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(54) Title: ELECTROMAGNETIC PIPE INSPECTION WITH AZIMUTHAL DEFECT EVALUATION

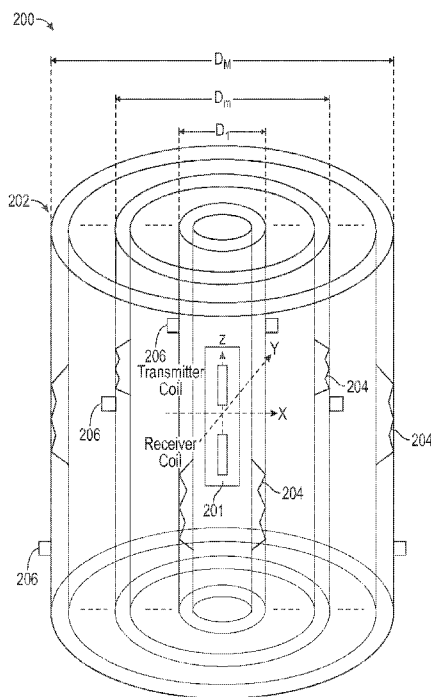


FIG. 2

(57) Abstract: Aspects of the subject technology relate to systems, methods, and computer-readable media for azimuthal defect evaluation through electromagnetic pipe inspection tools. A tool for monitoring an integrity of a well tubular can comprise a transmitter station with transmitter coil(s) configured to excite eddy currents in the well tubular. The tool can comprise a receiver station with receiver coil(s) to measure electromagnetic fields generated by the eddy currents. The tool can generate tool measurements in a first dimension that is axial depth, a second dimension that is azimuth, and a third dimension that is radial depth based on the measured electromagnetic field. At least one of the transmitter and receiver coils can have a polarization axis orthogonal to an axis of the well tubular. Further, one of the transmitter station and the receiver station comprises only non-azimuthal sensors.



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ELECTROMAGNETIC PIPE INSPECTION WITH AZIMUTHAL DEFECT EVALUATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit of U.S. Provisional Application No. 63/462,618 filed April 28, 2023, and claims benefit of U.S. Non-Provisional Application No. 18/385,764 filed October 31, 2023, which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present technology pertains to electromagnetic pipe inspection, and more particularly, to azimuthal defect evaluation through electromagnetic pipe inspection tools.

BACKGROUND

[0003] Electromagnetic pipe inspection tools have been developed for generating logs/representations of conditions downhole in wellbores. Specifically, electromagnetic pipe inspection tools and associated imaging techniques are used to monitor conditions of pipes, otherwise referred to as tubulars, in hydrocarbon wellbores that include various kinds of casing strings and tubing. One common electromagnetic imaging technique is the eddy current technique. In the eddy current technique, when a transmitter coil of an electromagnetic pipe inspection tool emits primary transient electromagnetic fields, eddy currents are induced in regions, e.g. the casing, surrounding the tool. As follows, these eddy currents produce secondary fields which are received along with the primary fields by a receiver coil of the electromagnetic pipe inspection tool. This acquired data can then be used in evaluating surroundings in the wellbore, e.g. pipes, to the tool.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] In order to describe the manner in which the features and advantages of this disclosure can be obtained, a more particular description is provided with reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only exemplary embodiments of the disclosure and are not therefore to be considered to be limiting of its scope, the principles herein are described and explained with additional specificity and detail through the use of the accompanying drawings.

[0005] FIG. 1A is a schematic diagram of an example logging while drilling wellbore operating environment, in accordance with various aspects of the subject technology.

[0006] FIG. 1B is a schematic diagram of an example downhole environment having tubulars, in accordance with various aspects of the subject technology.

[0007] FIG. 2 illustrates a schematic representation of an environment including the electromagnetic pipe inspection tool disposed in a nested pipe configuration, in accordance with various aspects of the subject technology.

[0008] FIG. 3A illustrates a side view of a configuration of transmitter stations and receiver stations of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0009] FIG. 3B illustrates a top view of the configuration of the transmitter stations and receiver stations of the pipe inspection tool that is shown in FIG. 3A, in accordance with various aspects of the subject technology.

[0010] FIG. 4A shows measurements made at varying depth and azimuth at short spacings between stations, in accordance with various aspects of the subject technology.

[0011] FIG. 4B shows measurements made at varying depth and azimuth at a longer spacing between stations in comparison to FIG. 4A, in accordance with various aspects of the subject technology.

[0012] FIG. 5A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0013] FIG. 5B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 5A, in accordance with various aspects of the subject technology.

[0014] FIG. 6A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0015] FIG. 6B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 6A, in accordance with various aspects of the subject technology.

[0016] FIG. 7A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology, in accordance with various aspects of the subject technology.

[0017] FIG. 7B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 7A, in accordance with various aspects of the subject technology.

[0018] FIG. 8A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0019] FIG. 8B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 8A, in accordance with various aspects of the subject technology.

[0020] FIG. 9A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0021] FIG. 9B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 9A, in accordance with various aspects of the subject technology.

[0022] FIG. 10A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0023] FIG. 10B illustrates a top view of the configuration of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 10A, in accordance with various aspects of the subject technology.

[0024] FIG. 11 illustrates a side perspective view of a station of an electromagnetic pipe inspection tool with ferromagnetic cores, in accordance with various aspects of the subject technology.

[0025] FIG. 12 illustrates a side perspective view of a station that is fitted around an internal mandrel of an electromagnetic pipe inspection tool, in accordance with various aspects of the subject technology.

[0026] FIG. 13A illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0027] FIG. 13B illustrates a top view of the configuration of the receiver station of the pipe inspection tool that is shown in FIG. 13A, in accordance with various aspects of the subject technology.

[0028] FIG. 14 illustrates a side view of another configuration of a transmitter station and receiver station of a pipe inspection tool, in accordance with various aspects of the subject technology.

[0029] FIG. 15 illustrates an example computing device architecture which can be employed to perform various steps, methods, and techniques disclosed herein.

DETAILED DESCRIPTION

[0030] Various embodiments of the disclosure are discussed in detail below. While specific implementations are discussed, it should be understood that this is done for illustration purposes only. A person skilled in the relevant art will recognize that other components and configurations may be used without parting from the spirit and scope of the disclosure.

[0031] Additional features and advantages of the disclosure will be set forth in the description which follows, and in part will be obvious from the description, or can be learned by practice of the principles disclosed herein. The features and advantages of the disclosure can be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. These and other features of the disclosure

will become more fully apparent from the following description and appended claims or can be learned by the practice of the principles set forth herein.

[0032] It will be appreciated that for simplicity and clarity of illustration, where appropriate, reference numerals have been repeated among the different figures to indicate corresponding or analogous elements. In addition, numerous specific details are set forth in order to provide a thorough understanding of the embodiments described herein. However, it will be understood by those of ordinary skill in the art that the embodiments described herein can be practiced without these specific details. In other instances, methods, procedures, and components have not been described in detail so as not to obscure the related relevant feature being described. The drawings are not necessarily to scale and the proportions of certain parts may be exaggerated to better illustrate details and features. The description is not to be considered as limiting the scope of the embodiments described herein.

[0033] As discussed previously, electromagnetic pipe inspection tools have been developed for generating logs/representations of conditions downhole in wellbores. Specifically, electromagnetic pipe inspection tools and associated imaging techniques are used to monitor conditions of pipes, otherwise referred to as tubulars, in hydrocarbon wellbores that include various kinds of casing strings and tubing. One common electromagnetic imaging technique is the eddy current technique. In the eddy current technique, when a transmitter coil of an electromagnetic pipe inspection tool emits primary transient electromagnetic fields, eddy currents are induced in regions, e.g. the casing, surrounding the tool. As follows, these eddy currents produce secondary fields which are received along with the primary fields by a receiver coil of the electromagnetic pipe inspection tool. This acquired data can then be used in evaluating surroundings in the wellbore, e.g. pipes, to the tool.

[0034] Currently, electromagnetic pipe inspection tools that use excited eddy currents for inspection can detect anomalies on one or more tubulars in a downhole environment, e.g. multiple nested tubulars. However, this type of tool can have low vertical resolution and can also lack azimuthal discrimination. To account for these discrepancies, the estimated metal loss can be determined as an average value of annular section of the pipe within the

tool vertical resolution range. However, this can lead to problems with the tool, such as an inability to accurately detect certain tubular flaws, such as, cracks, pitting, holes. In particular, by utilizing an average metal loss technique, the tool can under-estimate the severity of damage in well tubulars. In turn, this can necessitate expensive remedial actions and even cause the shutdown of production wells.

[0035] The disclosed technology addresses the foregoing by providing a tool capable of generating measurements in an azimuth dimension with respect to the tool operating within a well tubular. Further, the tool can generate measurements in an axial depth dimension with respect to the tool operating within the well tubular.

[0036] Turning now to FIG. 1A, a drilling arrangement is shown that exemplifies a Logging While Drilling (commonly abbreviated as LWD) configuration in a wellbore drilling scenario 100. Logging-While-Drilling typically incorporates sensors that acquire formation data. The drilling arrangement of FIG. 1A also exemplifies what is referred to as Measurement While Drilling (commonly abbreviated as MWD) which utilizes sensors to acquire data from which the wellbore's path and position in three-dimensional space can be determined. FIG. 1A shows a drilling platform 102 equipped with a derrick 104 that supports a hoist 106 for raising and lowering a drill string 108. The hoist 106 suspends a top drive 110 suitable for rotating and lowering the drill string 108 through a well head 112. A drill bit 114 can be connected to the lower end of the drill string 108. As the drill bit 114 rotates, it creates a wellbore 116 that passes through various subterranean formations 118. A pump 120 circulates drilling fluid through a supply pipe 122 to top drive 110, down through the interior of drill string 108 and out orifices in drill bit 114 into the wellbore. The drilling fluid returns to the surface via the annulus around drill string 108, and into a retention pit 124. The drilling fluid transports cuttings from the wellbore 116 into the retention pit 124 and the drilling fluid's presence in the annulus aids in maintaining the integrity of the wellbore 116. Various materials can be used for drilling fluid, including oil-based fluids and water-based fluids.

[0037] Logging tools 126 can be integrated into the bottom-hole assembly 125 near the drill bit 114. As the drill bit 114 extends the wellbore 116 through the formations 118, logging tools 126 collect measurements relating to various formation properties as well as

the orientation of the tool and various other drilling conditions. The bottom-hole assembly 125 may also include a telemetry sub 128 to transfer measurement data to a surface receiver 132 and to receive commands from the surface. In at least some cases, the telemetry sub 128 communicates with a surface receiver 132 using mud pulse telemetry. In some instances, the telemetry sub 128 does not communicate with the surface, but rather stores logging data for later retrieval at the surface when the logging assembly is recovered.

[0038] Each of the logging tools 126 may include one or more tool components spaced apart from each other and communicatively coupled by one or more wires and/or other communication arrangement. The logging tools 126 may also include one or more computing devices communicatively coupled with one or more of the tool components. The one or more computing devices may be configured to control or monitor a performance of the tool, process logging data, and/or carry out one or more aspects of the methods and processes of the present disclosure.

[0039] In at least some instances, one or more of the logging tools 126 may communicate with a surface receiver 132 by a wire, such as wired drill pipe. In other cases, the one or more of the logging tools 126 may communicate with a surface receiver 132 by wireless signal transmission. In at least some cases, one or more of the logging tools 126 may receive electrical power from a wire that extends to the surface, including wires extending through a wired drill pipe.

