors, etc. that perform particular tasks or implement particular abstract data types. Computer-executable instructions, associated data structures, and program modules represent examples of the program code for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represents examples of corresponding acts for implementing the functions described in such steps.

[0073] In additional examples, methods may be practiced in network computing environments with many types of computer system configurations, including personal computers, hand-held devices, multi-processor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. Examples may also be practiced in distributed computing environments where tasks are performed by local and remote processing devices that are linked (either by hardwired links, wireless links, or by a combination thereof)

through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

[0074] Figure 7 illustrates an example of one arrangement of resources in a computing network 700 that may employ the processes and techniques described herein, although many others are of course possible. As noted above, an information handling system 130, as part of their function, may utilize data, which includes files, directories, metadata (e.g., access control list (ACLS) creation/edit dates associated with the data, etc.), and other data objects. The data on the information handling system 130 is typically a primary copy (e.g., a production copy). During a copy, backup, archive or other storage operation, information handling system 130 may send a copy of some data objects (or some components thereof) to a secondary storage computing device 704 by utilizing one or more data agents 702.

[0075] A data agent 702 may be a desktop application, website application, or any software-based application that is run on information handling system 130. As illustrated, information handling system 130 may be disposed at any rig site (e.g., referring to Figure 1), off site location, or repair and manufacturing center. The data agent may communicate with a secondary storage computing device 704 using communication protocol 708 in a wired or wireless system. Communication protocol 708 may function and operate as an input to a website application. In the website application, field data related to pre- and post-operations, generated DTCs, notes, and the like may be uploaded. Additionally, information handling system 130 may utilize communication protocol 708 to access processed measurements, operations with similar DTCs, troubleshooting findings, historical run data, and/or the like. This information is accessed from secondary storage computing device 704 by data agent 702, which is loaded on information handling system 130.

[0076] Secondary storage computing device 704 may operate and function to create secondary copies of primary data objects (or some components thereof) in various cloud storage sites 706A-N. Additionally, secondary storage computing device 704 may run determinative algorithms on data uploaded from one or more information handling systems 144, discussed further below. Communications between the secondary storage computing devices 704 and cloud storage sites 706A-N may utilize REST protocols (Representational state transfer interfaces) that satisfy basic C/R/U/D semantics (Create/Read/Update/Delete semantics), or other hypertext transfer protocol ("HTTP")-based or file-transfer protocol ("FTP")-based protocols (e.g., Simple Object Access Protocol).

[0077] In conjunction with creating secondary copies in cloud storage sites 706A-N, the secondary storage computing device 704 may also perform local content indexing and/or local object-level, sub-object-level or block-level deduplication when performing storage operations

involving various cloud storage sites 706A-N. Cloud storage sites 706A-N may further record and maintain, EM logs, map DTC codes, store repair and maintenance data, store operational data, and/or provide outputs from determinative algorithms that are located in cloud storage sites 706A-N. In a non-limiting example, this type of network may be utilized as a platform to store, backup, analyze, import, preform extract, transform and load ("ETL") processes, mathematically process, apply machine learning models, and augment EM measurement data sets.

[0078] A machine learning model may be an empirically derived model which may result from a machine learning algorithm identifying one or more underlying relationships within a dataset. In comparison to a physics-based model, such as Maxwell's Equations, which are derived from first principles and define the mathematical relationship of a system, a pure machine learning model may not be derived from first principles. Once a machine learning model is developed, it may be queried in order to predict one or more outcomes for a given set of inputs. The type of input data used to query the model to create the prediction may correlate both in category and type to the dataset from which the model was developed.

[0079] The structure of, and the data contained within a dataset provided to a machine learning algorithm may vary depending on the intended function of the resulting machine learning model. The rows of data, or data points, within a dataset may contain one or more independent values. Additionally, datasets may contain corresponding dependent values. The independent values of a dataset may be referred to as "features," and a collection of features may be referred to as a "feature space." If dependent values are available in a dataset, they may be referred to as outcomes or "target values." Although dependent values may be a component of a dataset for certain algorithms, not all algorithms require a dataset with dependent values. Furthermore, both the independent and dependent values of the dataset may comprise either numerical or categorical values.

[0080] While it may be true that machine learning model development is more successful with a larger dataset, it may also be the case that the whole dataset isn't used to train the model. A test dataset may be a portion of the original dataset which is not presented to the algorithm for model training purposes. Instead, the test dataset may be used for what may be known as "model validation," which may be a mathematical evaluation of how successfully a machine learning algorithm has learned and incorporated the underlying relationships within the original dataset into a machine learning model. This may include evaluating model performance according to whether the model is over-fit or under-fit. As it may be assumed that all datasets contain some level of error, it may be important to evaluate and optimize the model performance and associated model fit by a model validation. In general, the variability in model fit (e.g.: whether a model is over-fit

or under-fit) may be described by the "bias-variance trade-off." As an example, a model with high bias may be an under-fit model, where the developed model is over-simplified, and has either not fully learned the relationships within the dataset or has over-generalized the underlying relationships. A model with high variance may be an over-fit model which has overlearned about non-generalizable relationships within training dataset which may not be present in the test dataset. In a non-limiting example, these non-generalizable relationships may be driven by factors such as intrinsic error, data heterogeneity, and the presence of outliers within the dataset. The selected ratio of training data to test data may vary based on multiple factors, including, in a non-limiting example, the homogeneity of the dataset, the size of the dataset, the type of algorithm used, and the objective of the model. The ratio of training data to test data may also be determined by the validation method used, wherein some non-limiting examples of validation methods include k-fold cross-validation, stratified k-fold cross-validation, bootstrapping, leave-one-out cross-validation, resubstitution, random subsampling, and percentage hold-out.

[0081] In addition to the parameters that exist within the dataset, such as the independent and dependent variables, machine learning algorithms may also utilize parameters referred to as "hyperparameters." Each algorithm may have an intrinsic set of hyperparameters which guide what and how an algorithm learns about the training dataset by providing limitations or operational boundaries to the underlying mathematical workflows on which the algorithm functions. Furthermore, hyperparameters may be classified as either model hyperparameters or algorithm parameters.

[0082] Model hyperparameters may guide the level of nuance with which an algorithm learns about a training dataset, and as such model hyperparameters may also impact the performance or accuracy of the model that is ultimately generated. Modifying or tuning the model hyperparameters of an algorithm may result in the generation of substantially different models for a given training dataset. In some cases, the model hyperparameters selected for the algorithm may result in the development of an over-fit or under-fit model. As such, the level to which an algorithm may learn the underlying relationships within a dataset, including the intrinsic error, may be controlled to an extent by tuning the model hyperparameters.

[0083] Model hyperparameter selection may be optimized by identifying a set of hyperparameters which minimize a predefined loss function. An example of a loss function for a supervised regression algorithm may include the model error, wherein the optimal set of hyperparameters correlates to a model which produces the lowest difference between the predictions developed by the produced model and the dependent values in the dataset. In addition to model hyperparameters, algorithm hyperparameters may also control the learning process of an

algorithm, however algorithm hyperparameters may not influence the model performance. Algorithm hyperparameters may be used to control the speed and quality of the machine learning process. As such, algorithm hyperparameters may affect the computational intensity associated with developing a model from a specific dataset.

[0084] Machine learning algorithms, which may be capable of capturing the underlying relationships within a dataset, may be broken into different categories. One such category may include whether the machine learning algorithm functions using supervised, unsupervised, semi-supervised, or reinforcement learning. The objective of a supervised learning algorithm may be to determine one or more dependent variables based on their relationship to one or more independent variables. Supervised learning algorithms are named as such because the dataset includes both independent and corresponding dependent values where the dependent value may be thought of as "the answer," that the model is seeking to predict from the underlying relationships in the dataset. As such, the objective of a model developed from a supervised learning algorithm may be to predict the outcome of one or more scenarios which do not yet have a known outcome. Supervised learning algorithms may be further divided according to their function as classification and regression algorithms. When the dependent variable is a label or a categorical value, the algorithm may be referred to as a classification algorithm. When the dependent variable is a continuous numerical value, the algorithm may be a regression algorithm. In a non-limiting example, algorithms utilized for supervised learning may include Neural Networks, K-Nearest Neighbors, Naïve Bayes, Decision Trees, Classification Trees, Regression Trees, Random Forests, Linear Regression, Support Vector Machines (SVM), Gradient Boosting Regression, and Perception Back-Propagation.

[0085] The objective of unsupervised machine learning may be to identify similarities and/or differences between the data points within the dataset which may allow the dataset to be divided into groups or clusters without the benefit of knowing which group or cluster the data may belong to. Datasets utilized in unsupervised learning may not include a dependent variable as the intended function of this type of algorithm is to identify one or more groupings or clusters within a dataset. In a non-limiting example, algorithms which may be utilized for unsupervised machine learning may include K-means clustering, K-means classification, Fuzzy C-Means, Gaussian Mixture, Hidden Markov Model, Neural Networks, and Hierarchical algorithms.

[0086] In examples to determine a relationship using machine learning, a neural network (NN) 800, as illustrated in Figure 8, may be utilized to model a three-dimensional finite element BHA to analyze lateral deflection experienced by BHA 118 (e.g., referring to Figure 1) in both its lateral deflection in both inclination and pseudo-azimuth planes in a curved borehole 116 (e.g., referring

to Figure 1). Figure 8 illustrates neural network (NN) 800. NN 800 may operate utilizing one or more information handling systems 130 (e.g., referring to Figure 1) on computing network 700. Although a NN is illustrated, multiple models may be used with input output structures. These models may include flexible empirical models such as NN, gaussian processing methods, kriging methods, evolutionary methods such as genetic algorithms, classification methods, clustering methods empirical methods, or physics based methods such as equations of state, thermodynamic models, geological, geochemistry, or chemistry models, or kinetic models or any combinations therein including recursive combinations of similar or dissimilar models and iterative model combinations. A NN 800 is an artificial neural network with one or more hidden layers 802 between input layer 804 and output layer 806. In examples, NN 800 may be software on a single information handling system 130. In other examples, NN 800 may software running on multiple information handling systems 130 connected wirelessly and/or by a hard wired connection in a network of multiple information handling systems 130. Herein, NN 800 may be applied in a wide array of implementations.

[0087] During operations, inputs 808 data are given to neurons 812 in input layer 804. Neurons 812, 814, and 816 are defined as individual or multiple information handling systems 130 connected in a computing network 700. The output from neurons 812 may be transferred to one or more neurons 814 within one or more hidden layers 802. Hidden layers 802 includes one or more neurons 814 connected in a network that further process information from neurons 812. The number of hidden layers 802 and neurons 812 in hidden layer 802 may be determined by personnel that designs NN 800. Hidden layers 802 is defined as a set of information handling system 130 assigned to specific processing. Hidden layers 802 spread computation to multiple neurons 812, which may allow for faster computing, processing, training, and learning by NN 800. Output from NN 800 may be computed by neurons 816. Output may reflect lateral deflection experienced by BHA 118 (e.g., referring to Figure 1) in both its lateral deflection in both inclination and pseudo-azimuth planes in a curved borehole 116 (e.g., referring to Figure 1).

[0088] Figure 9 is an illustrates a BHA model 900 that may be formed from the fundamental principle of virtual displacement. Euler-Bernoulli beam elements with two nodes at each end are used to discretize BHA 118 according to the variation of the BHA cross-sectional area as well as positions of stabilizers 902 and steering actuators 246. To solve the BHA deformation and obtain bending moment on bit (BOB), pin boundary condition is applied at the tail end of BHA 118 while fixed boundary condition may be applied at bit 124 with a certain value of bit tilt, in conjunction with borehole displacement constraints applied at stabilizers 902. Consideration of the variation of the RSS force magnitude and orientation by taking account of steering actuators 246 may be

utilized to determine health of steering actuators 246. In addition, utilizing a sensor rotating with bit 124, the simulated BOB may be projected to the sensor measurement plane such that a direct comparison between measured and simulated BOB may be implemented. A good agreement between measured and simulated BOB provides a better interpretation of the BOB data from the modeling perspective.

[0089] BHA model 900 may be developed based at least in part that a borehole centerline corresponding to the considered BHA length is a circular arc, which may be well approximated with segments of parabolas, the deformation of BHA 118 is expressed as a superposition of the borehole centerline and the displacement perturbations with respect to the borehole centerline, the cross section of borehole is assumed to be an ideal circular with its diameter the same as or larger than drill bit 124, the dynamic effects resulting from BHA vibrations and drilling fluid are neglected whereas the variation of steering actuators 246 as a function of time is considered, and in the static analysis, time is only adopted as a convenient variable to denote the variation of pad force magnitude and orientation.

[0090] With continued reference to Figure 9, a coordinate reference system is utilized in a BHA model 900 in a three-dimensional space. A coordinate reference system *O-xyz* is attached at bit 124 with *x*-axis pointing from bit 124 to tail end 904 of BHA 118, *y*-axis aligning with the high side of borehole 116 (e.g., referring to Figure 1), and *z*-axis determined according to the right-hand rule. The plane *O-xy* defines the inclination plane while plane *O-xz* is designated as the pseudo-azimuth plane. The BHA lateral deformation in inclination and pseudo-azimuth planes are described by translational displacements $V(x)$ and $W(x)$ and by rotational displacements $V'(x)$ and $W'(x)$, respectively. The axial deformation $U(x)$ is associated with the axial force as $F_a(x)$ through:

$$F_a(x) = EA(x)U'(x) \tag{1}$$

The variation of the axial force $F_a(x)$ along BHA 118 may be obtained directly by axial static equilibrium.

[0091] BHA model 900 is developed using the principal of virtual displacements given as

$$\int_0^L EI(x)(V''\delta V'' + W''\delta W'')dx + \int_0^L F_a(x)(V'\delta V' + W'\delta W')dx + \int_0^L q(x)\sin\Theta(x)\,\delta V dx = 0 \tag{2}$$

Equations (3) and (4) may lead to explicit displacement relationships between V and perturbation v in inclination plane and between W and perturbation w in pseudo-azimuth planes, given in

$$V = v + \frac{1}{2}\kappa_z x^2 - \frac{1}{2}\kappa_z L x \tag{3}$$

$$W = w - \frac{1}{2}\kappa_y x^2 + \frac{1}{2}\kappa_y L x \tag{4}$$

Substituting Eqs. (3) and (4) into Eq. (2) formulates the principle of virtual displacement in terms of displacement perturbations v and w, as given in:

$$\int_0^L EI(x)(v'' + \kappa_z)\delta v''dx + \int_0^L EI(x)(w'' - \kappa_y)\delta w''dx + \int_0^L F_a(x)\left(v' + \kappa_z x - \frac{1}{2}\kappa_z L\right)\delta v'dx + \int_0^L F_a(x)\left(w' - \kappa_y x + \frac{1}{2}\kappa_y L\right)\delta w'dx + \int_0^L q(x)\sin\Theta(x)\,\delta v dx = 0 \quad (5)$$

According to the variation of cross section and locations of stabilizers 902 and steering actuators 246, Eq. (6) is discretized into N intervals, as given in:

$$\sum_{i=1}^N \int_{l_{i-1}}^{l_i} EI(v'' + \kappa_z)\delta v''dx + \sum_{i=1}^N \int_{l_{i-1}}^{l_i} EI(w'' - \kappa_y)\delta w''d + \sum_{i=1}^N \int_{l_{i-1}}^{l_i} F_a\left(v' + \kappa_z x - \frac{1}{2}\kappa_z L\right)\delta v'dx + \sum_{i=1}^N \int_{l_{i-1}}^{l_i} F_a\left(w' - \kappa_y x + \frac{1}{2}\kappa_y L\right)\delta w'dx + \sum_{i=1}^N \int_{l_{i-1}}^{l_i} q\sin\Theta\,\delta v dx = 0 \quad (6)$$

[0092] After discretization, the flexural rigidity EI, axial force F_a, weight per unit length q, and borehole inclination Θ in each interval are regarded as constants. Each interval in Eq. (6) corresponds to a Euler-Bernoulli beam element, as shown in Figure 10. Beam element 1000 has two nodes 1002 and 1004 at each end and each node 1002 and 1004 has four degrees of freedom, namely, two lateral displacements and two rotational displacements. The continuous displacement field may be expressed in terms of the nodal displacement via interpolation functions, as given in

$$v(x) = (1 - 3\xi^2 + 2\xi^3)V_1 + l(\xi - 2\xi^2 + \xi^3)V_2 + (3\xi^2 - 2\xi^3)V_3 + l(\xi^3 - \xi^2)V_4 \quad (7)$$

$$w(x) = (1 - 3\xi^2 + 2\xi^3)W_1 - l(\xi - 2\xi^2 + \xi^3)W_2 + (3\xi^2 - 2\xi^3)W_3 - l(\xi^3 - \xi^2)W_4 \quad (8)$$

where

$$\xi = x/l \quad (9)$$

with l representing the element length. A substitution of Eqs. (7) and (8) into Eq. (6) and after some mathematical manipulations, a system of finite element equations governing the lateral deformation of the nodal points, which may be expressed in the matrix-vector form as in

$$KD = F \quad (10)$$

where D is the nodal displacement vector, K is the global stiffness matrix including the nonlinear stiffness matrix associated with the axial force, F is the vector of external forces due to axial force and borehole curvature, gravity, and RSS pad force.

[0093] In order to solve the finite element equations in (10), displacement boundary conditions and displacement constraints may be applied at stabilizers 902 (e.g., referring to Figures 9). A pin boundary condition is applied at tail end 904 of BHA 118 and a fixed boundary condition taking account of the bit tilt ψ_z at the bit end, as given in:

$$V|_{x=L} = 0,\ W|_{x=L} = 0 \quad (11)$$

$$V|_{x=0} = 0, W|_{x=0} = 0,\ V'|_{x=0} = -\psi_z - \frac{1}{2}\kappa_z L,\ W'|_{x=0} = \psi_y + \frac{1}{2}\kappa_y L \quad (12)$$

[0094] Figure 11 depicts borehole centerline 1100 in the coordinate reference systems and illustrates three direction vectors defined at bit 124. The inclinations of borehole centerline 1100 at tail end 904 and bit 124 are denoted by Θ_1 and Θ_0, respectively, leading to:

$$\beta = \Theta_0 - \Theta_1 \tag{13}$$

owing to the assumption that borehole centerline 1100 is a circular arc. The constant curvature κ_z is thus given by:

$$\kappa_z = \beta / L \tag{14}$$

The first direction vector $\hat{\boldsymbol{I}}_1$ is aligned with the undeformed BHA 118 and opposite to the positive direction of the *x*-axis; the second one $\boldsymbol{I}_1$ is tangent to borehole centerline 1100 at bit 124. The third one $\boldsymbol{i}_1$ is coaxial with bit axis. Bit tilt is defined as the angle from $\boldsymbol{I}_1$ to $\boldsymbol{i}_1$ and is related to the bit inclination θ_0 and borehole inclination Θ_0 as

$$\psi_z = \theta_0 - \Theta_0 \tag{15}$$

The angle $\delta = V'$ is the slope of borehole centerline 1100 at bit 124 measured in the coordinate reference system *O-xy* and is geometrically related to the borehole inclinations as:

$$\delta = -\beta/2 \tag{16}$$

[0095] Figure 12 depicts the counterparts of the geometrical relationships in the pseudo-azimuth plane as those presented in Figure 11. The included angle α in Figure 12 is given by:

$$\alpha = \Phi_0 \sin\langle\Theta\rangle - \Phi_1 \sin\langle\Theta\rangle \tag{17}$$

where Φ_0 and Φ_1 represents, respectively, the azimuth angles of borehole centerline 1100 at tail end 904 and at end of bit 124, where

$$\langle\Theta\rangle = \frac{\Theta_0 + \Theta_1}{2} \tag{18}$$

is the inclination angle of $\hat{\boldsymbol{I}}_1$, see Figure 11. The constant curvature κ_y is thus given by:

$$\kappa_y = \alpha / L \tag{19}$$

The angle $\gamma = W'$ is the slope of borehole centerline 1100 at bit 124 is measured in the coordinate reference system *O-xz*, (i.e., referring to Figure 9) and is geometrically related to the borehole azimuths as:

$$\gamma = \alpha/2 \tag{20}$$

The bit tilt ψ_y in the pseudo-azimuth plane is the difference of azimuth angles between I_1 and i_1, which can be expressed as:

$$\psi_y = (\phi_0 - \Phi_0) \sin\langle\Theta\rangle \tag{21}$$

with ϕ_0 denoting the bit azimuth angle.

[0096] The confinement of borehole 116 (e.g., referring to Figure 1) on the lateral deformation of BHA 118 is equivalent to apply displacement constraint conditions at contact points. In this model, contacts only at stabilizers 902 (e.g., referring to Figure 9) may be considered, which leads to:

$$\sqrt{v^2 + w^2} = g_i, i = 1,2,\ldots,n \tag{22}$$

where g_i is the clearance between the i-th stabilizer and the borehole wall and n is the total number of stabilizers 902. When the clearance is nonzero, the application of the displacement constraint at stabilizers 902 may possibly violate the compatibility of contact constraint, which is to state that the BHA displacement and the contact force may not be compatible. Figure 13 presents an example of the violation of the compatibility of contact constraint, where a contact 1300 occurs at the low side of borehole 116 but produces a contact force pointing downward, which is physically unprocurable. As disclosed, idealized stabilizers 902 may be considered such that the clearance g_i is zero, which leads to $v = 0$ and $w = 0$ at the stabilizer locations. Modelling of steering actuators 246 (e.g., referring to Figures 2-4) and pad force may allow for greater understanding of how force effect BHA 118. Steering actuators 246 of RSS 242 (e.g., referring to Figures 2-4) may be realized by harnessing the hydraulic power from the drilling fluid.

[0097] Figure 14 illustrates a hydraulic operation that moves each steering actuator 246. Each steering actuator 246 may be connected to a hydraulic cylinder, which causes steering actuators 246 to extend around a fixed hinged pin when the cylinder cavity is filled with hydraulic fluid. The flow of hydraulic fluid into the cylinder is regulated using a stationary valve 1400 and fluid conduits 1404. Stationary valve 1400 may be disposed internally in bottom-hole assembly 118 and coupled to conduit disc 1402 (with one or more fluid conduit(s) 1404 allowing for hydraulic fluid flow 1406 to one or more steering actuator(s) 246 (e.g., referring to Figures 2-4). Each of these components is described below.

[0098] Stationary valve 1400 is a mechanical structure which may control the flow of hydraulic fluid (i.e., hydraulic fluid flow 1406) to one or more steering actuator(s) 246. In any embodiment, stationary valve 1400 may not rotate with the other components of bottom-hole assembly 118 (e.g., via rotation 1408). Rather, stationary valve 1400 may remain rotationally stationary—but still move with bottom-hole assembly 118 in drilling direction. In any embodiment, stationary valve 1400 may be configured (e.g., constructed) and assembled such that, at any given time, one or more fluid conduit(s) 1404 are covered (by stationary valve 1400) while one or more fluid conduit(s) 1404 are open (not covered by stationary valve 1400).

[0099] In any embodiment, stationary valve 1400 may be controllably rotated (independent of rotation 1408 of bottom-hole assembly 118). Stationary valve 1400 may be rotated in response to a change in drilling direction, and the placement of where force is applied to borehole 116 (e.g., referring to Figure 13) by steering actuators 246. As a non-limiting example, if a more "upward" drilling direction is chosen, stationary valve 1400 may be rotated such that the open slice is positioned "downward" to allow steering actuators 246 on the bottoms-side of bottom-hole assembly 118 to receive hydraulic fluid flow 1406.

[0100] Conduit disc 1402 is a mechanical structure which may include one or more fluid conduit(s) 1404. In any embodiment, conduit disc 1402 provides a structure for including fluid conduit(s) 1404 in a geometry that complements stationary valve 1400 (e.g., both are substantially circular) and the steering actuators 246 disposed on bottom-hole assembly.

[0101] Fluid conduit 1404 is a structure which may provide an opening for hydraulic fluid flow 1406. In any embodiment, each fluid conduit 1404 may be aligned and affixed to an individual channel (not shown) leading to a single steering actuator 246. That is, each fluid conduit 1404 is paired with a steering actuator 246, through which hydraulic fluid flow 1406 provides the force to control the movement of the steering actuator 246.

[0102] Figure 15 is a diagram of an example stationary valve 1400. Stationary valve 1400 may be disposed internally in bottom-hole assembly 118 and coupled to conduit disc 1402 with one or more fluid conduit(s) 1404 allowing for hydraulic fluid flow 1406 to one or more steering actuator(s) 246. Each of these components is described below.

[0103] As shown in the example of Figure 15, as bottom-hole assembly 118 undergoes rotation 1408, fluid conduit(s) 1404 will either be (i) fully covered by stationary valve 1400, (ii) partially covered by stationary valve 1400 (and partially exposed), or (iii) fully exposed. Fluid conduits 1402 are partially or fully exposed during the portion of rotation 1408 where stationary valve 1400 does not cover conduit disc 1402.

[0104] During the portion of rotation 1408 when fluid conduit 1404 is not covered by stationary valve 1400, hydraulic fluid flow 1406 passes through fluid conduit 1404 and extends the steering actuator 246 that is paired with fluid conduit 1404. In any embodiment, consequently, when stationary valve 1400 covers fluid conduit 1404, steering actuator 246 retracts and the fluid is provided a path to escape.

[0105] As shown in the example of Figure 15, as bottom-hole assembly 118 rotates clockwise, so does conduit disc 1402 and the fluid conduit(s) 1404 disposed thereon. As fluid conduit 1404 moves from being covered behind stationary valve 1400 to being exposed, the paired steering actuator 246 (being fully retracted) undergoes actuator movement 1410 that extends the steering actuator 246. When fluid conduit 1404 is fully exposed, the paired steering actuator 246 is fully extended and there is no actuator movement 1410. Conversely, as fluid conduit 1404 moves from being fully exposed to being covered by stationary valve 1400, the paired steering actuator 246 (being fully extended) undergoes actuator movement 1410 that retracts steering actuator 246.

[0106] The steering modes may be classified as geo-stationary and neutral modes according to the rotational speed of the stationary valve 1400. The geo-stationary mode is achieved when the motor controls stationary valve 1400 to rotate at a speed equal to the drill collar but in an opposite

direction, making the rotary speed of stationary valve 1400 to be zero from the perspective of an inertial coordinate system. The invariant orientation of stationary valve 1400 in this scenario results in non-zero net resultant pad force when averaged over a few bit revolutions, which steers bit 124 to drill in the desirable direction. The neutral mode, on the other hand, is realized by controlling stationary valve 1400 to rotate at a speed 10 rev/min less than conduit disc 1402. This leads to the varying orientation of stationary valve 1400, which creates a zero net resultant pad force when averaged over a few bit revolutions.

[0107] The fact that the included angle of stationary valve 1400 is twice larger than that of conduit disc 1402 results in two scenarios in terms of pad actuation, as shown in Figures 16A and 16B. The first scenario is that two fluid conduits 1404 overlaps with stationary valve 1400 and thus only one steering actuator 246 is actuated. The second one is that two fluid conduits 1404 both partially overlap with stationary valve 1400, which causes two steering actuators 246 to actuate. For each steering actuator 246, the force F_p is a function of the overlapping angle ϑ between stationary valve 1400 and steering actuator 246, as given in:

$$F_p = \begin{cases} \frac{F_m \vartheta}{\vartheta^*} & 0 \le \vartheta \le \vartheta^* \\ F_m & \vartheta^* \le \vartheta \le \pi - \vartheta^* \\ \frac{F_m(\vartheta + \vartheta^* - \pi)}{\pi - \vartheta^*} & \pi - \vartheta^* \le \vartheta \le \pi \end{cases} \tag{23}$$

and illustrated in Figure 17, where F_m is the maximum magnitude of the pad force and ϑ^* is a threshold value over which the force reaches its maximum.

[0108] It is assumed that the line of action of force is aligned with the centerline of the overlapping angle. Hence, the magnitude of resultant force F_p and its orientation α_F with respect to y-axis (see Figures 16A and 16B) may be computed at a certain time instance given that the rotary speed ω of BHA 118 may be measured with downhole gyros or magnetometers. Once modeling has been completed, modeling and sensor measurements may be merged with each other.

[0109] The two strain gauges used to measure the BOB may be installed in the bit shank. Additionally, each strain gauge may be disposed 180 degrees apart from each other. In other examples, there may be three strain gauges disposed in the bit shank. In these embodiments, each strain gauge may be disposed 120 degrees apart from each other. In the BHA model 900 (e.g., referring to Figure 9), bit 124 is divided into two elements and the second node from bit end 904 (e.g., referring to Figure 9) corresponds to the sensor position. Once the respective bending moments (M_z and M_y) in both inclination and pseudo-azimuth planes are computed, the resultant bending moment M_R and its orientation α_M may be calculated, as given in:

$$M_R = \sqrt{M_y^2 + M_z^2} \tag{24}$$

$$\alpha_M = \begin{cases} 2\pi - \tan^{-1}\frac{M_z}{M_y}, & M_y > 0, M_z > 0 \\ -\tan^{-1}\frac{M_z}{M_y}, & M_y > 0, M_z < 0 \\ \pi - \tan^{-1}\frac{M_z}{M_y}, & M_y < 0 \end{cases} \quad (25)$$

respectively. It is noted that the orientation α_M is measured with respect to the y-axis in a clockwise direction, see Figure 18.

[0110] Since the strain gauge rotates with bit 124, computed BOB may be projected onto the sensor measurement plane. To this end, the unit direction may be defined as vectors n_M and n_S for the resultant BOB and the chord connecting two sensors and pointing from S_2 to S_1 in

$$\boldsymbol{n}_M = [\sin\alpha_M \quad \cos\alpha_M] \quad (26)$$

$$\boldsymbol{n}_S = \frac{1}{2}[\sin\alpha_1 - \sin(\alpha_1 + \pi) \quad \cos\alpha_1 - \cos(\alpha_1 + \pi)] \quad (27)$$

respectively, where α_1 is the orientation of the S_1 that may be calculated from the bit angular velocity. The sensor measurement direction n_d given in

$$\boldsymbol{n}_d = \frac{1}{2}[(\cos\alpha_1 - \cos(\alpha_1 + \pi)), \quad -(\sin\alpha_1 - \sin(\alpha_1 + \pi))] \quad (28)$$

is orthogonal to its chord direction due to the nature of BOB. Finally, using:

$$M_S = (\overrightarrow{n_M} \cdot \overrightarrow{d_n})M_R \quad (29)$$

projected the resultant BOB onto the sensor measurement direction for the sake of a direct comparison with downhole measurement BOB data. It is worth noting that in the simulation downhole measured angular velocity may be used to calculate the orientations of the stationary valve 1400, fluid conduit(s) 1404, and the strain gauge sensors.

[0111] Figures 19A and 19B show comparisons between simulated and downhole measured BOB using the measured bit angular velocities for nutating and geostationary modes, respectively. Other parameters used for simulation of nutating mode are listed in Table 1, whereas for simulation of geostationary mode, the RSS force reduces to 10000 N.

Table 1

Parameters	Symbol	Value	Unit
Average inclination	$\langle\Theta\rangle$	10	deg.
Curvature in inclination plane	κ_z	7.2	deg./30 m
Curvature in pseudo-azimuth plane	κ_y	0.76	Deg./30 m
RSS force magnitude	F_m	13500	N
Threshold of overlapping angle	ϑ^*	15	deg.
Initial tool-face orientation	θ	90	deg.
Initial orientation of first rotating value	χ	90	deg.
Initial orientation of first sensor	γ	30	deg.

Downhole BHA angular velocity	ω_r	140	rev/min
Angular velocity of geostationary valve	ω_g	130	rev/min

[0112] It is shown that the simulation results genearlly agree with downhole measurements in both cases. This results makes the model useful to explain the measurement data and monitor the force exereted by steering actuator 246. Moreover, the bit side force may be inferred from a combination of the BOB measurement and the model, which is paramount for the prediction of borehole propagation.

[0113] The framework of BHA model 900 proposed in this disclosure may be used to consider the contacts between BHA 118 and the wall of borehole 116 (e.g., referring to Figure 1) in two- and three-dimensional space, to calculate the BHA natural frequencies (critical speed) and mode shapes in a modal analysis, to investigate the instantaneous BHA lateral vibrations by including the inertial and damping effects, and to propagate the borehole evolution by combining with bit-rock interactions and bit kinematic relationships.