[0040] Collar 134 is a frequent component of a drill string 108 and generally resembles a very thick-walled cylindrical pipe, typically with threaded ends and a hollow core for the conveyance of drilling fluid. Multiple collars 134 can be included in the drill string 108 and are constructed and intended to be heavy to apply weight on the drill bit 114 to assist the drilling process. Because of the thickness of the collar's wall, pocket-type cutouts or other type recesses can be provided into the collar's wall without negatively impacting the integrity (strength, rigidity and the like) of the collar as a component of the drill string 108.

[0041] Referring to FIG. 1B, an example system 140 is depicted for conducting downhole measurements after at least a portion of a wellbore has been drilled and the drill string removed from the well. An electromagnetic pipe inspection tool can be operated in the example system 140 shown in FIG. 1B to log the wellbore. A downhole tool is shown

having a tool body 146 in order to carry out logging and/or other operations. For example, instead of using the drill string 108 of FIG. 1A to lower tool body 146, which can contain sensors and/or other instrumentation for detecting and logging nearby characteristics and conditions of the wellbore 116 and surrounding formations, a wireline conveyance 144 can be used. The tool body 146 can be lowered into the wellbore 116 by wireline conveyance 144. The wireline conveyance 144 can be anchored in the drill rig 142 or by a portable means such as a truck 145. The wireline conveyance 144 can include one or more wires, slicklines, cables, and/or the like, as well as tubular conveyances such as coiled tubing, joint tubing, or other tubulars.

[0042] The illustrated wireline conveyance 144 provides power and support for the tool, as well as enabling communication between data processors 148A-N on the surface. In some examples, the wireline conveyance 144 can include electrical and/or fiber optic cabling for carrying out communications. The wireline conveyance 144 is sufficiently strong and flexible to tether the tool body 146 through the wellbore 116, while also permitting communication through the wireline conveyance 144 to one or more of the processors 148A-N, which can include local and/or remote processors. Moreover, power can be supplied via the wireline conveyance 144 to meet power requirements of the tool. For slickline or coiled tubing configurations, power can be supplied downhole with a battery or via a downhole generator.

[0043] FIG. 2 illustrates a schematic representation of an environment 200 including an electromagnetic pipe inspection tool 201 disposed in a nested pipe configuration 202. The nested pipe configuration 202 can exist downhole. As follows, the electromagnetic pipe inspection tool 201 can be disposed downhole to gather measurements for characterizing the pipes in the nested pipe configuration 202 according to the technology described herein. The nested pipe configuration 202 includes concentric pipes. The electromagnetic pipe inspection tool 201 deployed inside the nested pipe configuration 202 can gather measurements for characterizing anomalies that exist in the nested pipe configuration 202, e.g. corruptions 204 and collars 206. Specifically, as the tool 201 moves within the nested pipe configuration 202, one or more transmitters are excited, and corresponding electromagnetic signals are received at one or more receivers and are recorded as part of

downhole measurements gathered by the electromagnetic pipe inspection tool 201. Specifically, eddy currents can be generated in the areas surrounding the tool 201. The eddy currents can generate electromagnetic fields that can be measured by the receivers, e.g. through a voltage that is generated at the receivers. In turn, the voltages at the receivers can be used in characterizing the area surrounding the tool 201.

[0044] The nested pipe configuration 202 shown in FIG. 2 is merely an example pipe configuration, and in various embodiments the electromagnetic pipe inspection tool 201 can be operated in different pipe configurations for characterizing features of the pipes.

[0045] The tools described herein can have various orientations of transmitter and receiver elements, e.g. coils, in both transmitter stations and receiver stations. A transmitter station can include one or more transmitter elements, e.g. coils, that are capable of transmitting an electromagnetic signal as part of operation of an electromagnetic pipe inspection tool. A receiver station can include one or more receiver elements, e.g. coils, that are capable of receiving an electromagnetic signal as part of operation of an electromagnetic pipe inspection tool. The transmitter elements of the transmitter stations described herein can function to also receive electromagnetic signals, thereby operating as a transceiver. Similarly, the receiver elements of the receiver stations described herein can function to also transmit electromagnetic signals, thereby operating as a transceiver.

[0046] The various orientations of transmitter and receiver elements described herein can include orientations that are along or otherwise parallel to the z axis shown in FIG. 2, herein referred to as z-orientation or z-orientated. The orientations of transmitter and receiver elements described herein can also include orientations that are the angles between the projection of a vector in the xy-plane and planes parallel the xy-plane shown in FIG. 2, herein referred to as phi-orientation or phi-orientated. Further, the orientations of transmit and receiver elements described herein can also include orientations that are along projections of a vector in the xy-plane and planes parallel the xy-plane shown in FIG. 2, herein referred to as radial-orientation or radially-orientated. These orientations can be used to make measurements along an axial depth of a tool disposed in one or more well tubulars. These orientations can also be used to make measurements at a varying azimuth in relation to a tool disposed in one or more well tubulars. Further, these orientations can

be used to make measurements along a radial depth in relation to a tool disposed in one or more well tubulars.

[0047] The disclosure now continues with a discussion of technology for overcoming the previously described deficiencies of inspecting tubulars through electromagnetic pipe inspection tools. Specifically, FIG. 3A illustrates a side view of a configuration 300 of transmitter stations and receiver stations of a pipe inspection tool. FIG. 3B illustrates a top view of the configuration 300 of the transmitter stations and receiver stations of the pipe inspection tool that is shown in FIG. 3A.

[0048] In FIGs. 3A and 3B, the pipe inspection tool includes a receiver station 302 and a first transmitter station 304-1, a second transmitter station 304-2, and a third transmitter station 304-3 (herein referred to as “transmitter stations 304”). While one receiver station and three transmitter stations are shown in the configuration 300, the pipe inspection tool can include an applicable number of stations.

[0049] As shown in FIGs. 3A and 3B, the tool comprises multiple z-orientated transmitter/receiver coils forming the transmitter stations 304. The tool also comprises multiple radially-orientated receiver/transmitter coils forming the receiver station 304. The multiple orientated transmitters can be located at different axial locations to achieve different depths of investigation along either or both an axial depth and a radial depth, e.g., shallow, medium and deep. The multiple radially-orientated coils can be located at the same axial location but different azimuthal angles to achieve 360° coverage around the tool during a pipe inspection operation.

[0050] Measurements made by the tool can include a complex-valued voltage response of each receiver when powering the transmitters with a known and controlled signal. Data from each transmitter-receiver spacing can be presented as a 2D image as shown in FIGs. 4A and 4B. Specifically, FIG. 4A shows measurements made at varying depth and azimuth at short spacings between stations. FIG. 4B shows measurements made at varying depth and azimuth at a longer spacing between stations in comparison to FIG. 4A. Different components of the complex-valued measurements can be displayed such as absolute values, phase values, real values, and imaginary values. Responses for each receiver can then be interpreted to detect defects with azimuthal and axial localization.

[0051] Applicable stations in the tools described herein can be mounted on devices for moving the stations towards the walls of well tubulars in which the tool is disposed. Specifically, receiver stations of the tools can be configured with devices that move the receiver stations towards the walls of well tubulars. Examples of such devices include pads, spring-loaded arms, or mandrels. Such devices can be designed to operate for differently sized well tubulars. For example, pads can be designed to fit in specifically sized well tubulars and facilitate operation of the tool within the tubulars. Further, the tools described herein can be modular with receiver station mandrels that are replaced to fit tubulars with different identifications and characteristics.

[0052] FIG. 5A illustrates a side view of another configuration 500 of a transmitter station and receiver station of a pipe inspection tool. FIG. 5B illustrates a top view of the configuration 500 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 5A.

[0053] In FIGs. 5A and 5B, the pipe inspection tool includes a receiver station 502 and a transmitter station 504. While one receiver station and one transmitter station are shown in the configuration 500, the pipe inspection tool can include an applicable number of stations.

[0054] The transmitter station 504 can include multiple z-orientated transmitter/receiver coils. The receiver station 502 can include multiple phi-orientated receiver/transmitter coils. The multiple z-orientated coils can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple phi-orientated coils can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0055] FIG. 6A illustrates a side view of another configuration 600 of a transmitter station and receiver station of a pipe inspection tool. FIG. 6B illustrates a top view of the configuration 600 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 6A.

[0056] In FIGs. 6A and 6B, the pipe inspection tool includes a receiver station 602 and a transmitter station 604. While one receiver station and one transmitter station are shown

in the configuration 600, the pipe inspection tool can include an applicable number of stations.

[0057] The transmitter station 604 can include multiple z-orientated transmitter/receiver coils. The receiver station 602 can include multiple phi-orientated receiver/transmitter coils and radially-orientated receiver/transmitter coils. The multiple z-orientated coils can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple phi-orientated coils and radially-orientated coils of the receiver station 602 can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0058] FIG. 7A illustrates a side view of another configuration 700 of a transmitter station and receiver station of a pipe inspection tool. FIG. 7B illustrates a top view of the configuration 700 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 7A.

[0059] In FIGs. 7A and 7B, the pipe inspection tool includes a receiver station 702 and a transmitter station 704. While one receiver station and one transmitter station are shown in the configuration 700, the pipe inspection tool can include an applicable number of stations.

[0060] The transmitter station 704 can include multiple radially-orientated transmitter/receiver coils. The receiver station 702 can include multiple radially-orientated receiver/transmitter coils. The multiple radially-orientated transmitters/receiver coils of the transmitter station 704 can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple radially-orientated coils of the receiver station 702 can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0061] FIG. 8A illustrates a side view of another configuration 800 of a transmitter station and receiver station of a pipe inspection tool. FIG. 8B illustrates a top view of the configuration 800 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 8A.

[0062] In FIGs. 8A and 8B, the pipe inspection tool includes a receiver station 802 and a transmitter station 804. While one receiver station and one transmitter station are shown in the configuration 800, the pipe inspection tool can include an applicable number of stations.

[0063] The transmitter station 804 can include multiple phi-orientated transmitter/receiver coils. The receiver station 802 can include multiple phi-orientated receiver/transmitter coils. The multiple phi-orientated transmitters/receiver coils of the transmitter station 804 can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple phi-orientated coils of the receiver station 802 can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0064] FIG. 9A illustrates a side view of another configuration 900 of a transmitter station and receiver station of a pipe inspection tool. FIG. 9B illustrates a top view of the configuration 900 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 9A.

[0065] In FIGs. 9A and 9B, the pipe inspection tool includes a receiver station 902 and a transmitter station 904. While one receiver station and one transmitter station are shown in the configuration 900, the pipe inspection tool can include an applicable number of stations.

[0066] The transmitter station 904 can include multiple radially-orientated transmitter/receiver coils. The receiver station 902 can include multiple phi-orientated receiver/transmitter coils and multiple radially-orientated receiver/transmitter coils. The multiple radially-orientated coils of the transmitter station 904 can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple phi-orientated coils and the multiple radially-orientated coils of the receiver station 902 can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0067] FIG. 10A illustrates a side view of another configuration 1000 of a transmitter station and receiver station of a pipe inspection tool. FIG. 10B illustrates a top view of the

configuration 1000 of the transmitter station and receiver station of the pipe inspection tool that is shown in FIG. 10A.