[0114] The bit-rock interaction may be modeled to be utilized with bit kinematic relationships. The bit-rock interaction model in direction drilling is given by Eq. (30)

$$\begin{bmatrix} W_a \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} H_1 & 0 & 0 \\ 0 & H_2 & H_3 \\ 0 & -H_3 & H_2 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \tag{30}$$

where

$$W_a = W_0 - W_f \tag{31}$$

is the active weight-on-bit, which is the nominal weight-on-bit W_0 minus the weight-on-bit W_f consumed at the bit wearflats. F_2 and F_3 are the bit side forces along the y- and z-axes, respectively; $d_1, d_2,$ and d_3 are the bit penetration depth along the x-, y- and z-axes, respectively. The terms $H_1, H_2,$ and H_3 depend on the bit geometry, on the rock strength, and on the parameter of cutter-rock interactions. The bit kinematics determines the bit tilt angle ψ_y and ψ_z using

$$\psi_y = -\frac{d_3}{d_1}, \psi_z = -\frac{d_2}{d_1} \tag{32}$$

which are treated as input parameters and subjected to be adjusted to so that simulated BOB may agree with measured BOB. After some simple mathematical manipulation on Eq. (30) and (32), the following may be used to relate the bit side force to the bit tilt angles.

$$\eta W_a = \frac{\sqrt{F_2^2 + F_3^2}}{\sqrt{\psi_2^2 + \psi_3^2}} \tag{33}$$

The parameter η is defined in Eq. (33), which is associated the bit side cutting efficiency and measures the relative difficulty of imposing a lateral penetration to the bit compared to an axial

penetration. By recognizing that in the BOB simulation the bit tilt is input parameter while the bit side force are the output responses, the parameter ηW_a may be estimated after the simulated BOB agrees with the measured BOB.

[0115] Given the estimated parameter ηW_a, the borehole dogleg severity (DLS) may be inferred either by using a borehole propagation model on the fly or by referring to a look-up table, which is created by the borehole propagation model that sweeps a large range of ηW_a and produces the corresponding DLS.

[0116] In borehole evolution, the output side force from RSS 242 may affect the steerability or dogleg creation. Although the side force is provided in the design specifications of RSS 242, real-time determination or measurement of the side force may help personnel to determine what may be the best operation parameters. In this disclosure, the side force of RSS 242 may be determined utilizing the BOB measurement as well as BHA model 900 that relates forces and moments to deflection, as described above. Further, bending moment may be measured in real time and frequency may go to 1KHz or even higher. With the BHA rotating one revolution, the BOB measurement may be used to determine the curvature of borehole 116 using BHA model 900, when bit 124 is off bottom and additional BOB due to reaction force from formation, when bit 124 is on bottom. For this disclosure, off-bottom is when bit 124 is hoisted such that the cutters lose contact of the bottom of borehole 116. Additionally, on-bottom is when bit 124 is lowered while in rotation and the bit-rock interaction commences. The offset of BOB readings from these two scenarios gives the net value that is purely due to the directional drilling action.

[0117] Figure 20A illustrates a force coordinate system for BHA 118. Using the force coordinate system, force from steering actuator 246 may be determined with the real-time BOB measurement at or near bit 124 using a sensor 2000 or other sensing techniques. In one example, the real-time BOB may be measured with sensor 2000 at bit 124. Assuming the deflection at bit 124 is negligible, the side force is obtained by the solution of an indeterminate beam problem, seen below:

$$F_{side} = f(l_1, l_2, l_3, BOB) \tag{34}$$

Where l_1 is the distance between bit 124 and a stabilizer 902 from bit 124, l_2 is the distance between steering actuator 246 and stabilizer 902 from bit 124, l_3 is the distance between bit 124 and location of sensor 2000. Additionally, function f may be derived using the beam theory.

[0118] For example, RSS 242 using a Euler Bernoulli beam theory, neglecting the deflection at bit 124 and the gravity force as shown in Figure 20, force from steering actuator 246 may be found using:

$$F_{iCruise} = B_{CF}\left(\frac{2L_{bit}^3}{L_{CF}(3L_{bit}-L_{iCruise})L_{iCruise}^2}\right) \quad (35)$$

If the output force of Equation (35) is measurable and known, several correlations may be drawn from the data in real time or through the use in the control system logic. For example, using Equation (35) may be utilized for real-time BOB measurements, which may provide possibility for service quality improvements, effective duty cycles, health status of steering actuator 246 (applied force measurement), Measurement of error angle between intended/actual tool face, measurement of applied force by steering actuator 246, and force measurement differences in nutating and steering modes. Additionally, Equation (35) may be used to calculate BOB magnitude throughout a drilling stand, taken during in low/no curvature intervals, to determine real-time DLS estimation. BOB_{max}-BOB_{min} constant duty cycle, curvature results in less at bit side force measured below from steering actuator 246, estimation of rock strength, and BOB_{max}-BOB_{min} during nutating modes.

[0119] In other examples, gravitation force may be utilized in Equation (35) to form the following:

$$F_{icruise} = B_{CF} \times \frac{2L_{bit}^3}{L_{CF}(3L_{bit}-L_{iCruise})L_{iCruise}^2} + F_G \cos\Delta \sin\langle\Theta\rangle \times \frac{L_{FG}^2(3L_{bit}-L_{FG})}{L_{iCruise}^2(3L_{bit}-L_{iCruise})} \quad (36)$$

Where F_G is the gravitation force of BHA 118 from bit 124 to stabilizer 902. Angle Δ is the angle between the BOB sensor plane and the vertical plane. Angle $\langle\Theta\rangle$ is an inclination angle. L_{FG} is the distance between the center of mass F_G and stabilizer 902 as shown in Figure 20B. With continued reference to Figure 20B, in examples in which a BOB sensor plane is not aligned with the force from steering actuator 246, the BOB sensor plane may be projected to the plane of steering actuator 246, or vice versa, for a solution.

[0120] In another example, BHA 118 may be represented using BHA model 900 (e.g., referring to Figure 9) to relate the BOB measurement to the side force. Additionally, the deflection of bit 124 may be further accounted for. Using a drill bit model to simulate drilling operations from cutting structure of bit 124 and rock strength. Using the drill bit model, the side cutting depth may be estimated, which may be used as the bit deflection. It is subsequently input into a BHA model 900 (e.g., referring to Figure 9) to determine the side force.

[0121] As noted above, side force may be utilized to determine health of one or more steering actuators 246 utilized with RSS 242. Activation of all steering actuator 246 (e.g., referring to Figures 2-4) may be utilized in directional drilling operations. Therefore, it is beneficial to personnel to know whether a steering actuator 246 is activated or not. As discussed above, steering actuator 246 may be activated sequentially to generate a side force. In geostationary mode, side force is pushing bit 124 to the intended tool face direction. There are six activation modes,

activation of steering actuator 1, activation of steering actuators 1 & 2, activation of steering actuator 2, activation of steering actuators 2 & 3, activation of steering actuator 3, and activation of pads 3 & 1. Each mode of activation may generate a force having a fixed angle respective to a sensor plane of BOB. Therefore, as the modes are activated sequentially, they may generate a unique bending moment signature, that is recorded by sensor 2000 (e.g., referring to Figures 20A and 20B). Comparing the recorded downhole signal to a reference signal generated by BHA model 900 (e.g., referring to Figure 9), discussed above, it may detect if there is any steering actuator 246 that is not activated, or the activation force is low.

[0122] In examples, real-time BOB may be measured using sensor 2000 (e.g., referring to Figures 20A and 20B) at bit 124. Assuming the deflection at bit 124 is negligible, the expected BOB for a given BHA 118 with a known pad force $F_{pad(t)}$ is:

$$BOB(t) = f(l_1, l_2, l_3, F_{Pad}(t),\ \omega(t)\ ) \tag{37}$$

Where BOB is the bending moment measured by in-bit or near-bit using sensor 2000, l_1 is the distance between bit 124 and stabilizer 902 from bit 124, l_2 is the distance between steering actuator 246 and stabilizer 902 from bit 124, l_3 is the distance between bit 124 and location of sensor 2000 (e.g., referring to Figures 20A and 20B). $F_{pad(t)}$ is the force profile and $\omega(t)$ is related to the angular velocity of BHA 118 and the angular velocity of stationary valve 1400 (e.g., referring to Figure 14).

[0123] Figure 21 is a graph charting a nutating mode. In a nutating mode, steering actuators 246 may be activated sequentially to generate a side force. In geostationary mode, the force is pushing bit 124 to the intended tool face direction. The geostationary mode is achieved when the motor controls stationary valve 1400 (e.g., referring to Figure 14) to rotate at a speed equal to the drill collar but in an opposite direction, making the rotary speed of stationary valve 1400 to be zero from the perspective of an inertial coordinate system attached at to the ground. The invariant orientation of stationary valve 1400 in this scenario results in non-zero net resultant force from steering actuator 246 when averaged over a few bit revolutions, which steers bit 124 to drill in the desirable direction. The neutral mode, on the other hand, is realized by controlling stationary valve 1400 to rotate at a speed 10 rev/min less than the rotating valve. This leads to the varying orientation of stationary valve 1400, which creates a zero net resultant force from steering actuator 246 when averaged over a few bit revolutions.

[0124] There are six activation patterns in nutating mode, among which three are from a single steering actuator 246 activation and the other three are from dual steering actuators 246 activation. For example, as seen in Figure 22, a healthy repeated sequence of patterns might look like the following, … pads 3&1, pad 1, pads 1&2, pad 2, pads 2&3, pad 3, pads 3&1, ….

[0125] Each pattern of steering actuator 246 activation may generate a resultant force having its own angle with respective to the BOB sensor plane. Therefore, projection to the sensor plane is different. As the patterns are activated sequentially, they may generate a unique bending moment signature that is recorded by sensor 2000 as shown in Figure 22. A local peak to peak duration represents the time BHA 118 rotates 1 revolution. Comparing the recorded downhole signal to a reference signal generated from BHA model 900 (e.g., referring to Figure 9), it may detect if there is any steering actuator 246 that is not activated, or the activation force is deviated from the expected value.

[0126] Differences between the angular velocity of the two valve causes the BOB to fluctuate at two frequencies, a fast variation due to the rotation of BHA 118 and a slower variation due to the stationary valve revolution with respect to borehole 116 (e.g., referring to Figure 1). In a case where one or more steering actuators 246 malfunctioned, the bending on bit generated by the force at each malfunctioned steering actuator 246 may change.

[0127] Figures 23-26 illustrate the comparison of the simulated bending on bit 124 caused by normal steering actuators 246 and malfunction steering actuators 246. In Figure 23, a graph illustrates the BOB signal when Pad 2 (steering actuators 246 may also be referred to as pads) malfunctioned vs all pads functioned normally in neutral mode. In Figure 24, a graph illustrates the BOB signal when Pads 1 and 3 malfunctioned vs all pads functioned normally in neutral mode. In Figure 25, a graph illustrates the BOB signal when Pad 2 malfunctioned vs all pads functioned normally in geostationary mode. In Figure 26, a graph illustrates the BOB signal when Pads 1 and 3 malfunctioned vs all pads functioning normally in geostationary mode. It is demonstrated that the BOB signal may deviate from normal signal when a pad or pads malfunctioned. It may be detected through signal comparison and identification. BOB comparisons in Figures 23-26 clearly show the effect of steering actuators 246 health condition. Steering actuators 246 health prediction may be performed by using a modeled based method or a machine learning method.

[0128] Figure 27 illustrates a workflow 2700 to determine health for each steering actuator 246. Workflow 2700 may be at least partially implemented on information handling system 130 and/or NN 800 (e.g., referring to Figure 8). Workflow 2700 may begin with block 2702. In block 2702, real-time BOB data may be taken by sensor 2000 (E.g., referring to Figure 20). Further real-time RPM of bit 124 may be taken from a gyro disposed within BHA 118. This data may be processed by an information handling system 130 within BHA 118, at the surface, and/or at least partially processed downhole and/or at surface. During processing, the measure RPM of bit 124 may be used to calculate the orientations of stationary valve 1400 (i.e., referring to Figure 14) and sensors 2000 (i.e., referring to Figure 20A). The orientation of stationary valve 1400 may be used to

calculate the force from a steering actuator 246 using the graph, methods, and systems described in Figure 17 above. Further, the orientation of sensor 2000 may be used to project the simulated BOB onto the sensor measurement plane, as illustrated in Fig. 18. The real-time measured BOB and RPM at a high frequency may also be filtered and down-sampled in order to accelerate the simulations and facilitate subsequent comparisons between simulated and measured BOBs. The data from block 2702 may be utilized in block 2704 and/or block 2706.

[0129] In block 2704, the data from block 2702 may be placed into BHA model 900 (e.g., referring to Figure 9). BHA model 900 in block 2704 may be set to replicate a configuration of BHA 118, as discussed above, in block 2706. Referring back to block 2704, BHA model 900 may be pre-run to provide a steering actuator 246 force lookup table, as discussed above. It may also be run real-time downhole to predict a real-time force from steering actuator 246 based on borehole geometry and configuration of BHA 118.

[0130] In block 2708, BHA model 900 from block 2704 and measurement from block 2702 are compared to each other for pattern recognition and classification. For example, with a known force for a steering actuator 246 and downhole RPM, BHA model 900 may simulate a variation of BOB with time, from which a fluctuation magnitude and frequency may be determined. The simulation may be performed for different dysfunction scenarios for each steering actuator 246, as discussed above. The measured BOB data may also be processed to determine fluctuation and frequency, which may be compared to the patterns obtained using simulation for pattern recognition and classification.

[0131] For pattern recognition, during drilling operation, in which a pre-determined force is created by each steering actuator 246, the cyclic pattern of BOB is expected and may be simulated using BHA model 900. The measured BOB and the simulated BOB may be compared in one or more of the parameters such as frequency, magnitude, phase shift and their min, max, and standard deviation. The results may be classified as malfunctioning or functioning, in block 2710, of one or more steering actuators 246. The difference between the normal BOB signal and the BOB with one or two unhealthy steering actuators 246 are illustrated in Figures 23-26.

[0132] In block 2710, for obtaining classification, under machine learning methods a classification method may be based on a machine learning algorithm such as NN 800 (e.g., referring to Figure 8) or tree-based methods. A trained model may be used for the classification of real-time BOB data. Feature engineering may be performed on BOB data to convert a real time stream of BOB data to a machine learning parameter. Herein, feature engineering may convert BOB into more usable features comprising average magnitude, maximum magnitude, minimum magnitude, and/or dominant frequencies of the data identified as one or more revolution of the

BHA 118. Machine learning parameters may comprise average magnitude, max, min, SD, dominant frequencies, and/or the like.

[0133] Pattern recognition and classification may be utilized in NN 800 to determine and/or predict health conditions of one or more steering actuators 246. For a rule-based method, one example is that a certain force of steering actuator 246 is expected under a given operating condition. The force computed from the real-time BOB either using the simplified model or BHA model 900 is compared to a design specification of BHA 118. If the force from steering actuator 246 is lower, higher, or the same as pre-determined threshold values for force to emanate from steering actuator 246, NN 800 and/or information handling system 130 may categorize the health condition of steering actuator 246 as malfunctioning for forces being higher or lower and function for forces that are in line with a pre-determined force. For a supervised machine learning method, NN 800 may be trained with a labeled BOB data set. The real-time BOB data is fed to the pretrained model to classify health conditions of steering actuator 246. In block 2712, the health conditions for each steering actuator 246 may be communicated to surface through BHA 118 to be reviewed by personnel.

[0134] The methods and systems described above are an improvement over the current technology as the methods and systems described herein provide a systematic way of employing downhole measured BOB and its simulation counterpart to monitor the health of the push-the-bit RSS and assess its directional capability in real-time or in post-job analysis.

[0135] The systems and methods may comprise any of the various features disclosed herein, comprising one or more of the following statements.

[0136] Statement 1: A method, comprising forming a bottom-hole assembly (BHA) model, taking a bending moment on bit (BOB) measurement from a sensor disposed in a BHA, and comparing the BOB measurement to the BHA model to determine if a steering actuator is malfunctioning, wherein the steering actuator is disposed on the BHA.

[0137] Statement 2: The method of statement 1, further comprising creating a pattern recognition from the comparing of the BOB measurement and the BHA model.

[0138] Statement 3: The method of statement 2, further comprising training a neural network (NN) with the pattern recognition to determine if the steering actuator is malfunctioning.

[0139] Statement 4: The method of statement 3, further comprising taking a second measurement of the BOB with the sensor and inputting the second measurement into the NN to determine if one or more steering actuators disposed on the BHA are malfunctioning using the pattern recognition.