[0068] In FIGs. 10A and 10B, the pipe inspection tool includes a receiver station 1002 and a transmitter station 1004. While one receiver station and one transmitter station are shown in the configuration 1000, the pipe inspection tool can include an applicable number of stations.

[0069] The transmitter station 1004 can include multiple phi-orientated transmitter/receiver coils. The receiver station 902 can include multiple phi-orientated receiver/transmitter coils and multiple radially-orientated receiver/transmitter coils. The multiple phi-orientated coils of the transmitter station 1004 can be located at different axial locations to achieve different depth of investigation, e.g., shallow, medium and deep. The multiple phi-orientated coils and the multiple radially-orientated coils of the receiver station 1002 can be located at the same axial location but different azimuthal angles to achieve 360° coverage of the pipe inspection.

[0070] FIG. 11 illustrates a side perspective view of a station 1100 of an electromagnetic pipe inspection tool with ferromagnetic cores. Specifically and as shown in FIG. 11, the station includes a plurality of coils. The coils 1102 include cores 1104 that are comprised of a ferromagnetic material. The ferromagnetic material can affect signals that are either received or transmitted by the station to improve imaging in tubulars.

[0071] FIG. 12 illustrates a side perspective view of a station 1200 that is fitted around an internal mandrel 1202 of an electromagnetic pipe inspection tool. Specifically, the station 1200 can include multiple directional receivers that are fitted around an internal 1202 mandrel to form a crown like section. The mandrel can be comprised of a ferromagnetic material to improve the tools signal level response.

[0072] In various embodiments, a station of an electromagnetic pipe inspection tool of the technology described herein can be rotated. Specifically, the station can include a rotating base that allows the station to be rotated all or a portion of 360° about an electromagnetic pipe inspection tool. For example, a receiver station can include a rotating based that displaces the receiver station 360° in an azimuthal angle about an electromagnetic pipe inspection tool. FIG. 13A illustrates a side view of another configuration 1300 of a

transmitter station and receiver station 1302 of a pipe inspection tool. FIG. 13B illustrates a top view of the configuration 1300 of the receiver station 1302 of the pipe inspection tool that is shown in FIG. 13A. The receiver station 1302 can include a C-shield.

[0073] In various embodiments, transmitter coils of the stations described herein can be replaced by 2 axial coils that are excited with opposite polarity to mimic simultaneous transmitters, e.g. radially orientated transmitters. For example, multiple simultaneously excited multiple radially-orientated coils can be replaced with two z-orientated coils with opposite polarization.

[0074] FIG. 14 illustrates a side view of another configuration 1400 of a transmitter station and receiver station of a pipe inspection tool. The configuration 1400 includes a first transmitter station 1402-1, a second transmitter station 1402-2, and a third receiver station 1404. The first transmitter station 1402-1 and the second transmitter station 1402-2 are located on opposing ends of the receiver station 1404 in the configuration 1400. Each transmitter pair can be excited with opposite polarity to radially focus magnetic fields at the receiver station 1404. Alternatively, each transmitter pair can be excited with same polarity to axially focus magnetic fields at the receiver station 1404.

[0075] Measurements can be made through the tools described herein by measuring the differential voltage response of each pair of receivers displaced 180 degrees apart when powering the transmitters with a known and controlled signal. Polar differential voltage responses for each pair of receivers can then be interpreted to detect defects with azimuthal and axial localization. Alternatively, measurements can be made through the tools described herein by measuring the differential voltage response of each pair of adjacent receivers when powering the transmitters with a known and controlled signal. Adjacent differential voltage responses for each pair of receivers can then be interpreted to detect defects with azimuthal and axial localization.

[0076] FIG. 15 illustrates an example computing device architecture 1500 which can be employed to perform various steps, methods, and techniques disclosed herein. The various implementations will be apparent to those of ordinary skill in the art when practicing the present technology. Persons of ordinary skill in the art will also readily appreciate that other system implementations or examples are possible.

[0077] As noted above, FIG. 15 illustrates an example computing device architecture 1500 of a computing device which can implement the various technologies and techniques described herein. The components of the computing device architecture 1500 are shown in electrical communication with each other using a connection 1505, such as a bus. The example computing device architecture 1500 includes a processing unit (CPU or processor) 1510 and a computing device connection 1505 that couples various computing device components including the computing device memory 1515, such as read only memory (ROM) 1520 and random access memory (RAM) 1525, to the processor 1510.

[0078] The computing device architecture 1500 can include a cache of high-speed memory connected directly with, in close proximity to, or integrated as part of the processor 1510. The computing device architecture 1500 can copy data from the memory 1515 and/or the storage device 1530 to the cache 1512 for quick access by the processor 1510. In this way, the cache can provide a performance boost that avoids processor 1510 delays while waiting for data. These and other modules can control or be configured to control the processor 1510 to perform various actions. Other computing device memory 1515 may be available for use as well. The memory 1515 can include multiple different types of memory with different performance characteristics. The processor 1510 can include any general purpose processor and a hardware or software service, such as service 1 1532, service 2 1534, and service 3 1536 stored in storage device 1530, configured to control the processor 1510 as well as a special-purpose processor where software instructions are incorporated into the processor design. The processor 1510 may be a self-contained system, containing multiple cores or processors, a bus, memory controller, cache, etc. A multi-core processor may be symmetric or asymmetric.

[0079] To enable user interaction with the computing device architecture 1500, an input device 1545 can represent 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. An output device 1535 can also be one or more of a number of output mechanisms known to those of skill in the art, such as a display, projector, television, speaker device, etc. In some instances, multimodal computing devices can enable a user to provide multiple types of input to communicate with the computing device

architecture 1500. The communications interface 1540 can generally govern and manage the user input and computing device output. There is no restriction on operating on any particular hardware arrangement and therefore the basic features here may easily be substituted for improved hardware or firmware arrangements as they are developed.

[0080] Storage device 1530 is a non-volatile memory and can be a hard disk or other types of computer readable media which can store data that are accessible by a computer, such as magnetic cassettes, flash memory cards, solid state memory devices, digital versatile disks, cartridges, random access memories (RAMs) 1525, read only memory (ROM) 1520, and hybrids thereof. The storage device 1530 can include services 1532, 1534, 1536 for controlling the processor 1510. Other hardware or software modules are contemplated. The storage device 1530 can be connected to the computing device connection 1505. In one aspect, a hardware module that performs a particular function can include the software component stored in a computer-readable medium in connection with the necessary hardware components, such as the processor 1510, connection 1505, output device 1535, and so forth, to carry out the function.

[0081] For clarity of explanation, in some instances the present technology may be presented as including individual functional blocks including functional blocks comprising devices, device components, steps or routines in a method embodied in software, or combinations of hardware and software.

[0082] In some embodiments the computer-readable storage devices, mediums, and memories can include a cable or wireless signal containing a bit stream and the like. However, when mentioned, non-transitory computer-readable storage media expressly exclude media such as energy, carrier signals, electromagnetic waves, and signals per se.

[0083] Methods according to the above-described examples can be implemented using computer-executable instructions that are stored or otherwise available from computer readable media. Such instructions can include, for example, instructions and data which cause or otherwise configure a general purpose computer, special purpose computer, or a processing device to perform a certain function or group of functions. Portions of computer resources used can be accessible over a network. The computer executable instructions may be, for example, binaries, intermediate format instructions such as assembly language,

firmware, source code, etc. Examples of computer-readable media that may be used to store instructions, information used, and/or information created during methods according to described examples include magnetic or optical disks, flash memory, USB devices provided with non-volatile memory, networked storage devices, and so on.

[0084] Devices implementing methods according to these disclosures can include hardware, firmware and/or software, and can take any of a variety of form factors. Typical examples of such form factors include laptops, smart phones, small form factor personal computers, personal digital assistants, rackmount devices, standalone devices, and so on. Functionality described herein also can be embodied in peripherals or add-in cards. Such functionality can also be implemented on a circuit board among different chips or different processes executing in a single device, by way of further example.

[0085] The instructions, media for conveying such instructions, computing resources for executing them, and other structures for supporting such computing resources are example means for providing the functions described in the disclosure.

[0086] In the foregoing description, aspects of the application are described with reference to specific embodiments thereof, but those skilled in the art will recognize that the application is not limited thereto. Thus, while illustrative embodiments of the application have been described in detail herein, it is to be understood that the disclosed concepts may be otherwise variously embodied and employed, and that the appended claims are intended to be construed to include such variations, except as limited by the prior art. Various features and aspects of the above-described subject matter may be used individually or jointly. Further, embodiments can be utilized in any number of environments and applications beyond those described herein without departing from the broader spirit and scope of the specification. The specification and drawings are, accordingly, to be regarded as illustrative rather than restrictive. For the purposes of illustration, methods were described in a particular order. It should be appreciated that in alternate embodiments, the methods may be performed in a different order than that described.

[0087] Where components are described as being “configured to” perform certain operations, such configuration can be accomplished, for example, by designing electronic circuits or other hardware to perform the operation, by programming programmable

electronic circuits (e.g., microprocessors, or other suitable electronic circuits) to perform the operation, or any combination thereof.

[0088] The various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the examples disclosed herein may be implemented as electronic hardware, computer software, firmware, or combinations thereof. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present application.

[0089] The techniques described herein may also be implemented in electronic hardware, computer software, firmware, or any combination thereof. Such techniques may be implemented in any of a variety of devices such as general purposes computers, wireless communication device handsets, or integrated circuit devices having multiple uses including application in wireless communication device handsets and other devices. Any features described as modules or components may be implemented together in an integrated logic device or separately as discrete but interoperable logic devices. If implemented in software, the techniques may be realized at least in part by a computer-readable data storage medium comprising program code including instructions that, when executed, performs one or more of the method, algorithms, and/or operations described above. The computer-readable data storage medium may form part of a computer program product, which may include packaging materials.

[0090] The computer-readable medium may include memory or data storage media, such as random access memory (RAM) such as synchronous dynamic random access memory (SDRAM), read-only memory (ROM), non-volatile random access memory (NVRAM), electrically erasable programmable read-only memory (EEPROM), FLASH memory, magnetic or optical data storage media, and the like. The techniques additionally, or alternatively, may be realized at least in part by a computer-readable communication

medium that carries or communicates program code in the form of instructions or data structures and that can be accessed, read, and/or executed by a computer, such as propagated signals or waves.

[0091] Other embodiments of the disclosure 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. Embodiments 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.

[0092] In the above description, terms such as "upper," "upward," "lower," "downward," "above," "below," "downhole," "uphole," "longitudinal," "lateral," and the like, as used herein, shall mean in relation to the bottom or furthest extent of the surrounding wellbore even though the wellbore or portions of it may be deviated or horizontal. Correspondingly, the transverse, axial, lateral, longitudinal, radial, etc., orientations shall mean orientations relative to the orientation of the wellbore or tool. Additionally, the illustrate embodiments are illustrated such that the orientation is such that the right-hand side is downhole compared to the left-hand side.

[0093] The term "coupled" is defined as connected, whether directly or indirectly through intervening components, and is not necessarily limited to physical connections. The connection can be such that the objects are permanently connected or releasably connected. The term "outside" refers to a region that is beyond the outermost confines of a physical object. The term "inside" indicates that at least a portion of a region is partially contained within a boundary formed by the object. The term "substantially" is defined to be essentially conforming to the particular dimension, shape or another word that substantially modifies, such that the component need not be exact. For example, substantially cylindrical means that the object resembles a cylinder, but can have one or more deviations from a true cylinder.