[0140] Statement 5: The method of statement 1 or 2, further comprising creating a classification from the comparing of the BOB measurement and the BHA model.

[0141] Statement 6: The method of statement 5, further comprising training a neural network (NN) with the classification to determine if the steering actuator is malfunctioning.

[0142] Statement 7: The method of statement 6, further comprising taking a second measurement of the BOB with the sensor and inputting the second measurement into the NN to determine if one or more steering actuators disposed on the BHA are malfunctioning using the classification.

[0143] Statement 8: The method of any previous statements 1, 2, or 5, wherein the BOB is at least partially altered by a force exerted by a steering actuator.

[0144] Statement 9: The method of statements 1, 2, 5, or 8, further comprising applying a gravitational force measurement to the BHA model.

[0145] Statement 10: The method of statement 9, further comprising transmitting if the steering actuator is malfunctioning from the BHA to personnel at surface.

[0146] Statement 11: A system may comprise a bottom-hole assembly (BHA) that includes at least one sensor disposed on the BHA, wherein the at least one sensor takes at least one bending moment on bit (BOB) measurement and a plurality of steering actuators disposed on the BHA. The system may further comprise an information handling system in communication with the BHA and configured to form a bottom-hole assembly (BHA) model and compare the at least one BOB measurement to the BHA model to determine if each of the plurality of steering actuators are malfunctioning.

[0147] Statement 12: The system of statement 11, wherein the information handling system is further configured to create a pattern recognition from the comparing of the BOB measurement and the BHA model.

[0148] Statement 13: The system of statement 12, wherein the information handling system is further configured to train a neural network (NN) with the pattern recognition to determine if any of the plurality of steering actuators are malfunctioning.

[0149] Statement 14: The system of statement 13, wherein the at least one sensor takes a second measurement of the BOB with the sensor and inputs the second measurement into the NN to if any of the plurality of steering actuators are malfunctioning.

[0150] Statement 15: The system of statements 11 or 12, wherein the information handling system is further configured to create a classification from the comparing of the BOB measurement and the BHA model.

[0151] Statement 16: The system of statement 15, wherein the information handling system is further configured to train a neural network (NN) with the classification to determine if any of the plurality of steering actuators are malfunctioning.

[0152] Statement 17: The system of statement 16, wherein the at least one sensor takes a second measurement of the BOB with the sensor and inputting the second measurement into the NN if any of the plurality of steering actuators are malfunctioning.

[0153] Statement 18: The system of statements 11, 12, or 15, wherein the BOB is at least partially altered by a force exerted by each of the plurality of steering actuators.

[0154] Statement 19: The system of statements 11, 12, 15, or 16, wherein the information handling system is further configured to apply a gravitational force measurement to the BHA model.

[0155] Statement 20: The system of statement 19, wherein the information handling system is further configured to transmit if any of the plurality of steering actuators are malfunctioning from the BHA to personnel at surface.

[0156] As it is impracticable to disclose every conceivable embodiment of the technology described herein, the figures, examples, and description provided herein disclose only a limited number of potential embodiments. One of ordinary skill in the art would appreciate that any number of potential variations or modifications may be made to the explicitly disclosed embodiments, and that such alternative embodiments remain within the scope of the broader technology. Accordingly, the scope should be limited only by the attached claims. Further, the compositions and methods are described in terms of "comprising," "containing," or "including" various components or steps, the compositions and methods may also "consist essentially of" or "consist of" the various components and steps. Moreover, the indefinite articles "a" or "an," as used in the claims, are defined herein to mean one or more than one of the elements that it introduces. Certain technical details, known to those of ordinary skill in the art, may be omitted for brevity and to avoid cluttering the description of the novel aspects.

[0157] For further brevity, descriptions of similarly named components may be omitted if a description of that similarly named component exists elsewhere in the application. Accordingly, any component described with respect to a specific figure may be equivalent to one or more

similarly named components shown or described in any other figure, and each component incorporates the description of every similarly named component provided in the application (unless explicitly noted otherwise). A description of any component is to be interpreted as an optional embodiment—which may be implemented in addition to, in conjunction with, or in place of an embodiment of a similarly-named component described for any other figure.

[0158] As used herein, adjective ordinal numbers (e.g., first, second, third, etc.) are used to distinguish between elements and do not create any particular ordering of the elements. As an example, a "first element" is distinct from a "second element", but the "first element" may come after (or before) the "second element" in an ordering of elements. Accordingly, an order of elements exists only if ordered terminology is expressly provided (e.g., "before", "between", "after", etc.) or a type of "order" is expressly provided (e.g., "chronological", "alphabetical", "by size", etc.). Further, use of ordinal numbers does not preclude the existence of other elements. As an example, a "table with a first leg and a second leg" is any table with two or more legs (e.g., two legs, five legs, thirteen legs, etc.). A maximum quantity of elements exists only if express language is used to limit the upper bound (e.g., "two or fewer", "exactly five", "nine to twenty", etc.). Similarly, singular use of an ordinal number does not imply the existence of another element. As an example, a "first threshold" may be the only threshold and therefore does not necessitate the existence of a "second threshold".

[0159] As used herein, the word "data" may be used as an "uncountable" singular noun—not as the plural form of the singular noun "datum". Accordingly, throughout the application, "data" is generally paired with a singular verb (e.g., "the data is modified"). However, "data" is not redefined to mean a single bit of digital information. Rather, as used herein, "data" means any one or more bit(s) of digital information that are grouped together (physically or logically). Further, "data" may be used as a plural noun if context provides the existence of multiple "data" (e.g., "the two data are combined").

[0160] As used herein, the term "operative connection" (or "operatively connected") means the direct or indirect connection between devices that allows for interaction in some way (e.g., via the exchange of information). For example, the phrase 'operatively connected' may refer to a direct connection (e.g., a direct wired or wireless connection between devices) or an indirect connection (e.g., multiple wired and/or wireless connections between any number of other devices connecting the operatively connected devices).

CLAIMS

What is claimed is:

1. A method, comprising:

forming a bottom-hole assembly (BHA) model;

taking a bending moment on bit (BOB) measurement from a sensor disposed in a BHA; and

comparing the BOB measurement to the BHA model to determine if a steering actuator is malfunctioning, wherein the steering actuator is disposed on the BHA.

2. The method of claim 1, further comprising creating a pattern recognition from the comparing of the BOB measurement and the BHA model.

3. The method of claim 2, further comprising training a neural network (NN) with the pattern recognition to determine if the steering actuator is malfunctioning.

4. The method of claim 3, further comprising taking a second measurement of the BOB with the sensor and inputting the second measurement into the NN to determine if one or more steering actuators disposed on the BHA are malfunctioning using the pattern recognition.

5. The method of claim 1, further comprising creating a classification from the comparing of the BOB measurement and the BHA model.

6. The method of claim 5, further comprising training a neural network (NN) with the classification to determine if the steering actuator is malfunctioning.

7. The method of claim 6, further comprising taking a second measurement of the BOB with the sensor and inputting the second measurement into the NN to determine if one or more steering actuators disposed on the BHA are malfunctioning using the classification.

8. The method of claim 1, wherein the BOB is at least partially altered by a force exerted by a steering actuator.

9. The method of claim 1, further comprising applying a gravitational force measurement to the BHA model.

10. The method of claim 9, further comprising transmitting if the steering actuator is malfunctioning from the BHA to personnel at surface.

11. A system, comprising:

a bottom-hole assembly (BHA) that comprises:

at least one sensor disposed on the BHA, wherein the at least one sensor takes at least one bending moment on bit (BOB) measurement; and

a plurality of steering actuators disposed on the BHA; and

an information handling system in communication with the BHA and configured to:

form a bottom-hole assembly (BHA) model; and

compare the at least one BOB measurement to the BHA model to determine if each of the plurality of steering actuators are malfunctioning.

12. The system of claim 11, wherein the information handling system is further configured to create a pattern recognition from the comparing of the BOB measurement and the BHA model.

13. The system of claim 12, wherein the information handling system is further configured to train a neural network (NN) with the pattern recognition to determine if any of the plurality of steering actuators are malfunctioning.

14. The system of claim 13, wherein the at least one sensor takes a second measurement of the BOB with the sensor and inputs the second measurement into the NN to if any of the plurality of steering actuators are malfunctioning.

15. The system of claim 11, wherein the information handling system is further configured to create a classification from the comparing of the BOB measurement and the BHA model.

16. The system of claim 15, wherein the information handling system is further configured to train a neural network (NN) with the classification to determine if any of the plurality of steering actuators are malfunctioning.

17. The system of claim 16, wherein the at least one sensor takes a second measurement of the BOB with the sensor and inputting the second measurement into the NN if any of the plurality of steering actuators are malfunctioning.

18. The system of claim 11, wherein the BOB is at least partially altered by a force exerted by each of the plurality of steering actuators.

19. The system of claim 11, wherein the information handling system is further configured to apply a gravitational force measurement to the BHA model.

20. The system of claim 19, wherein the information handling system is further configured to transmit if any of the plurality of steering actuators are malfunctioning from the BHA to personnel at surface.