[0094] The term "radially" means substantially in a direction along a radius of the object, or having a directional component in a direction along a radius of the object, even if the object is not exactly circular or cylindrical. The term "axially" means substantially along a direction of the axis of the object. If not specified, the term axially is such that it refers to the longer axis of the object.

[0095] Although a variety of information was used to explain aspects within the scope of the appended claims, no limitation of the claims should be implied based on particular features or arrangements, as one of ordinary skill would be able to derive a wide variety of implementations. Further and although some subject matter may have been described in language specific to structural features and/or method steps, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to these described features or acts. Such functionality can be distributed differently or performed in components other than those identified herein. The described features and steps are disclosed as possible components of systems and methods within the scope of the appended claims.

[0096] Moreover, claim language reciting "at least one of" a set indicates that one member of the set or multiple members of the set satisfy the claim. For example, claim language reciting "at least one of A and B" means A, B, or A and B.

[0097] Statements of the disclosure include:

[0098] Statement 1. A tool for monitoring an integrity of a well tubular comprising: at least one transmitter station comprising at least one transmitter coil configured to excite eddy currents in the well tubular; at least one receiver station comprising at least one receiver coil configured to measure an electromagnetic field that is generated in part by the eddy currents and is sensitive to a thickness of the well tubular; and one or more processors configured to generate tool measurements in a first dimension that is axial depth in relation to the tool disposed in the well tubular, a second dimension that is azimuth in relation to the tool disposed in the well tubular, and a third dimension that is radial depth in relation to the tool disposed in the well tubular based on the measured electromagnetic field; wherein: at least one of the transmitter coil and the receiver coil has a polarization axis

orthogonal to an axis of the well tubular; and one of the transmitter station and the receiver station comprises only non-azimuthal sensors.

[0099] Statement 2. The tool of statement 1, wherein the receiver station comprises a plurality of radially-oriented receiver coils arranged at different azimuthal directions to span a circumference defined with respect to the tool.

[0100] Statement 3. The tool of any of statements 1 and 2, wherein the receiver station comprises a plurality of azimuthally oriented receiver coils arranged at different azimuthal directions to span a circumference defined with respect to the tool.

[0101] Statement 4. The tool of any of statements 1 through 3, wherein the transmitter station comprises a plurality of radially oriented transmitter coils arranged at different azimuthal directions to span a circumference defined with respect to the tool and the transmitter coils are excited either independently or simultaneously.

[0102] Statement 5. The tool of any of statements 1 through 4, wherein the transmitter station comprises a plurality of azimuthally oriented transmitter coils arranged at different azimuthal directions to span a circumference defined with respect to the tool and the transmitter coils are excited either independently or simultaneously.

[0103] Statement 6. The tool of any of statements 1 through 5, wherein the transmitter station comprises two axial coils and the two axial coils are either: excited with the same polarity to provide an equivalent axial transmitter; or excited with opposite polarity to provide an equivalent radial transmitter.

[0104] Statement 7. The tool of any of statements 1 through 6, wherein the transmitter station comprises one axial coil mounted on a body of the tool.

[0105] Statement 8. The tool of any of statements 1 through 7, wherein the transmitter station and the receiver station are disposed at different axial positions such that the tool measurements can be generated at multiple radial depths.

[0106] Statement 9. The tool of statement 8, wherein the well tubular is an innermost tubular of a plurality of tubulars and the tool measurements generated at multiple radial depths comprise a shallow depth of investigation sensitive to anomalies on the innermost tubular and the tool measurements generated at multiple radial depths comprise a deeper

depth of investigation in relation to the shallow depth of investigation that is sensitive to anomalies on an outer tubular of the plurality of tubulars with respect to the innermost tubular.

[0107] Statement 10. The tool of any of statements 1 through 9, wherein at least one of the transmitter station and the receiver station comprises extendable arms, spring-loaded pads, or packers coupled to a body of the tool to move one or more coils of either or both the transmitter station and the receiver station towards an inner wall of the tubular.

[0108] Statement 11. The tool of any of statements 1 through 10, wherein the transmitter station is disposed on the a mandrel of the tool and the receiver station is disposed on one of extendable arms, spring-loaded pads, or packers to move one or more coils of the receiver station towards an inner wall of the tubular.

[0109] Statement 12. The tool of any of statements 1 through 11, wherein the tool comprises a plurality of transmitter stations and corresponding first and second transmitters stations of the plurality of transmitter stations are disposed symmetrically on opposing sides of the receiver station and the first and second transmitters are either excited with the same polarity to form an equivalent axial transmitter or with opposite polarity to form an equivalent radial transmitter.

[0110] Statement 13. The tool of any of statements 1 through 12, wherein transmitter and receiver coils are wound around cores made of high magnetic permeability material.

[0111] Statement 14. The tool of any of statements 1 through 13, wherein the at least one receiver coil is coupled to an electromagnetic shield made of a material with an electrical conductivity or magnetic permeability to affect azimuthal focusing.

[0112] Statement 15. The tool of any of statements 1 through 14, wherein at least one of the transmitter station and the receiver station further comprises at least one radially oriented coil placed within an electromagnetic shield and mounted on a rotating head.

[0113] Statement 16. The tool of any of statements 1 through 15, wherein the at least one transmitter coil is excited with continuous-wave current with at least one frequency.

[0114] Statement 17. The tool of any of statements 1 through 16, further comprising a navigation module comprising a tri-axial accelerometer or gyroscope to detect an azimuth

of the tool with respect to a reference and the one or more processors configured to generate display data images indicative of a true azimuth determined based on the azimuth of the tool.

[0115] Statement 18. A method for monitoring an integrity of a well tubular comprising: disposing a tool in proximity to the well tubular, the tool comprising: at least one transmitter station comprising at least one transmitter coil configured to excite eddy currents in the well tubular; at least one receiver station comprising at least one receiver coil configured to measure an electromagnetic field that is generated in part by the eddy currents and is sensitive to a thickness of the well tubular; and one or more processors configured to generate tool measurements in a first dimension that is axial depth in relation to the tool disposed in the well tubular, a second dimension that is azimuth in relation to the tool disposed in the well tubular, and a third dimension that is radial depth in relation to the tool disposed in the well tubular based on the measured electromagnetic field; wherein: at least one of the transmitter coil and the receiver coil has a polarization axis orthogonal to an axis of the well tubular; and one of the transmitter station and the receiver station comprises only non-azimuthal sensors.

[0116] Statement 19. The method of statement 18, wherein the receiver station comprises a first receiver coil and a second receiver coil disposed 180 degrees apart and differential voltage measurements between the first receiver coil and the second receiver coil are made based on excitation of the transmitter station with a known and controlled signal.

[0117] Statement 20. The method of any of statements 18 and 19, wherein the receiver station comprises a first receiver coil and a second receiver coil adjacent to the first receiver coil and differential voltage measurements between the first receiver coil and the second receiver coil are made based on excitation of the transmitter station with a known and controlled signal.

CLAIMS

WHAT IS CLAIMED IS:

1. A tool for monitoring an integrity of a well tubular comprising:
 - at least one transmitter station comprising at least one transmitter coil configured to excite eddy currents in the well tubular;
 - at least one receiver station comprising at least one receiver coil configured to measure an electromagnetic field that is generated in part by the eddy currents and is sensitive to a thickness of the well tubular; and
 - one or more processors configured to generate tool measurements in a first dimension that is axial depth in relation to the tool disposed in the well tubular, a second dimension that is azimuth in relation to the tool disposed in the well tubular, and a third dimension that is radial depth in relation to the tool disposed in the well tubular based on the measured electromagnetic field;wherein:
 - at least one of the transmitter coil and the receiver coil has a polarization axis orthogonal to an axis of the well tubular; and
 - one of the transmitter station and the receiver station comprises only non-azimuthal sensors.
2. The tool of claim 1, wherein the receiver station comprises a plurality of radially-oriented receiver coils arranged at different azimuthal directions to span a circumference defined with respect to the tool.
3. The tool of claim 1, wherein the receiver station comprises a plurality of azimuthally oriented receiver coils arranged at different azimuthal directions to span a circumference defined with respect to the tool.

4. The tool of claim 1, wherein the transmitter station comprises a plurality of radially oriented transmitter coils arranged at different azimuthal directions to span a circumference defined with respect to the tool and the transmitter coils are excited either independently or simultaneously.

5. The tool of claim 1, wherein the transmitter station comprises a plurality of azimuthally oriented transmitter coils arranged at different azimuthal directions to span a circumference defined with respect to the tool and the transmitter coils are excited either independently or simultaneously.

6. The tool of claim 1, wherein the transmitter station comprises two axial coils and the two axial coils are either:

excited with the same polarity to provide an equivalent axial transmitter; or

excited with opposite polarity to provide an equivalent radial transmitter.

7. The tool of claim 1, wherein the transmitter station comprises one axial coil mounted on a body of the tool.

8. The tool of claim 1, wherein the transmitter station and the receiver station are disposed at different axial positions such that the tool measurements can be generated at multiple radial depths.

9. The tool of claim 8, wherein the well tubular is an innermost tubular of a plurality of tubulars and the tool measurements generated at multiple radial depths comprise a shallow depth of investigation sensitive to anomalies on the innermost tubular and the tool measurements generated at multiple radial depths comprise a deeper depth of investigation in relation to the shallow depth of investigation that is sensitive to anomalies on an outer tubular of the plurality of tubulars with respect to the innermost tubular.

10. The tool of claim 1, wherein at least one of the transmitter station and the receiver station comprises extendable arms, spring-loaded pads, or packers coupled to a body of the tool to move one or more coils of either or both the transmitter station and the receiver station towards an inner wall of the tubular.

11. The tool of claim 1, wherein the transmitter station is disposed on the a mandrel of the tool and the receiver station is disposed on one of extendable arms, spring-loaded pads, or packers to move one or more coils of the receiver station towards an inner wall of the tubular.

12. The tool of claim 1, wherein the tool comprises a plurality of transmitter stations and corresponding first and second transmitters stations of the plurality of transmitter stations are disposed symmetrically on opposing sides of the receiver station and the first and second transmitters are either excited with the same polarity to form an equivalent axial transmitter or with opposite polarity to form an equivalent radial transmitter.

13. The tool of claim 1, wherein transmitter and receiver coils are wound around cores made of high magnetic permeability material.

14. The tool of claim 1, wherein the at least one receiver coil is coupled to an electromagnetic shield made of a material with an electrical conductivity or magnetic permeability to affect azimuthal focusing.

15. The tool of claim 1, wherein at least one of the transmitter station and the receiver station further comprises at least one radially oriented coil placed within an electromagnetic shield and mounted on a rotating head.

16. The tool of claim 1, wherein the at least one transmitter coil is excited with continuous-wave current with at least one frequency.

17. The tool of claim 1, further comprising a navigation module comprising a tri-axial accelerometer or gyroscope to detect an azimuth of the tool with respect to a reference and the one or more processors configured to generate display data images indicative of a true azimuth determined based on the azimuth of the tool.