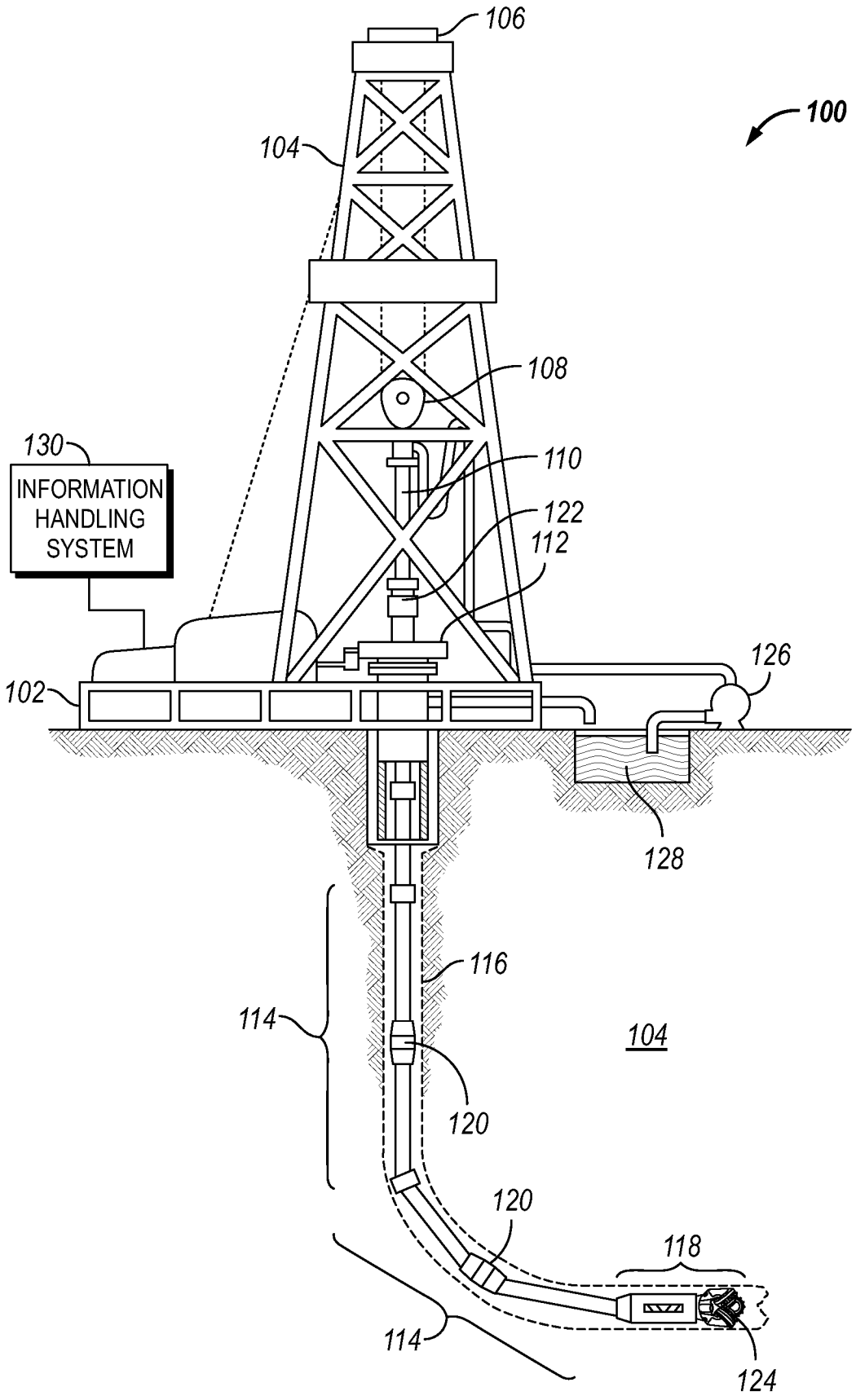

106
100
104
108
130
INFORMATION HANDLING SYSTEM
110
122
112
126
102
128
116
114
104
120
120
118
114
124

FIG. 1

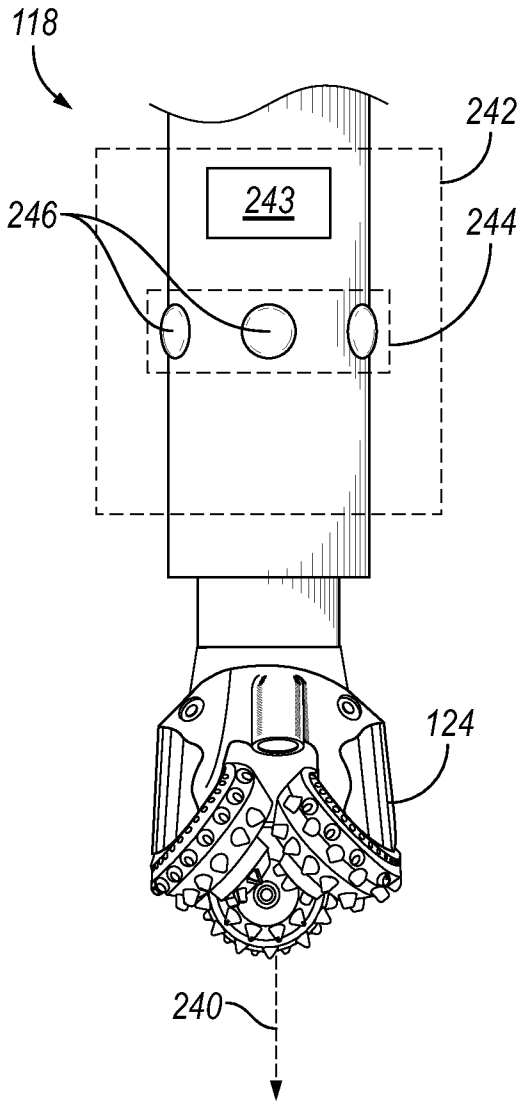


FIG. 2

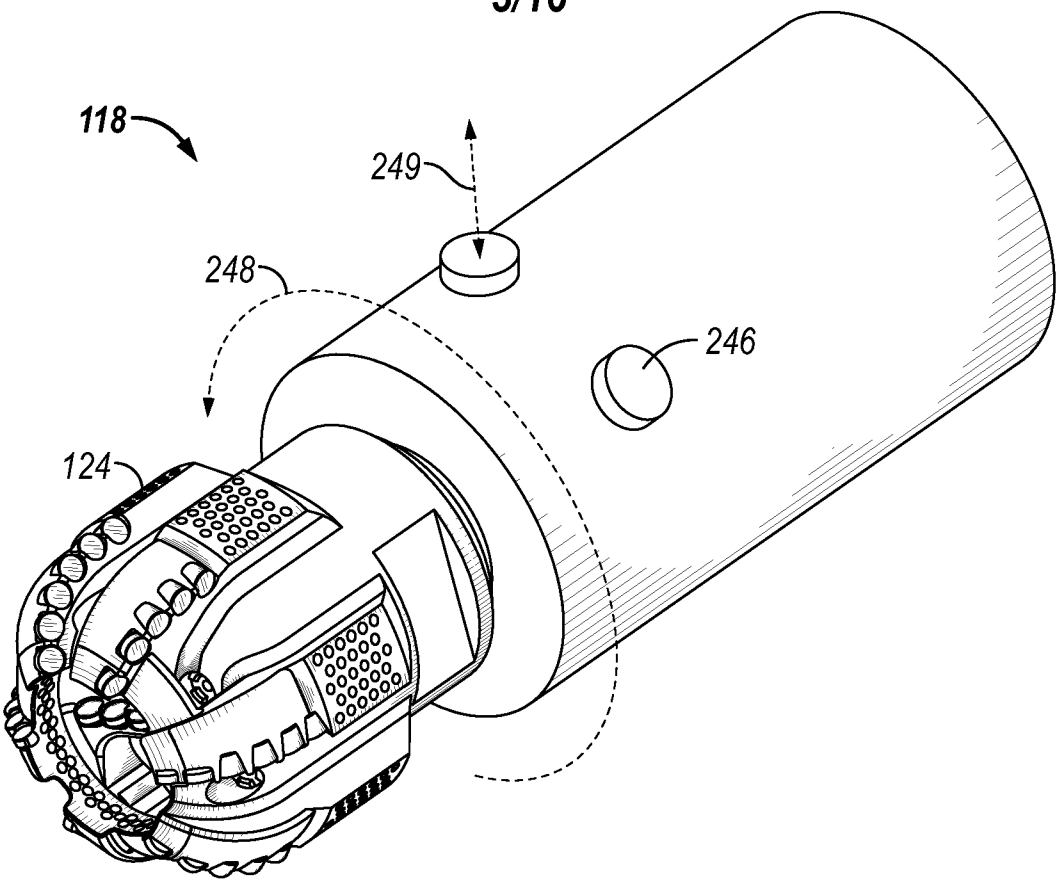


FIG. 3

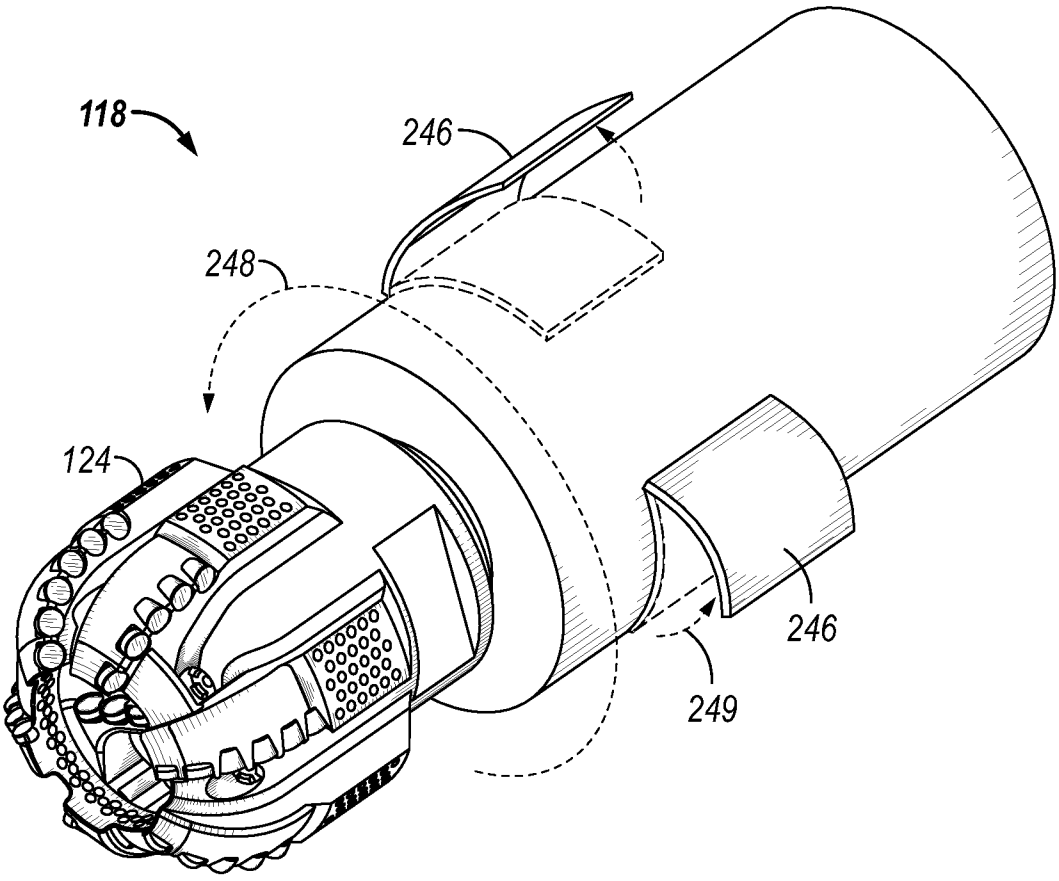


FIG. 4

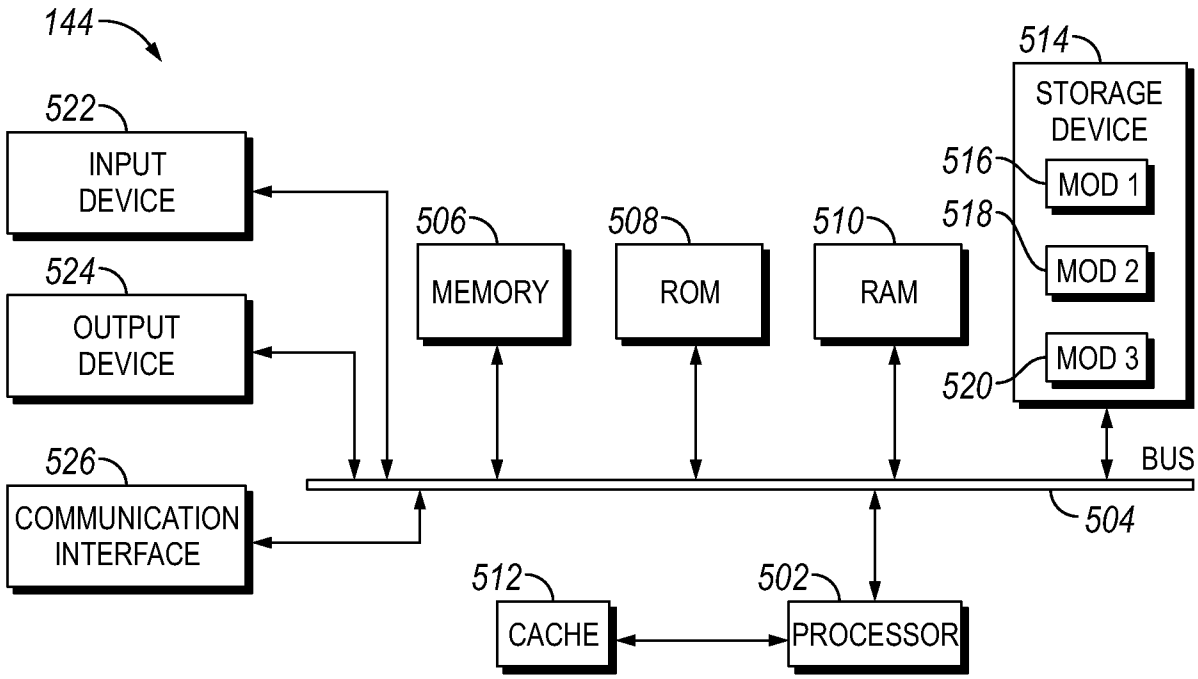

144
514
STORAGE DEVICE
522
INPUT DEVICE
516
MOD 1
506
MEMORY
508
ROM
510
RAM
518
MOD 2
524
OUTPUT DEVICE
MOD 3
520
526
BUS
COMMUNICATION INTERFACE
504
512
CACHE
502
PROCESSOR

FIG. 5

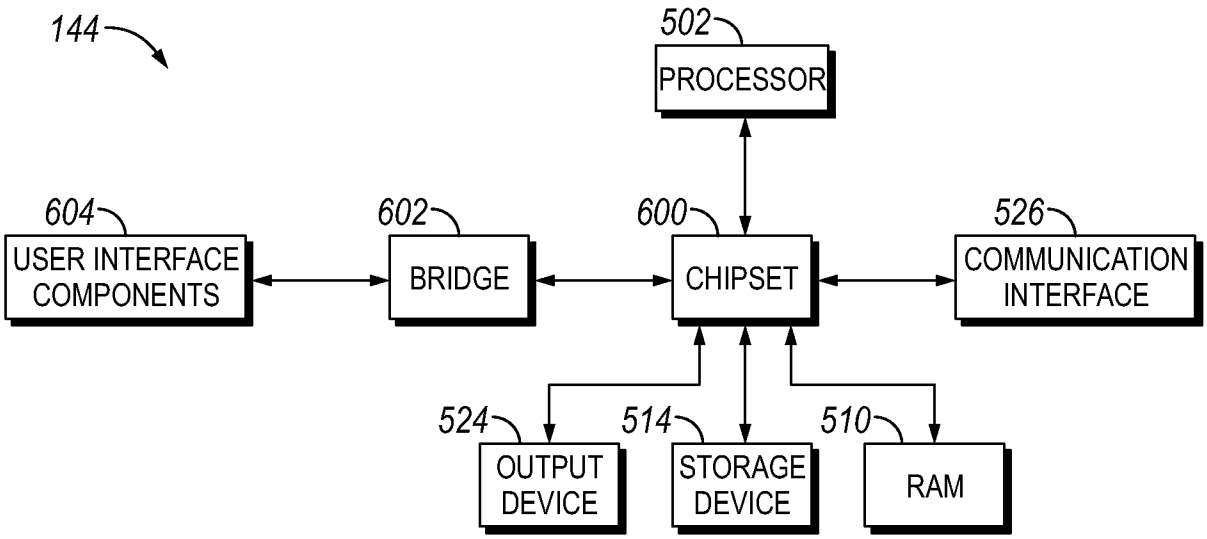

144
502
PROCESSOR
604
602
600
526
USER INTERFACE COMPONENTS
BRIDGE
CHIPSET
COMMUNICATION INTERFACE
524
514
510
OUTPUT DEVICE
STORAGE DEVICE
RAM

FIG. 6

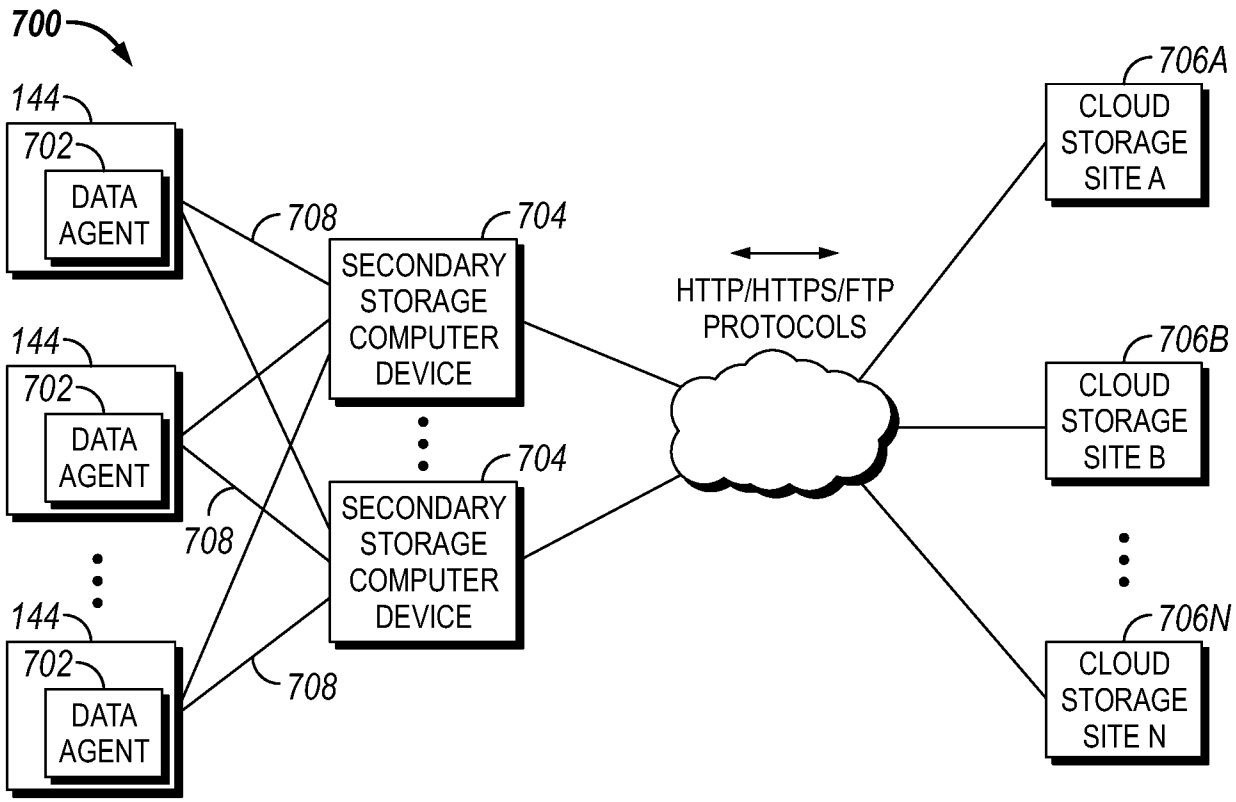

700
144
702
DATA AGENT
144
702
DATA AGENT
144
702
DATA AGENT
708
708
708
704
SECONDARY STORAGE COMPUTER DEVICE
704
SECONDARY STORAGE COMPUTER DEVICE
HTTP/HTTPS/FTP PROTOCOLS
706A
CLOUD STORAGE SITE A
706B
CLOUD STORAGE SITE B
706N
CLOUD STORAGE SITE N