18. A method for monitoring an integrity of a well tubular comprising:

disposing a tool in proximity to the well tubular, the tool comprising:

at least one transmitter station comprising at least one transmitter coil configured to excite eddy currents in the well tubular;

at least one receiver station comprising at least one receiver coil configured to measure an electromagnetic field that is generated in part by the eddy currents and is sensitive to a thickness of the well tubular; and

one or more processors configured to generate tool measurements in a first dimension that is axial depth in relation to the tool disposed in the well tubular, a second dimension that is azimuth in relation to the tool disposed in the well tubular, and a third dimension that is radial depth in relation to the tool disposed in the well tubular based on the measured electromagnetic field;

wherein:

at least one of the transmitter coil and the receiver coil has a polarization axis orthogonal to an axis of the well tubular; and

one of the transmitter station and the receiver station comprises only non-azimuthal sensors.

recording voltages at the at least one receiver coil at different axial locations, azimuthal locations, and multiple depths of investigation of the well tubular based on the measured electromagnetic field that is generated by the eddy currents;

generating the tool measurements based on the voltages recorded at the at least one receiver coil; and

displaying the measurements as 2-D images with the first dimension of the axial depth and the second dimension of the azimuth in relation to the tool disposed in the well tubular, and each 2-D image of the 2-D images has a different depth of investigation.

19. The method of claim 18, wherein the receiver station comprises a first receiver coil and a second receiver coil disposed 180 degrees apart and differential voltage measurements between the first receiver coil and the second receiver coil are made based on excitation of the transmitter station with a known and controlled signal.

20. The method of claim 18, wherein the receiver station comprises a first receiver coil and a second receiver coil adjacent to the first receiver coil and differential voltage measurements between the first receiver coil and the second receiver coil are made based on excitation of the transmitter station with a known and controlled signal.

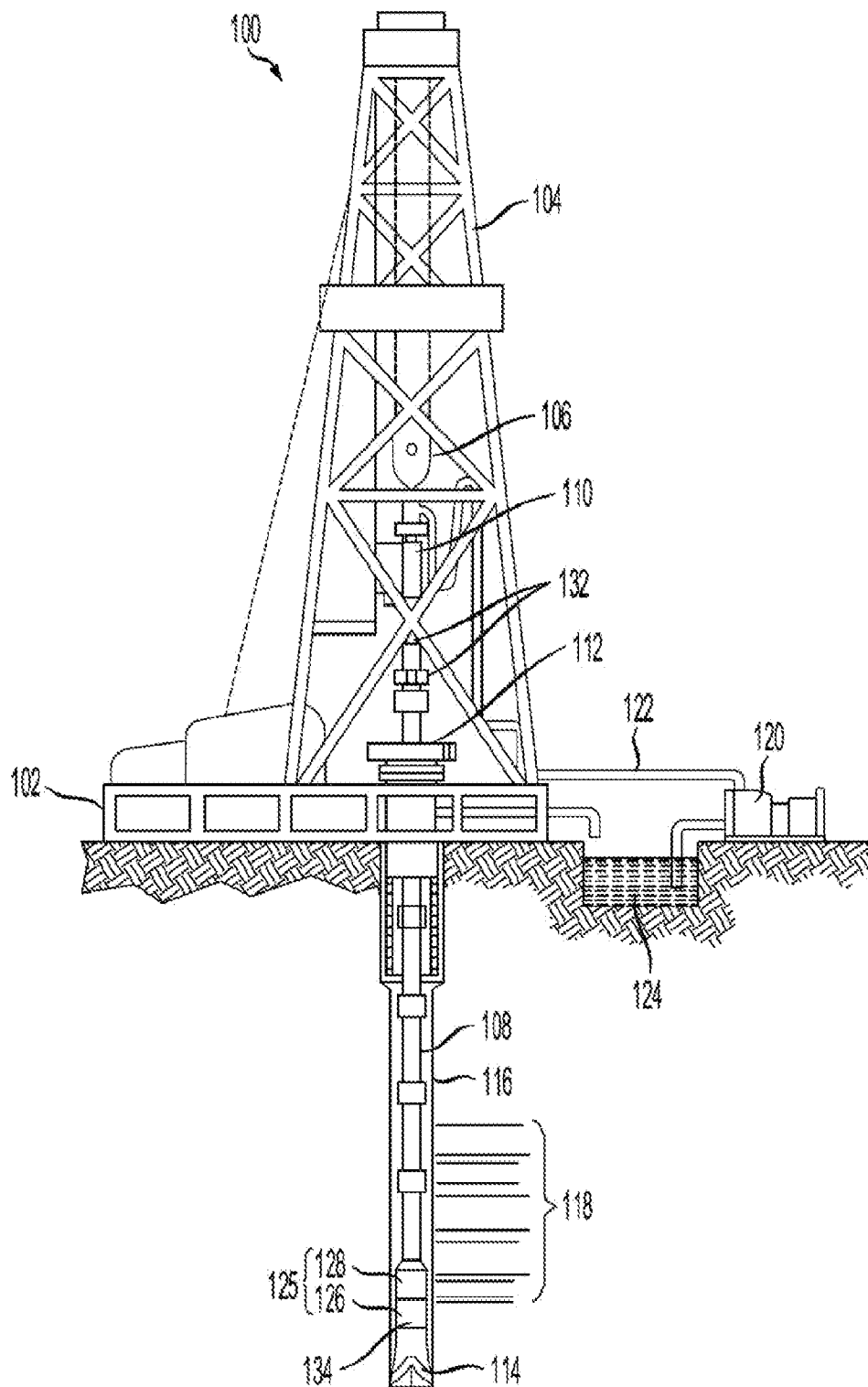


FIG. 1A

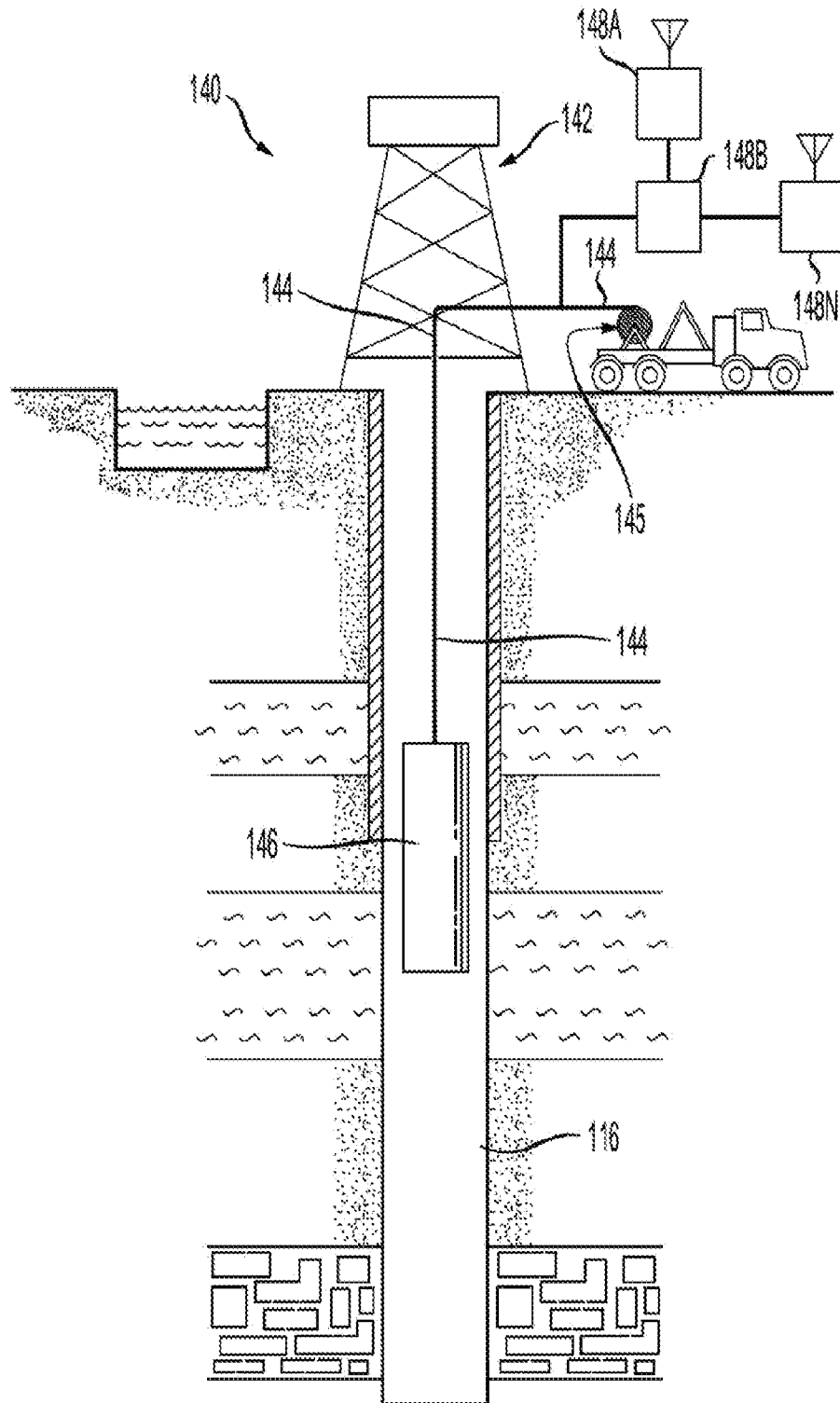


FIG. 1B

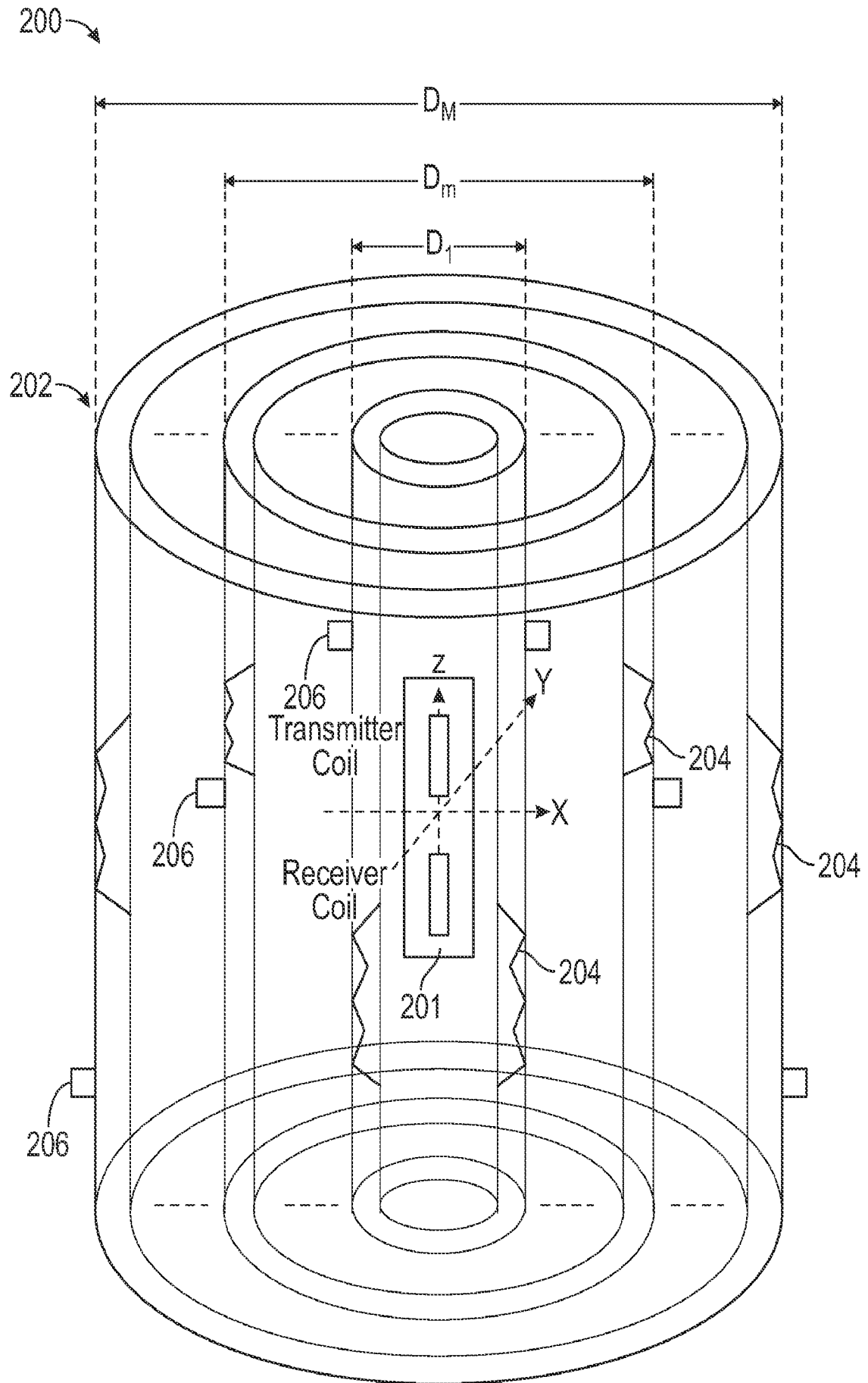


FIG. 2

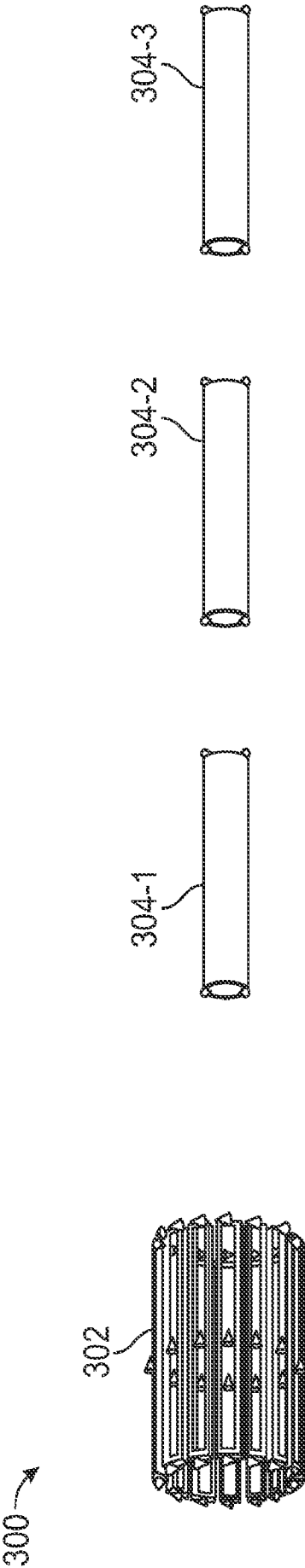


FIG. 3A

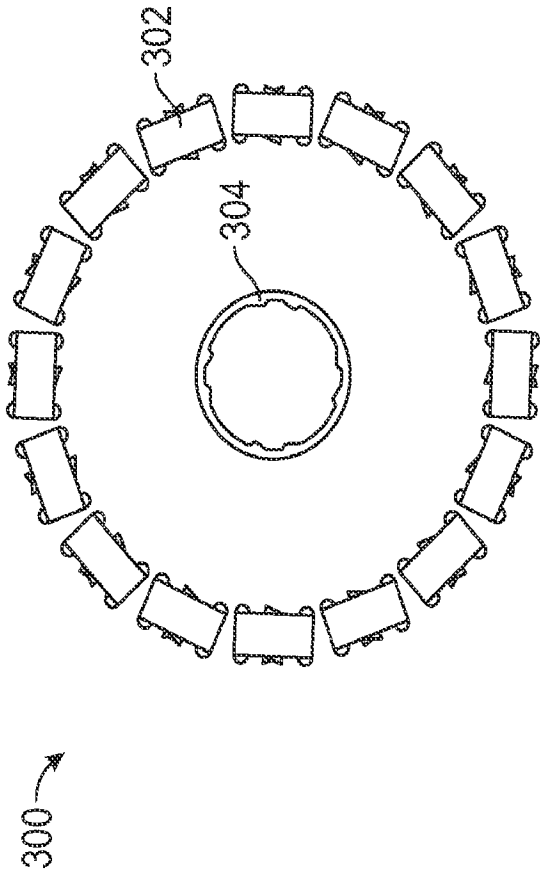


FIG. 3B

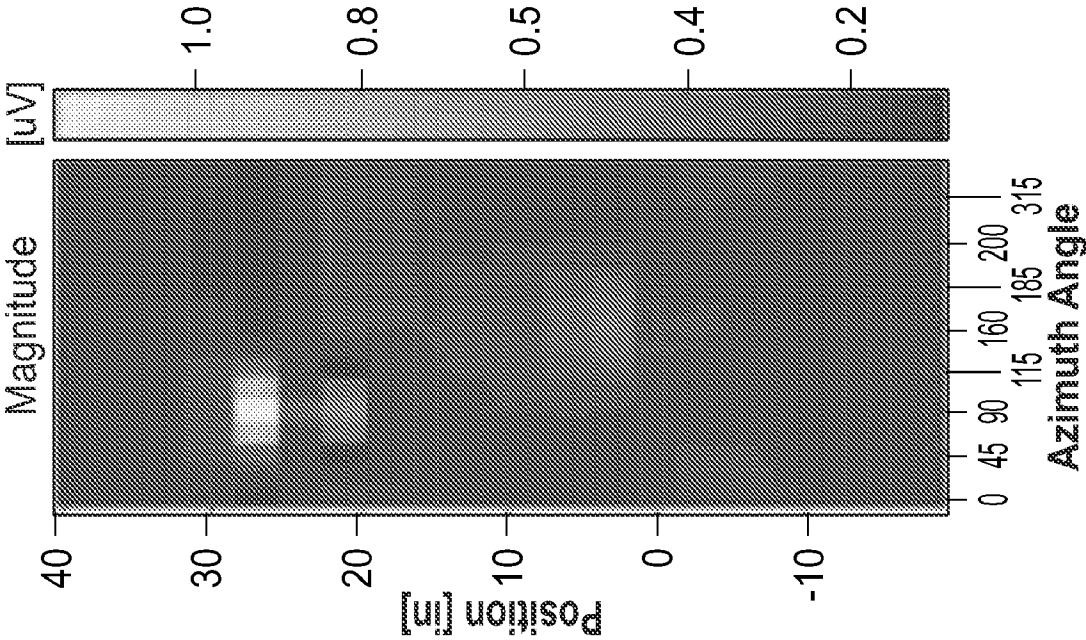


FIG. 4B

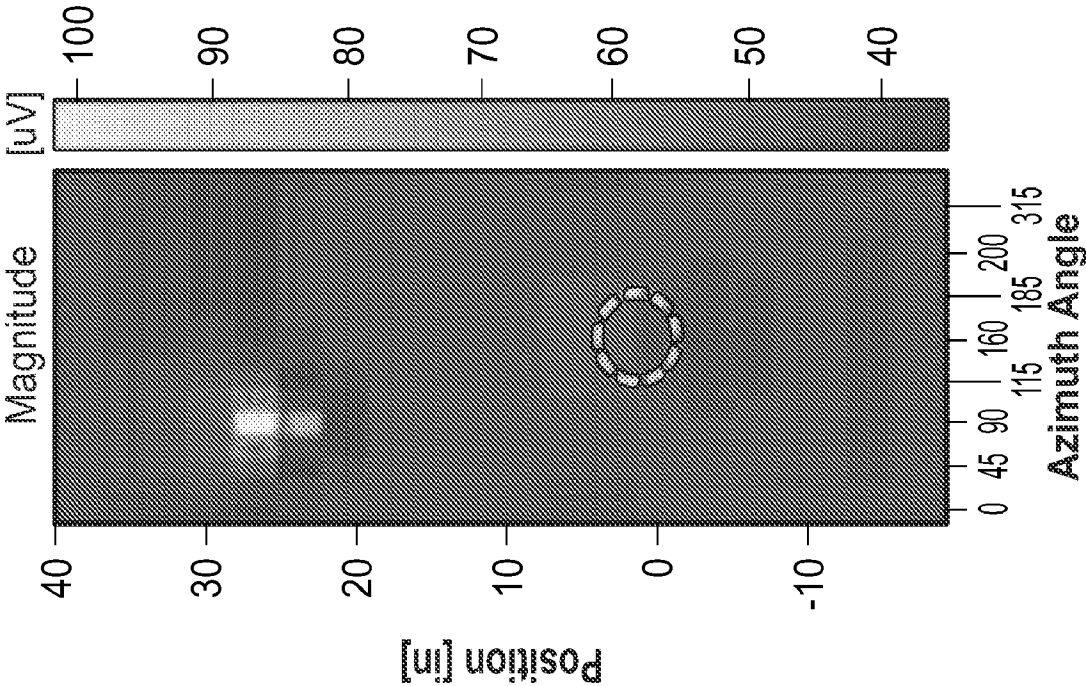


FIG. 4A

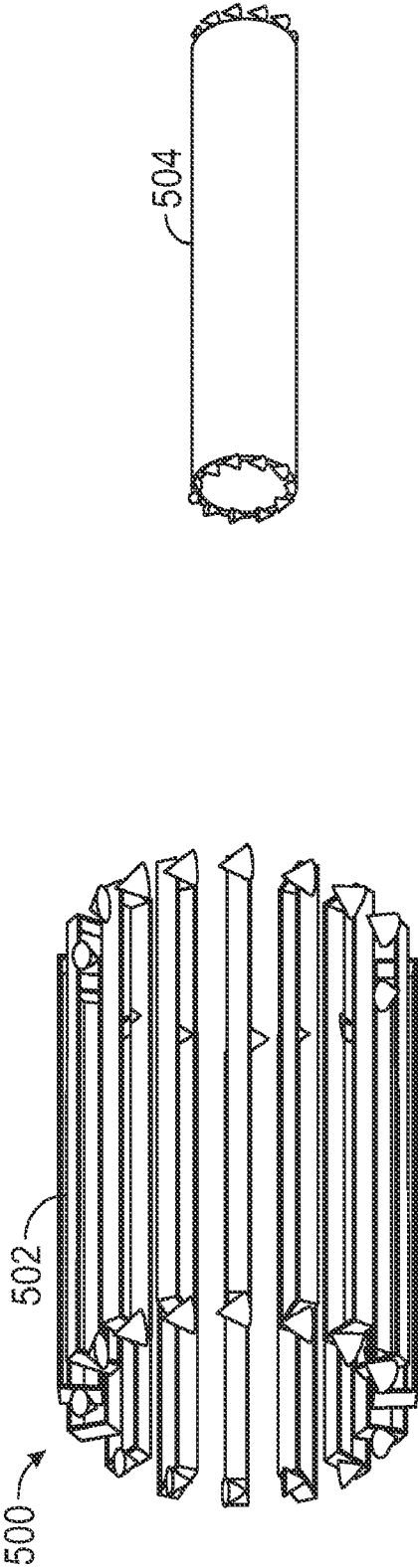


FIG. 5A

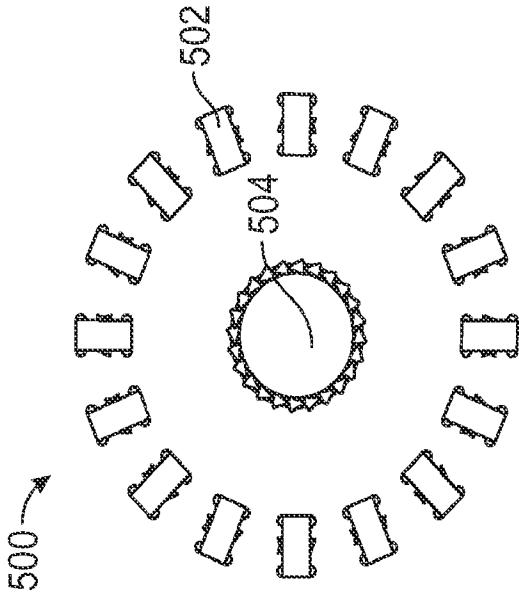