FIG. 7

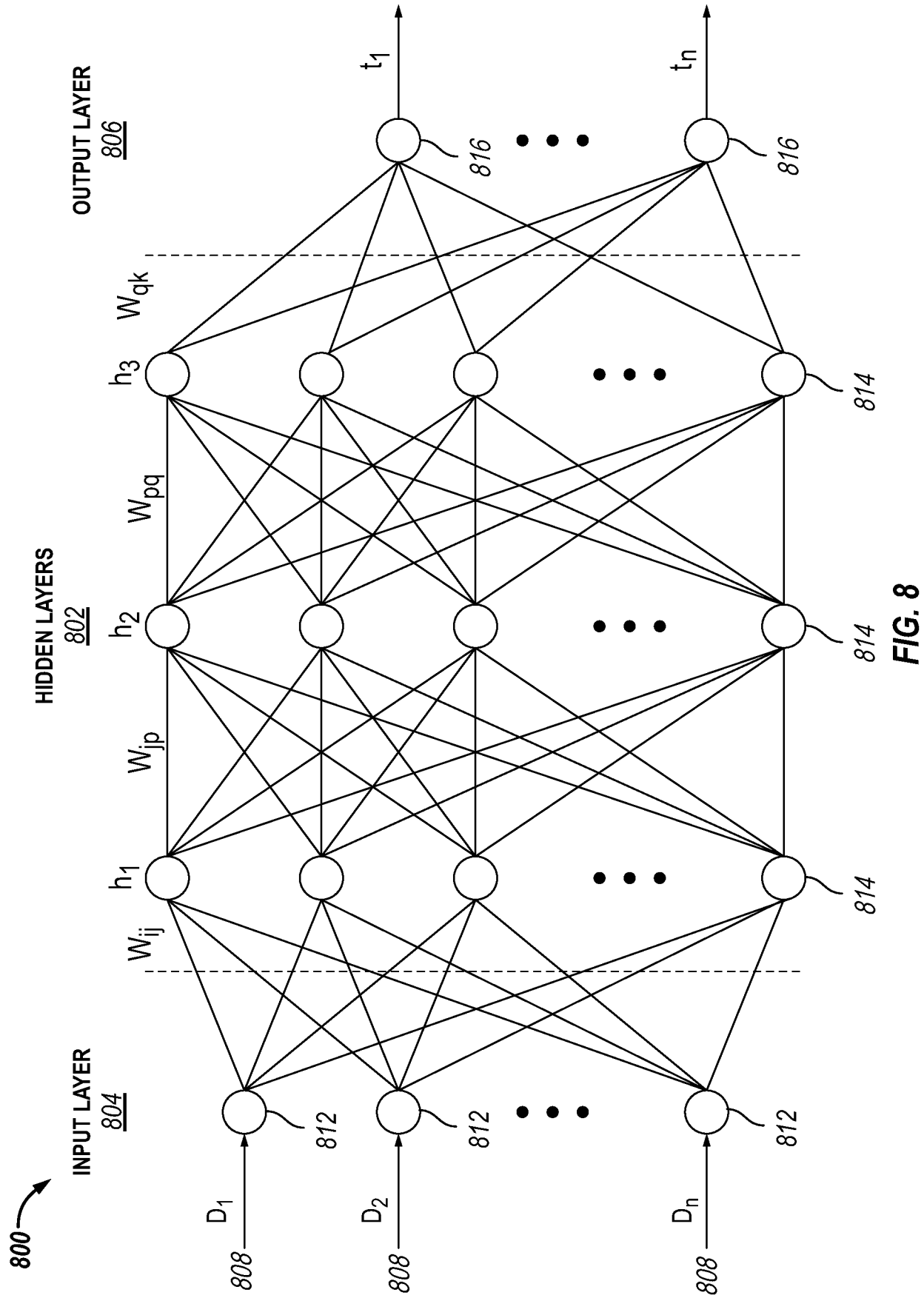

800
INPUT LAYER
804
HIDDEN LAYERS
802
OUTPUT LAYER
806
D1
D2
Dn
808
812
814
816
h1
h2
h3
Wij
Wjp
Wpq
Wqk
t1
tn

FIG. 8

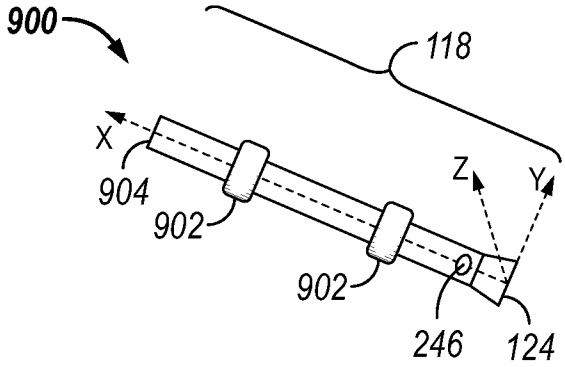


FIG. 9

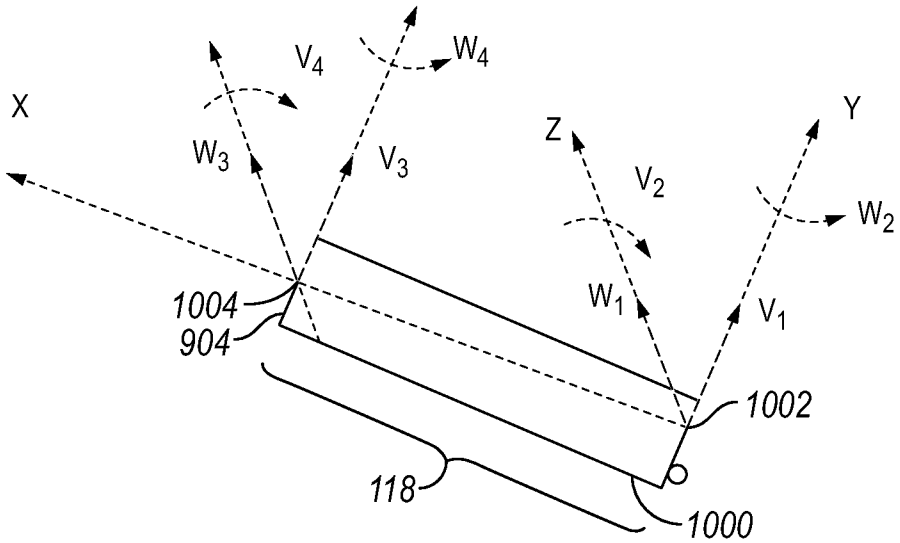


FIG. 10

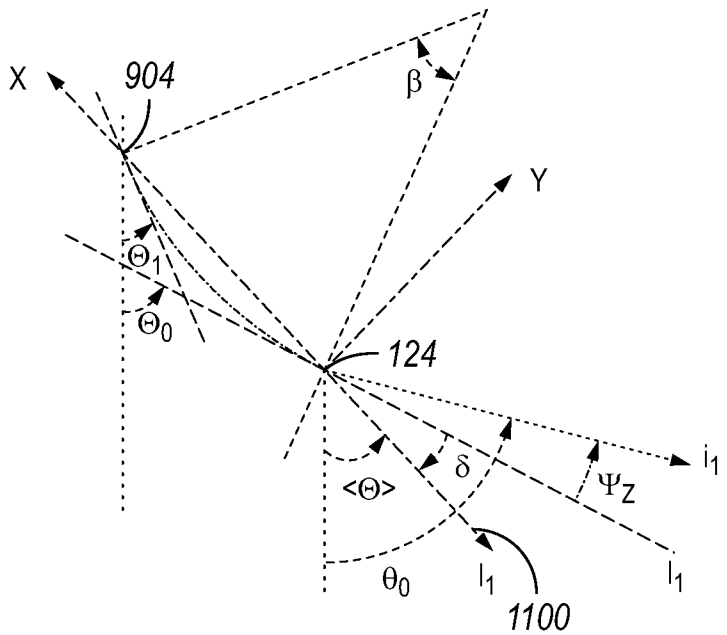


FIG. 11

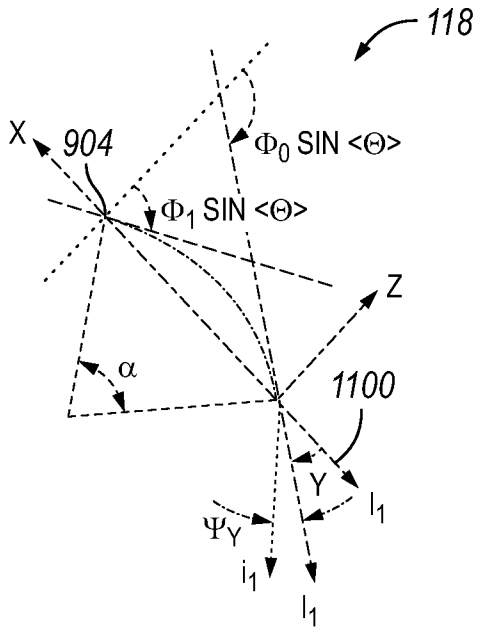


FIG. 12

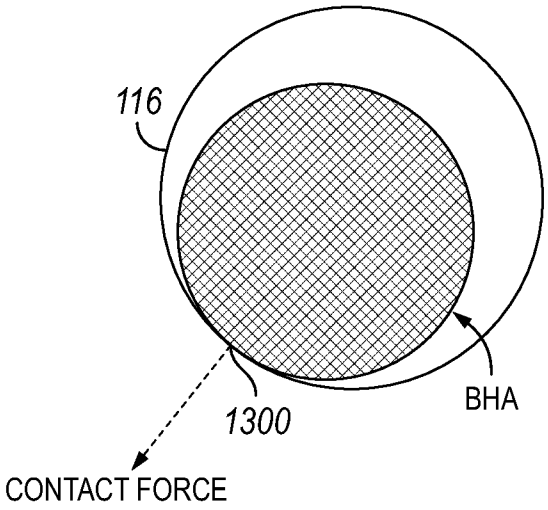


FIG. 13

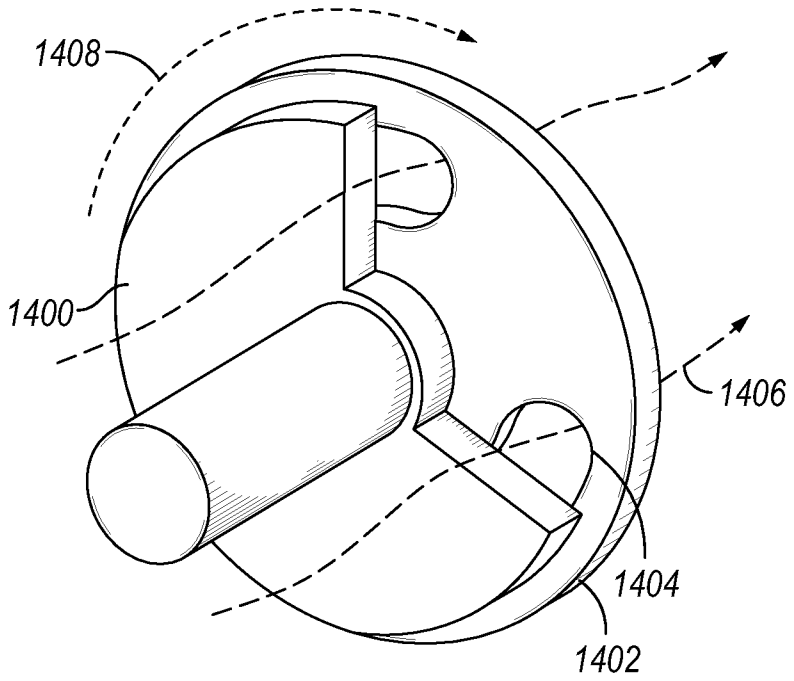


FIG. 14

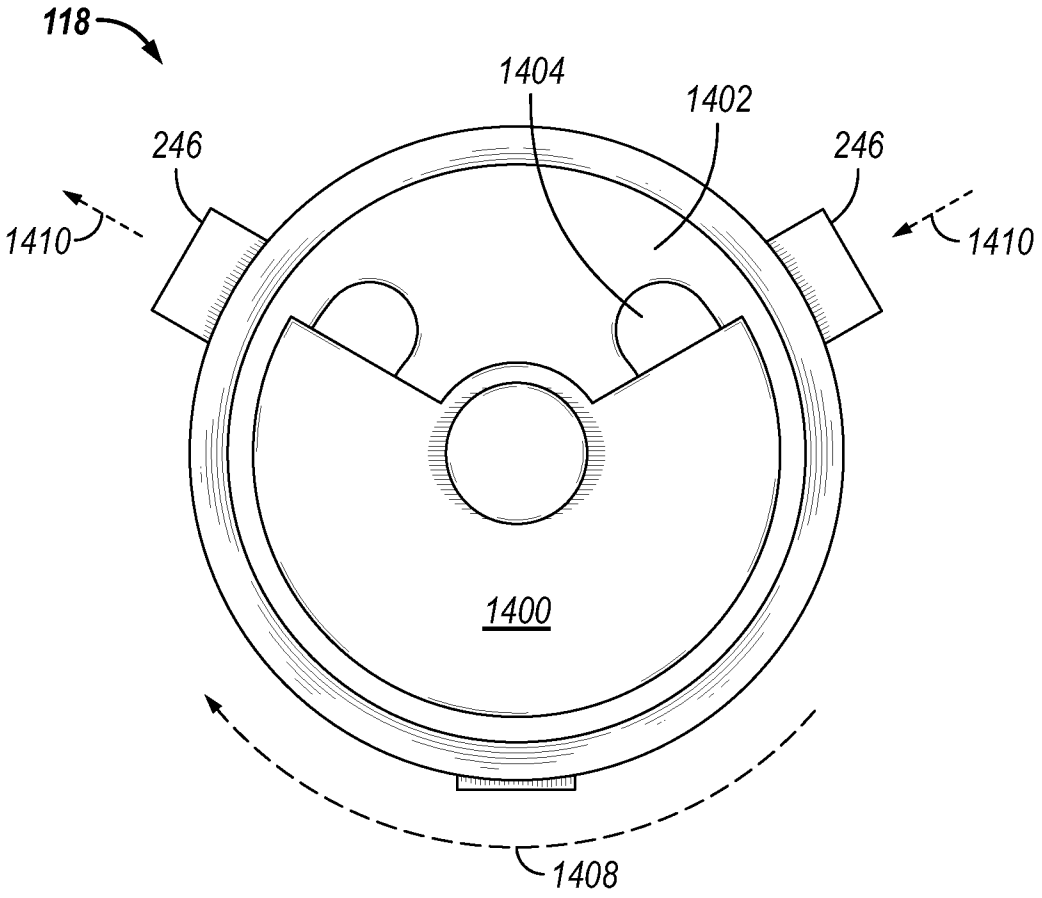


FIG. 15

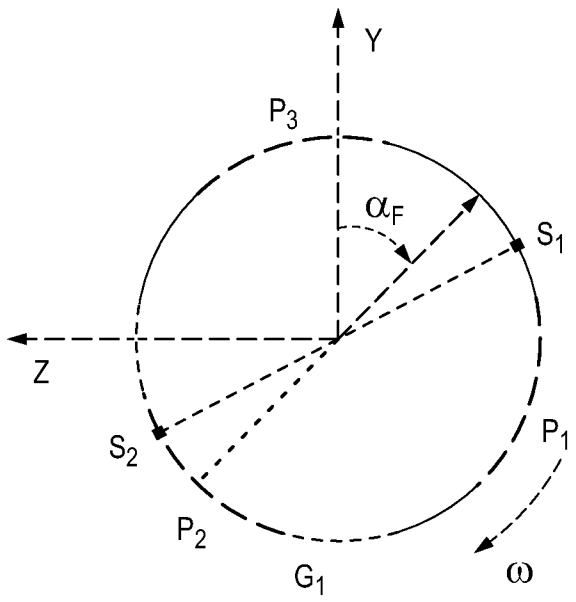


FIG. 16A

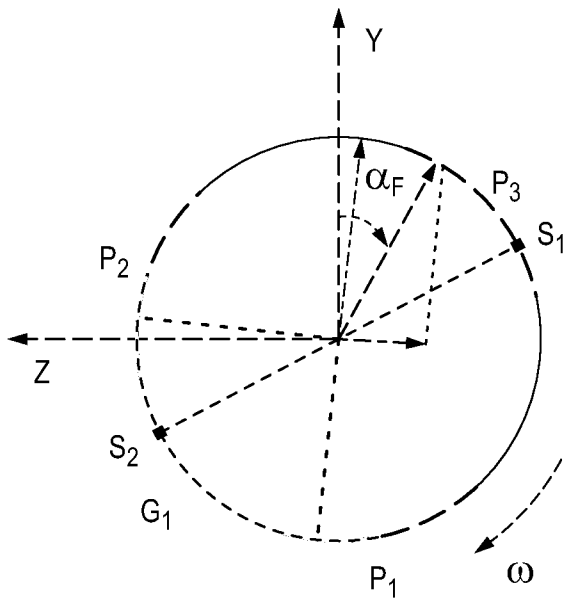


FIG. 16B

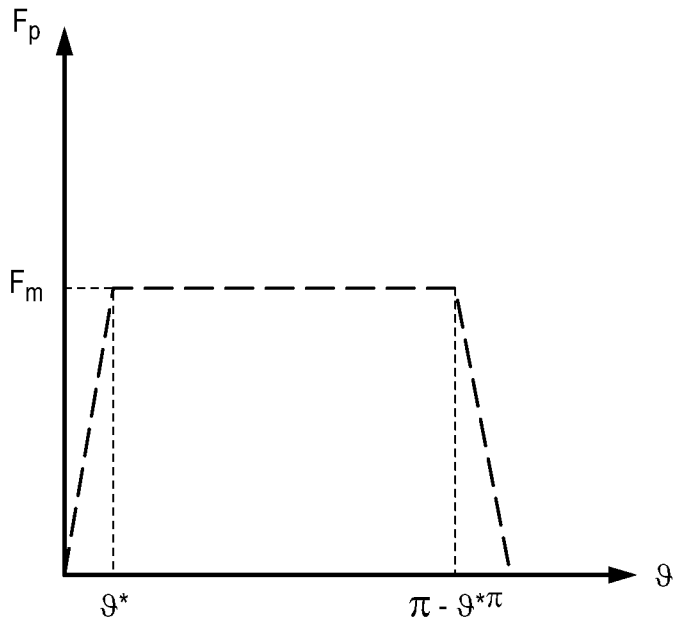


FIG. 17

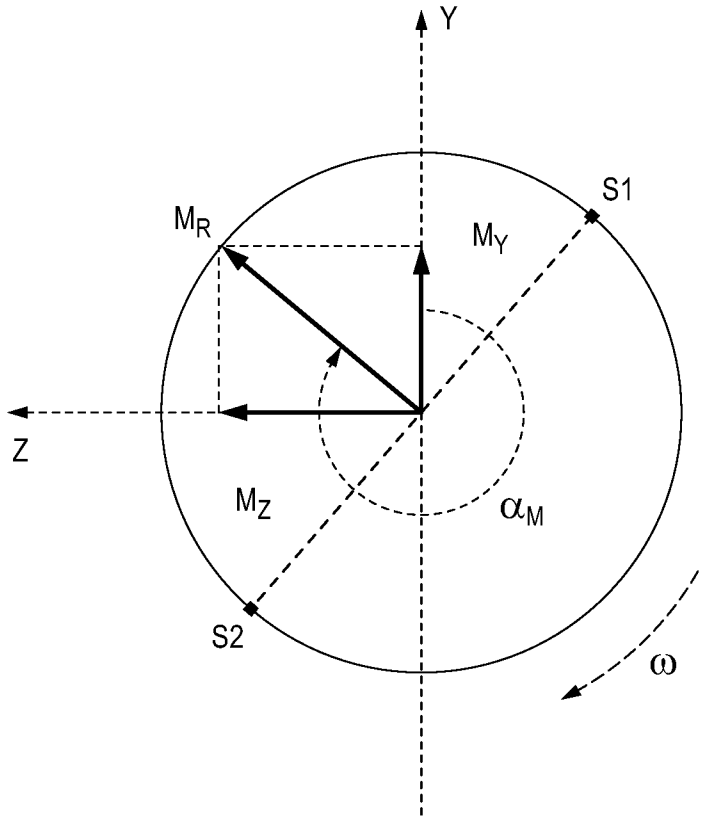


FIG. 18

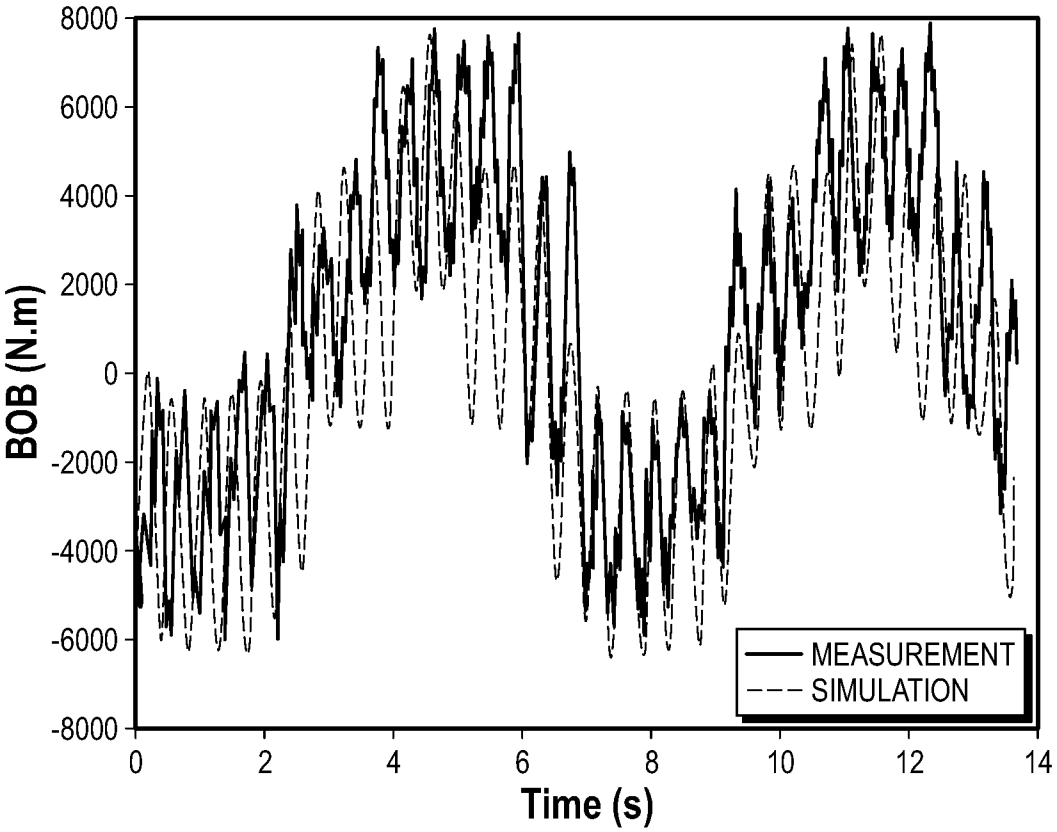


FIG. 19A

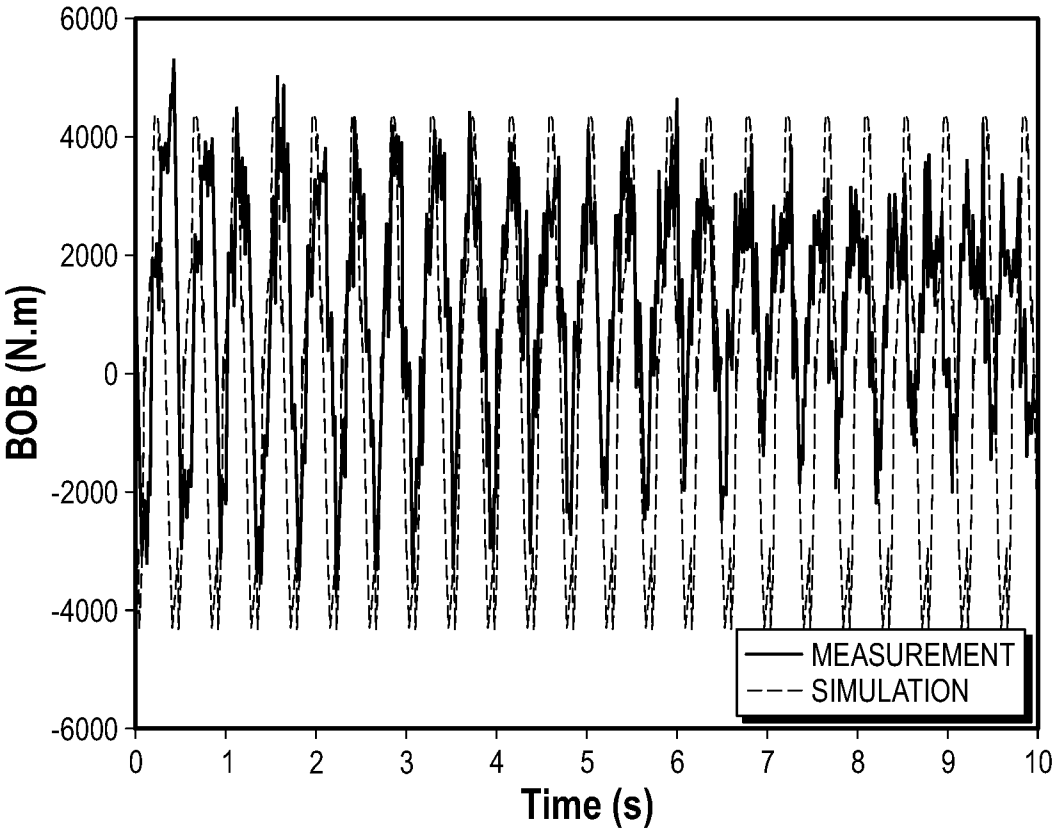


FIG. 19B

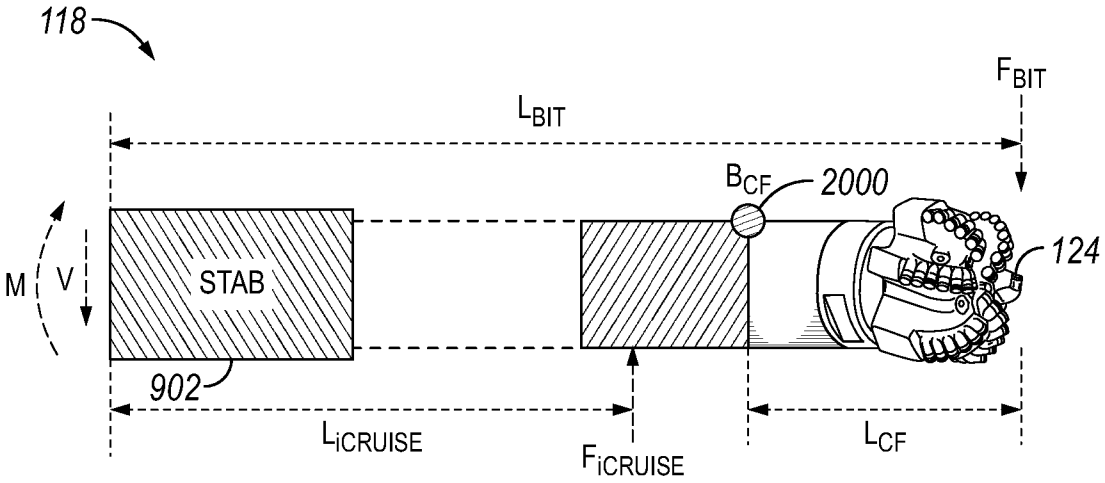


FIG. 20A

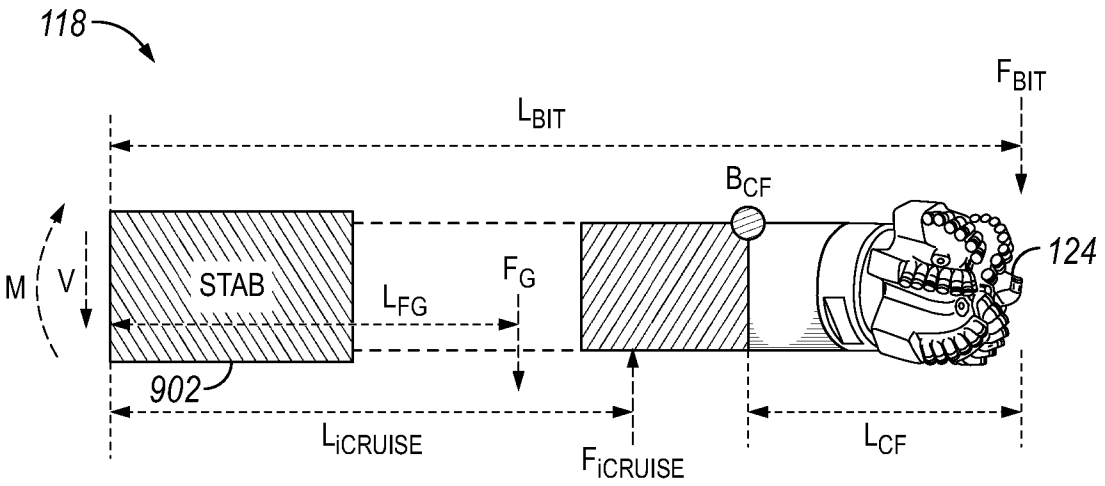


FIG. 20B

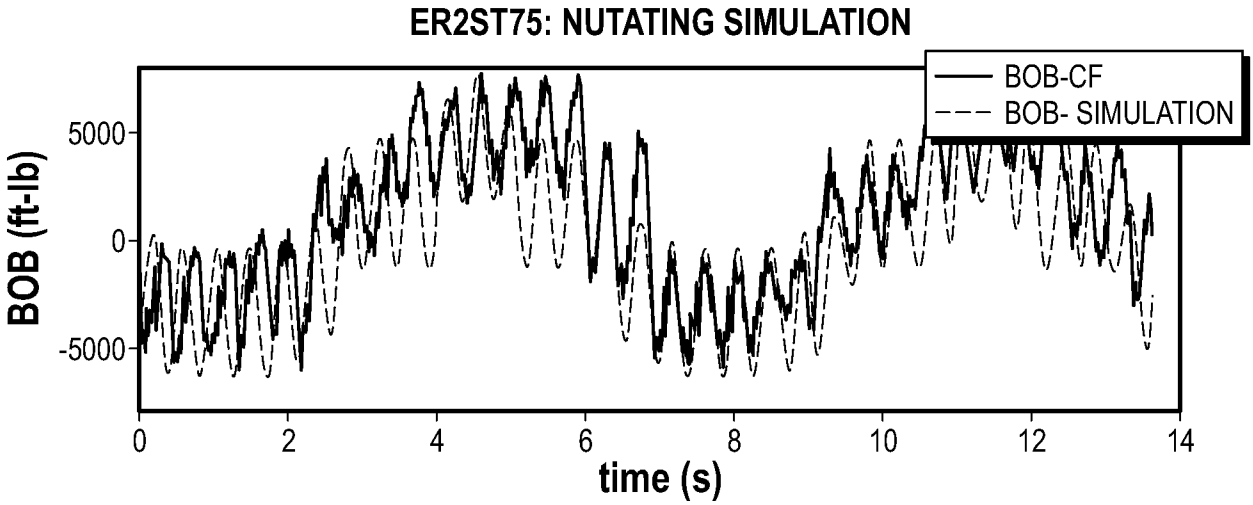

ER2ST75: NUTATING SIMULATION
BOB-CF
BOB- SIMULATION
BOB (ft-lb)
5000
0
-5000
0
2
4
6
8
10
12
14
time (s)

FIG. 21

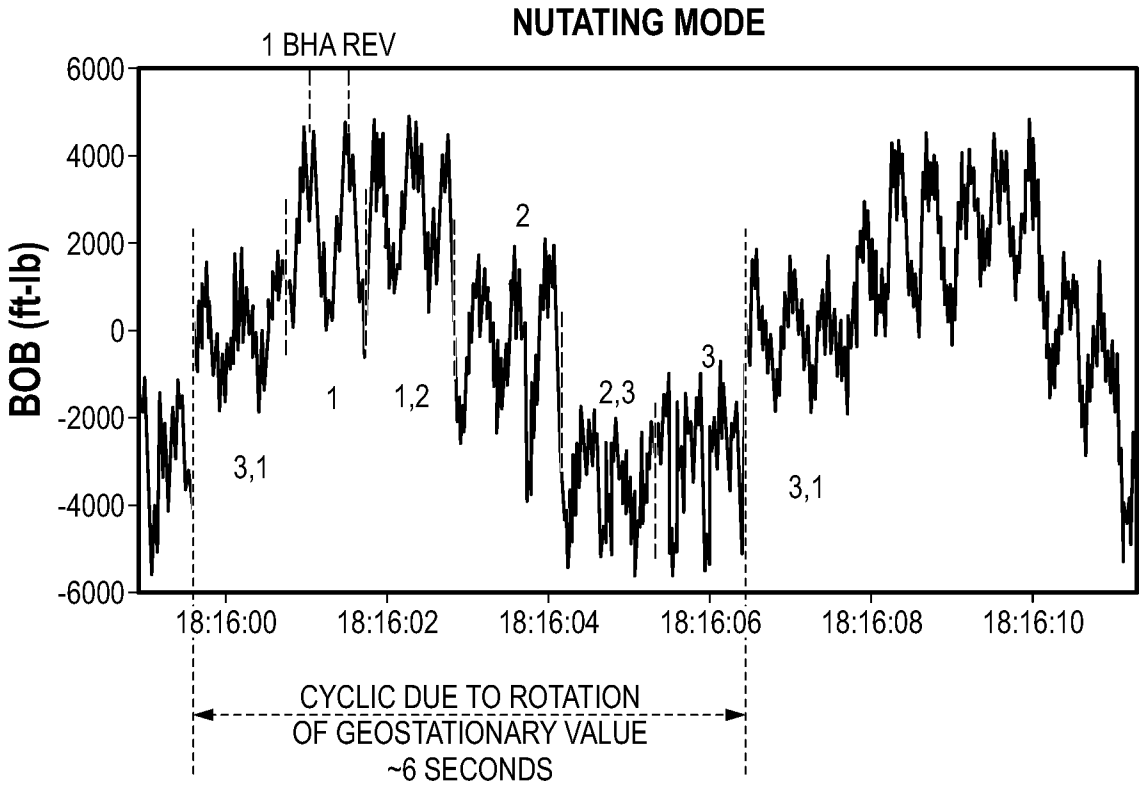

NUTATING MODE
1 BHA REV
BOB (ft-lb)
6000
4000
2000
0
-2000
-4000
-6000
1
1,2
2
2,3
3
3,1
3,1
18:16:00
18:16:02
18:16:04
18:16:06
18:16:08
18:16:10
CYCLIC DUE TO ROTATION
OF GEOSTATIONARY VALUE
~6 SECONDS