FIG. 5B



FIG. 6A

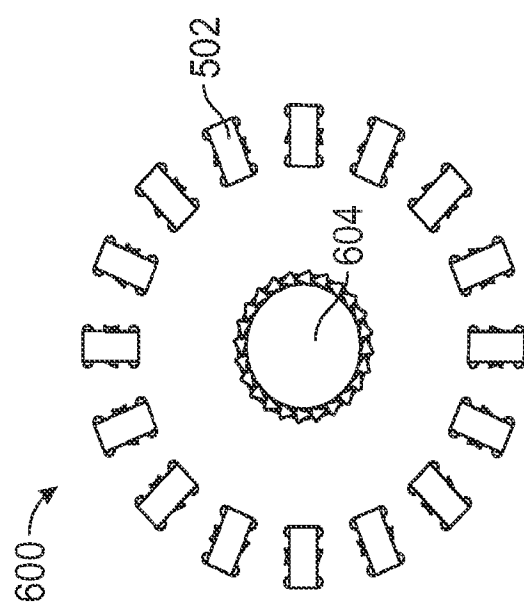


FIG. 6B

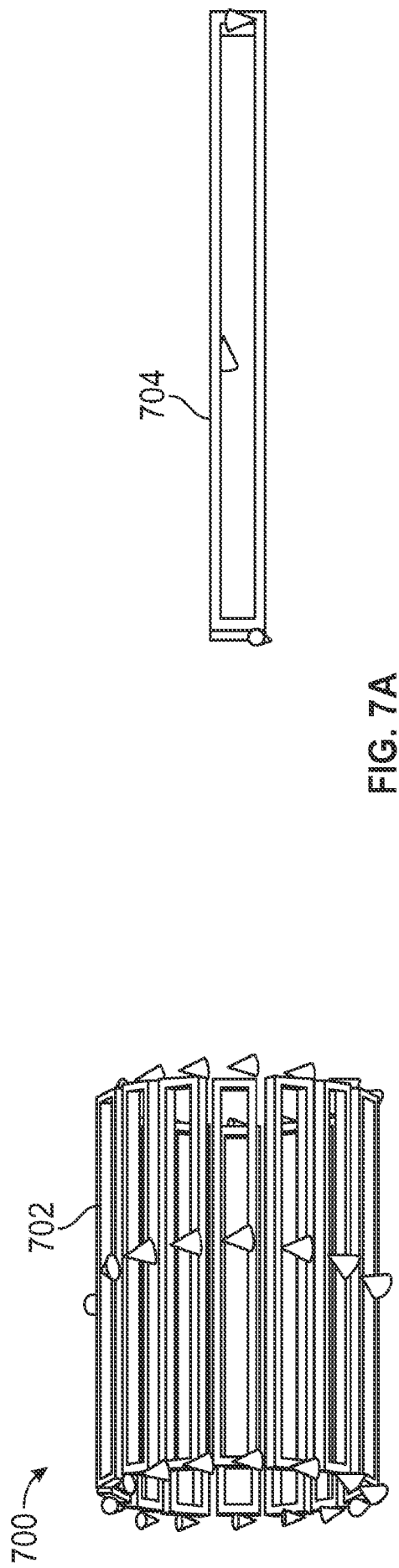


FIG. 7A

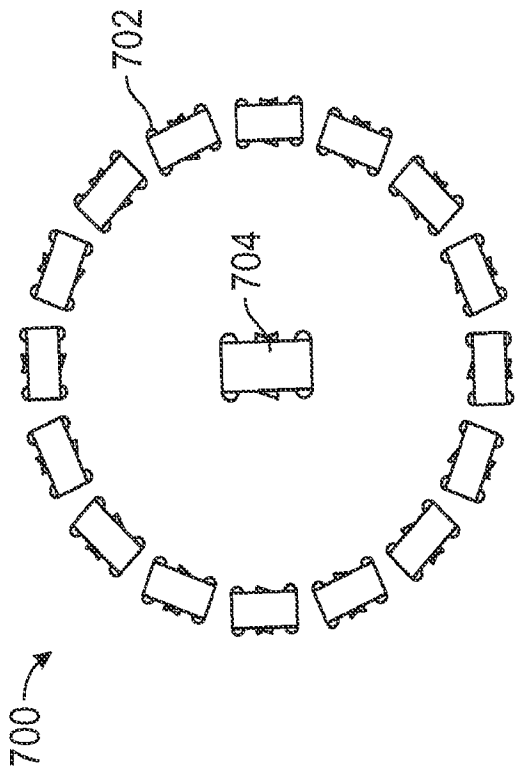


FIG. 7B

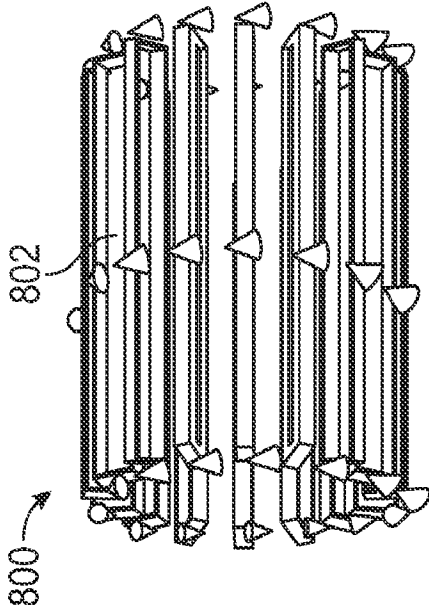


FIG. 8A

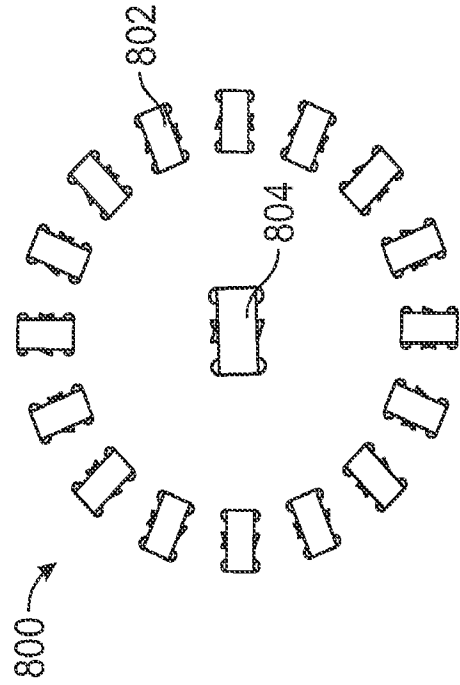
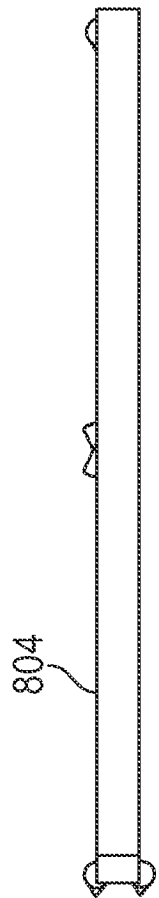


FIG. 8B



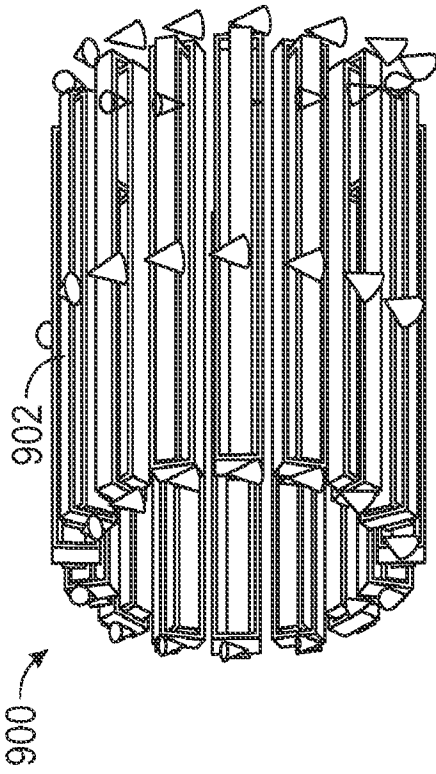


FIG. 9A

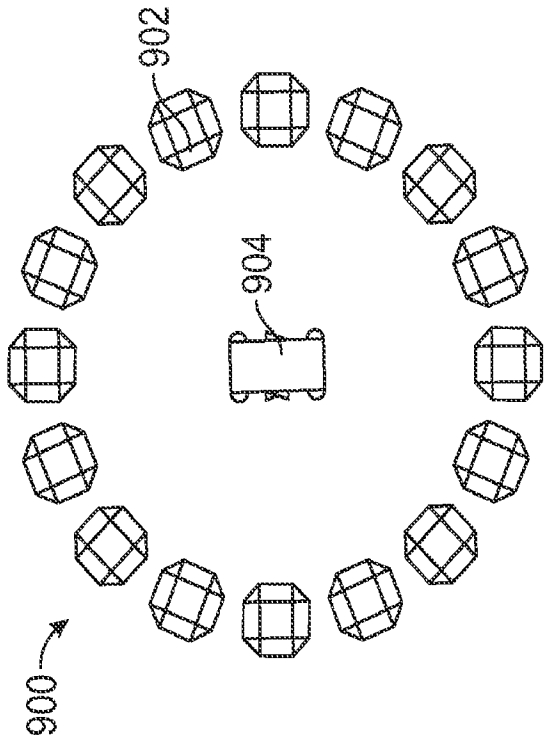
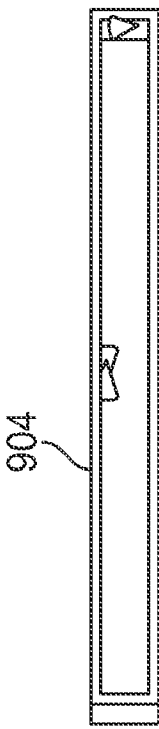