FIG. 22

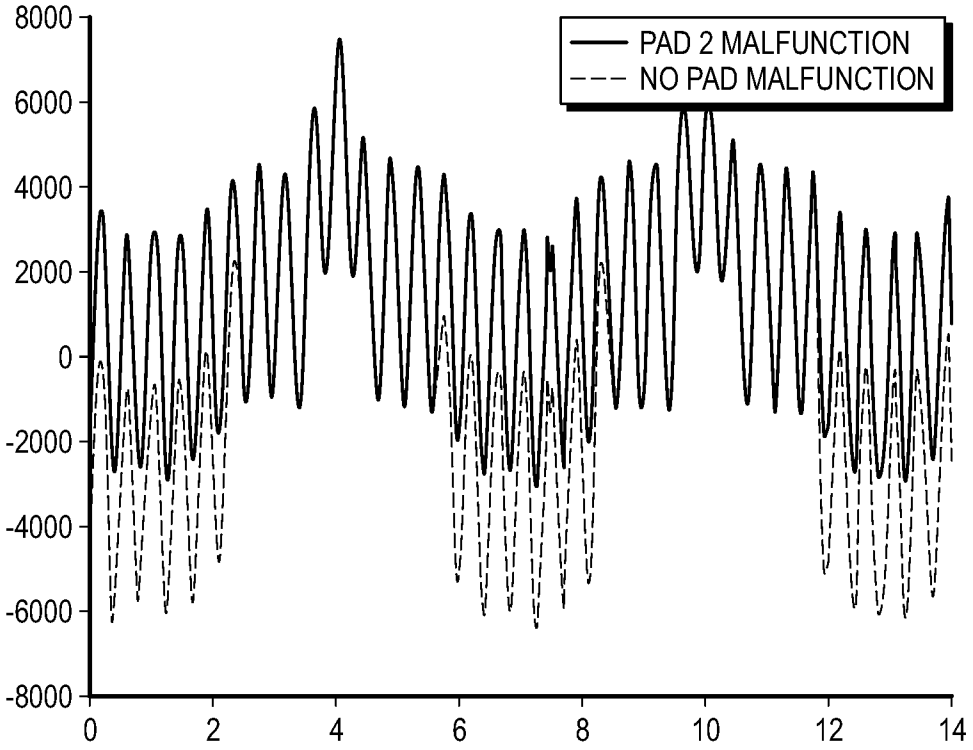

PAD 2 MALFUNCTION
NO PAD MALFUNCTION
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
0
2
4
6
8
10
12
14

FIG. 23

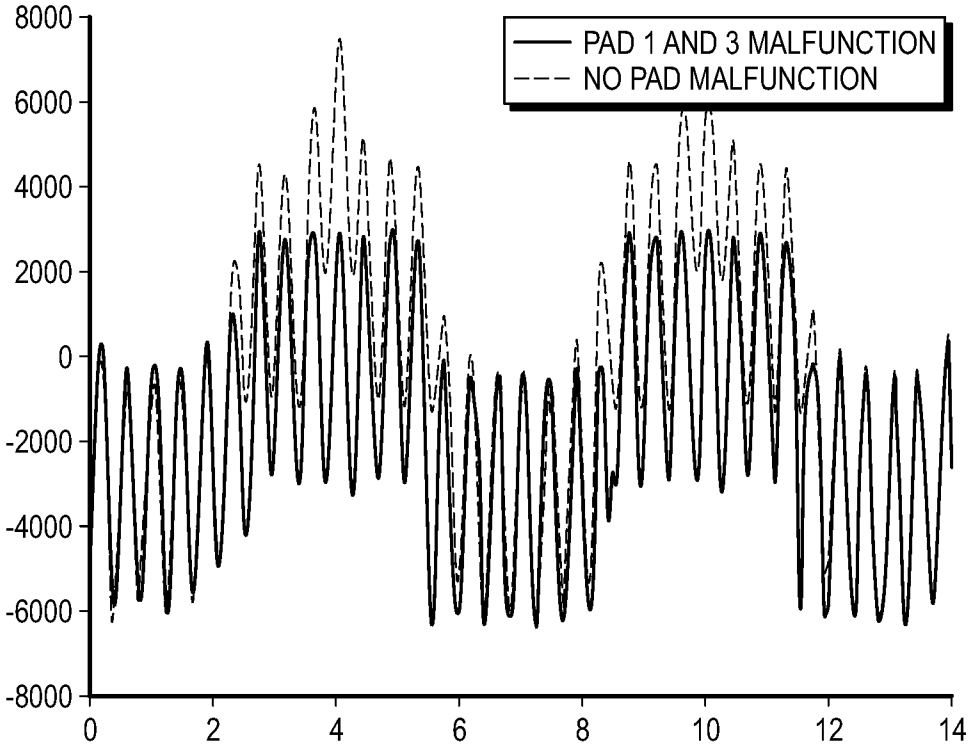

PAD 1 AND 3 MALFUNCTION
NO PAD MALFUNCTION
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
0
2
4
6
8
10
12
14

FIG. 24

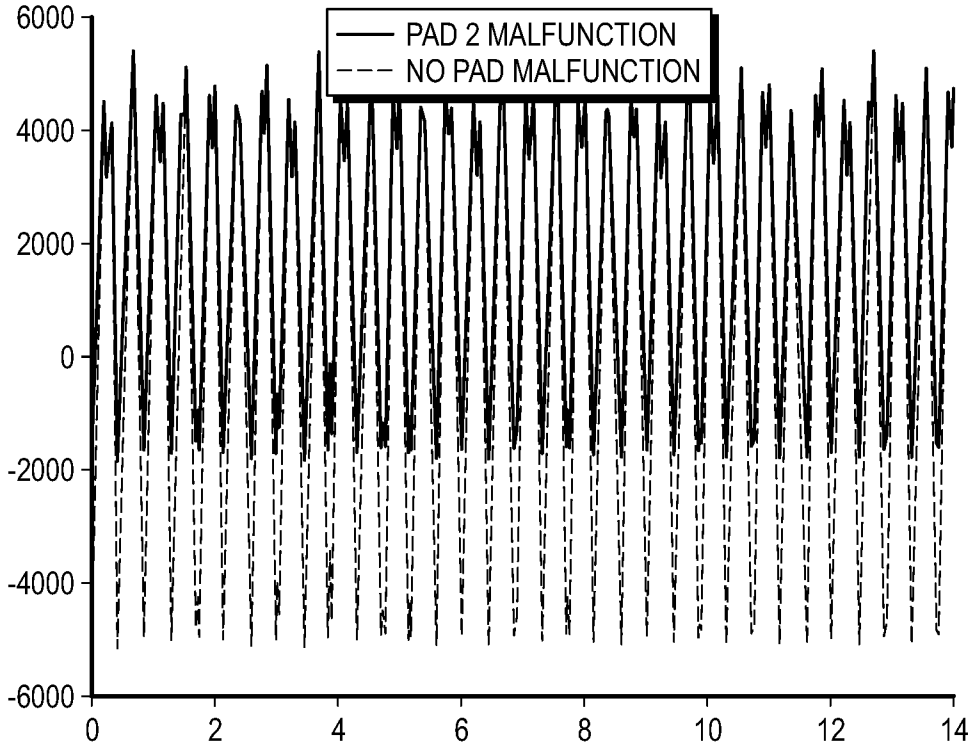

PAD 2 MALFUNCTION
NO PAD MALFUNCTION
6000
4000
2000
0
-2000
-4000
-6000
0
2
4
6
8
10
12
14

FIG. 25

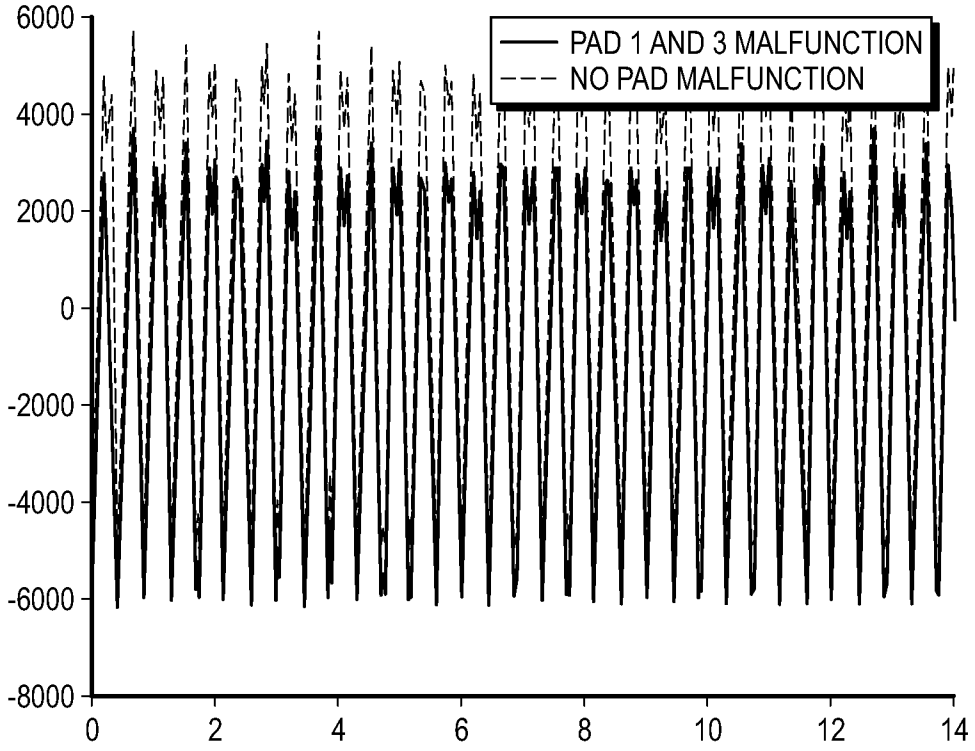

PAD 1 AND 3 MALFUNCTION
NO PAD MALFUNCTION
6000
4000
2000
0
-2000
-4000
-6000
-8000
0
2
4
6
8
10
12
14

FIG. 26

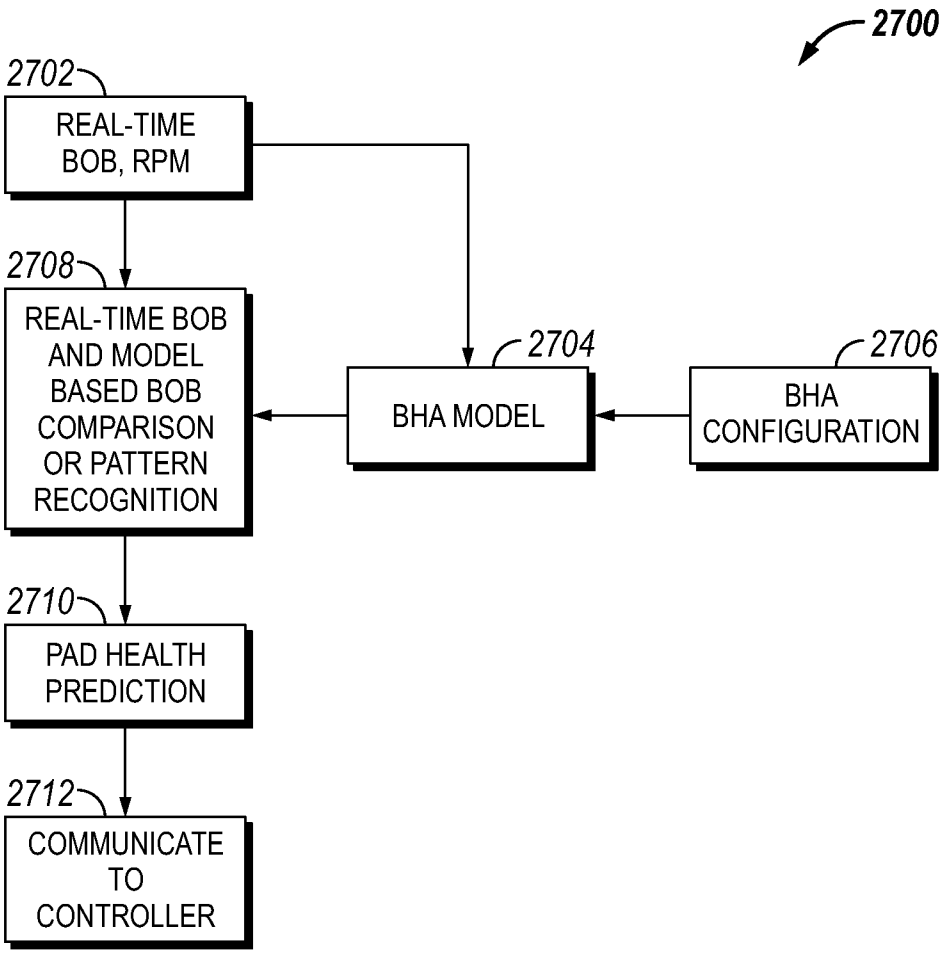

2700
2702
REAL-TIME BOB, RPM
2708
REAL-TIME BOB AND MODEL BASED BOB COMPARISON OR PATTERN RECOGNITION
2704
BHA MODEL
2706
BHA CONFIGURATION
2710
PAD HEALTH PREDICTION
2712
COMMUNICATE TO CONTROLLER

FIG. 27

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/012216

A. CLASSIFICATION OF SUBJECT MATTER

E21B 44/02(2006.01)i; **E21B 47/01**(2006.01)i; **E21B 7/06**(2006.01)i

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)

E21B 44/02(2006.01); E21B 21/08(2006.01); E21B 41/00(2006.01); E21B 44/00(2006.01); E21B 47/00(2006.01); E21B 7/00(2006.01); G06F 15/18(2006.01); G06G 7/48(2006.01)

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

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: bottom-hole assembly model, bending moment on bit measurement, steering actuator, malfunctioning

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8417495 B2 (DASHEVSKIY, DMITRIY) 09 April 2013 (2013-04-09) column 1, line 15 - column 8, line 46; claims 1-22; and figures 1-5	1,8,11,18
Y		2-7,9-10,12-17,19-20
Y	US 2019-0345809 A1 (BAKER HUGHES, A GE COMPANY, LLC.) 14 November 2019 (2019-11-14) paragraphs [0039]-[0074]; and figures 1-6	2-7,12-17
Y	EP 2359306 B1 (EXXONMOBIL UPSTREAM RESEARCH COMPANY) 02 August 2017 (2017-08-02) paragraphs [0118], [0130]; and figure 1	9-10,19-20
A	US 2020-0355061 A1 (HALLIBURTON ENERGY SERVICES, INC.) 12 November 2020 (2020-11-12) claims 11-20; and figures 1-10	1-20
A	US 5721376 A (PAVONE et al.) 24 February 1998 (1998-02-24) column 1, line 5 – column 6, line 2; and figures 1-4	1-20

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 September 2024	**20 September 2024**

Name and mailing address of the ISA/KR	Authorized officer
Korean Intellectual Property Office **189 Cheongsa-ro, Seo-gu, Daejeon** **35208, Republic of Korea**	**PARK, Tae Wook**
Facsimile No. **+82-42-481-8578**	Telephone No. **+82-42-481-3405**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2024/012216

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US 8417495 B2	09 April 2013	CA 2705194 A1	14 May 2009
		CA 2705194 C	09 September 2014
		GB 2467074 A	21 July 2010
		GB 2467074 B	22 February 2012
		US 2009-0114445 A1	07 May 2009
		WO 2009-062037 A2	14 May 2009
		WO 2009-062037 A3	27 January 2011
US 2019-0345809 A1	14 November 2019	BR 112020022959 A2	02 February 2021
		EP 3791042 A1	17 March 2021
		US 11066917 B2	20 July 2021
		WO 2019-217813 A1	14 November 2019
EP 2359306 B1	02 August 2017	AU 2009-318062 A1	27 May 2010
		AU 2009-318062 B2	29 January 2015
		AU 2014-274572 A1	29 January 2015
		AU 2014-274572 B2	18 February 2016
		AU 2014-274573 A1	29 January 2015
		AU 2014-274573 B2	10 December 2015
		CA 2744419 A1	27 May 2010
		CA 2744419 C	13 August 2013
		EA 029182 B1	28 February 2018
		EA 032474 B1	28 June 2019
		EA 033087 B1	30 August 2019
		EA 201170598 A1	30 December 2011
		EA 201300951 A1	30 January 2014
		EA 201391698 A1	31 March 2014
		EP 2359306 A1	24 August 2011
		EP 3236384 A1	25 October 2017
		EP 3236384 B1	05 December 2018
		EP 3236385 A1	25 October 2017
		EP 3236385 B1	21 November 2018
		US 2011-0214878 A1	08 September 2011
		US 8214188 B2	03 July 2012
		WO 2010-059295 A1	27 May 2010
US 2020-0355061 A1	12 November 2020	NO 20211033 A1	27 August 2021
		US 11448058 B2	20 September 2022
		WO 2020-226631 A1	12 November 2020
US 5721376 A	24 February 1998	FR 2732403 A1	04 October 1996
		FR 2732403 B1	09 May 1997
		GB 2299415 A	02 October 1996