FIG. 9B



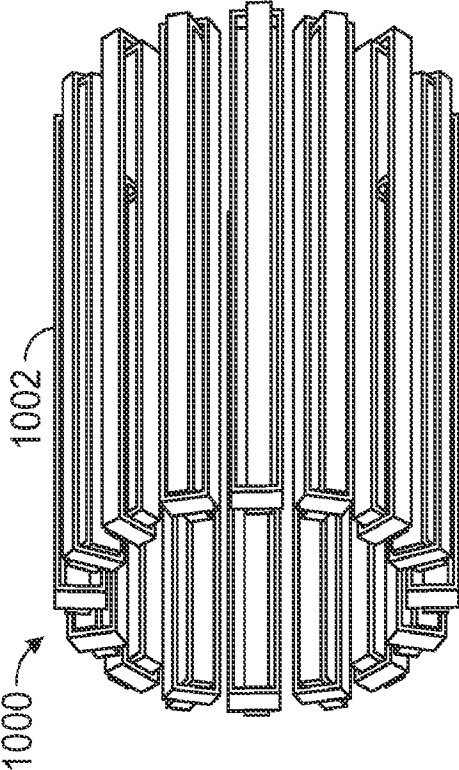
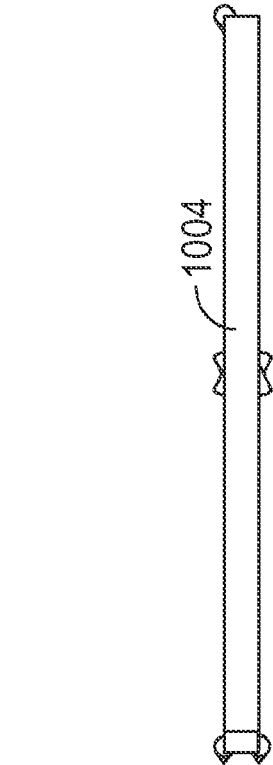


FIG. 10A

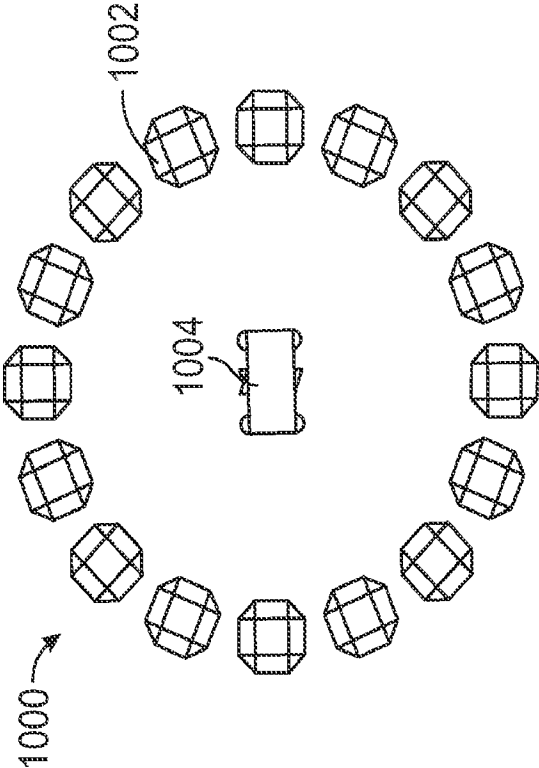


FIG. 10B

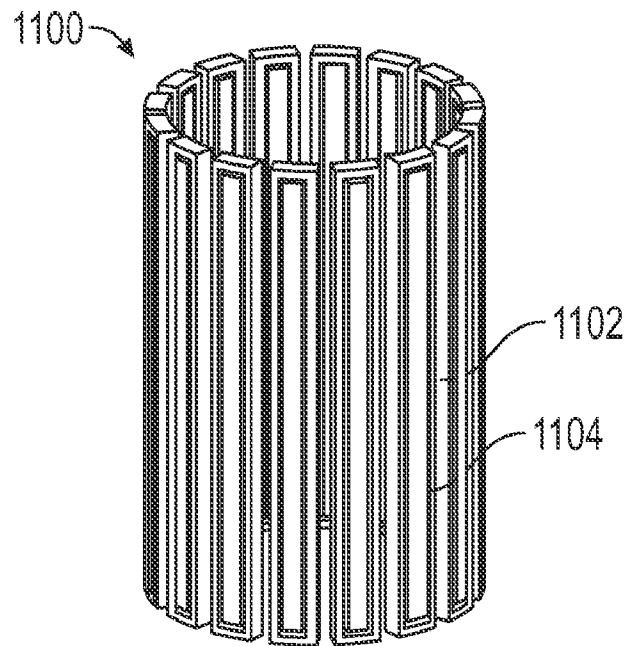


FIG. 11

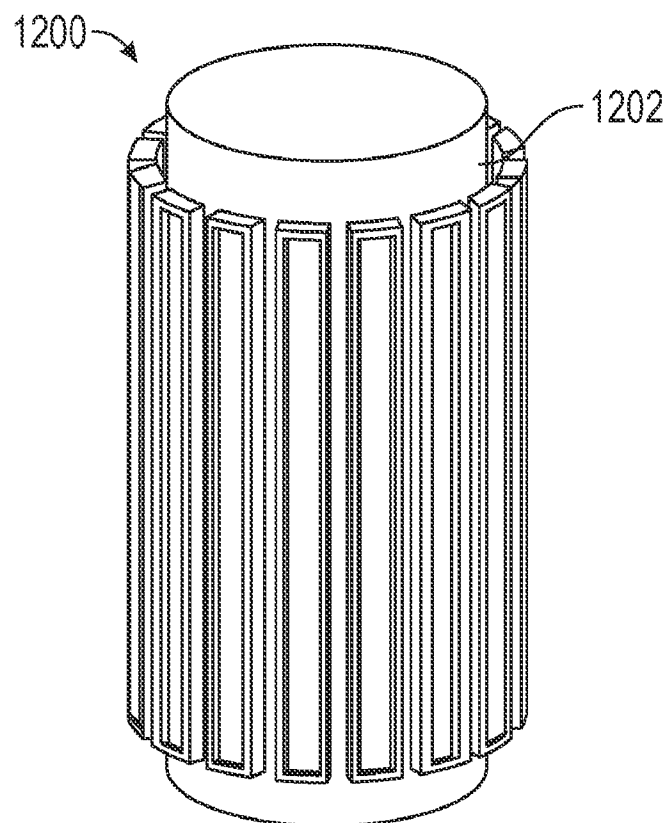


FIG. 12

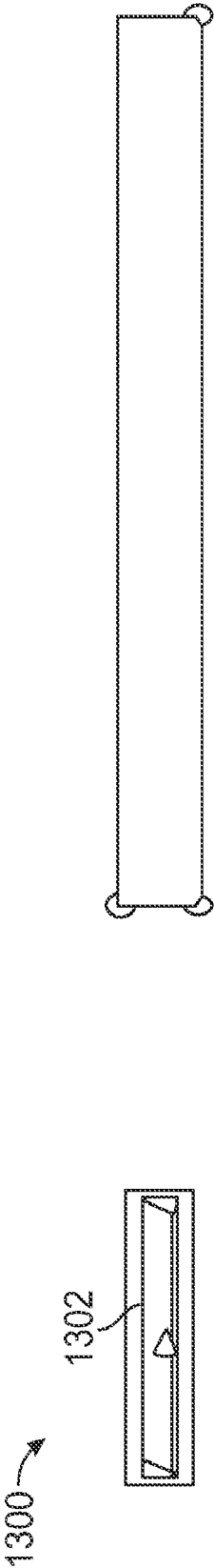


FIG. 13A

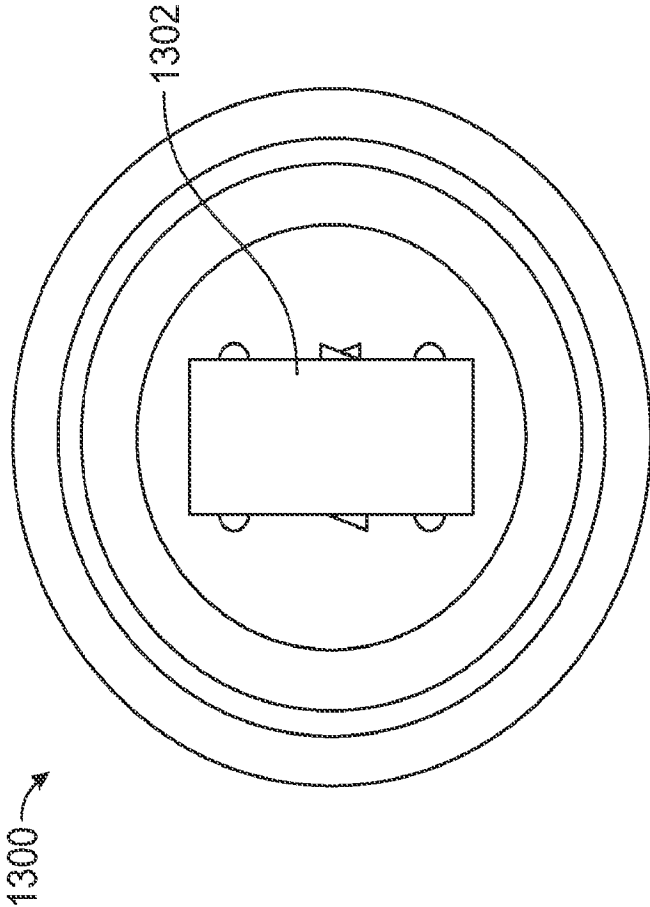


FIG. 13B

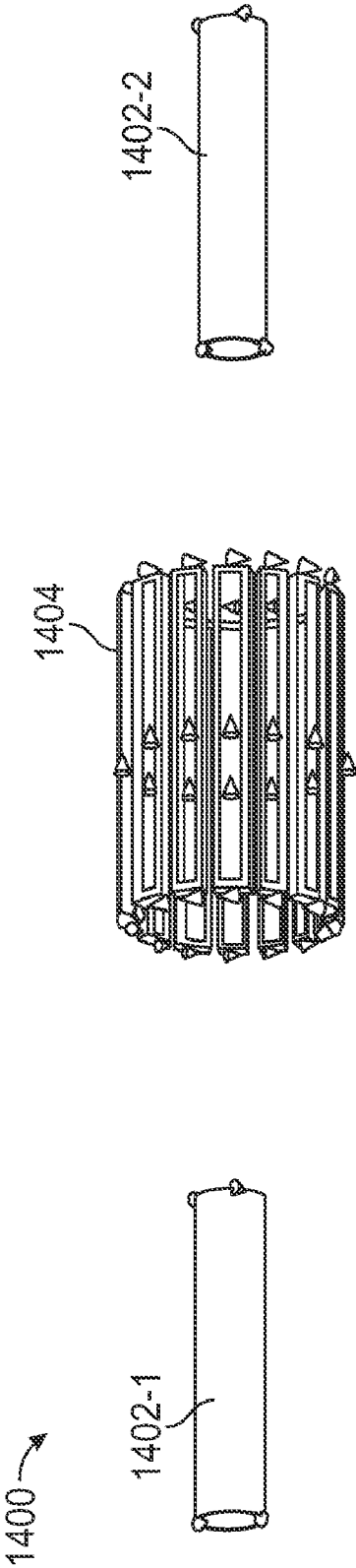


FIG. 14

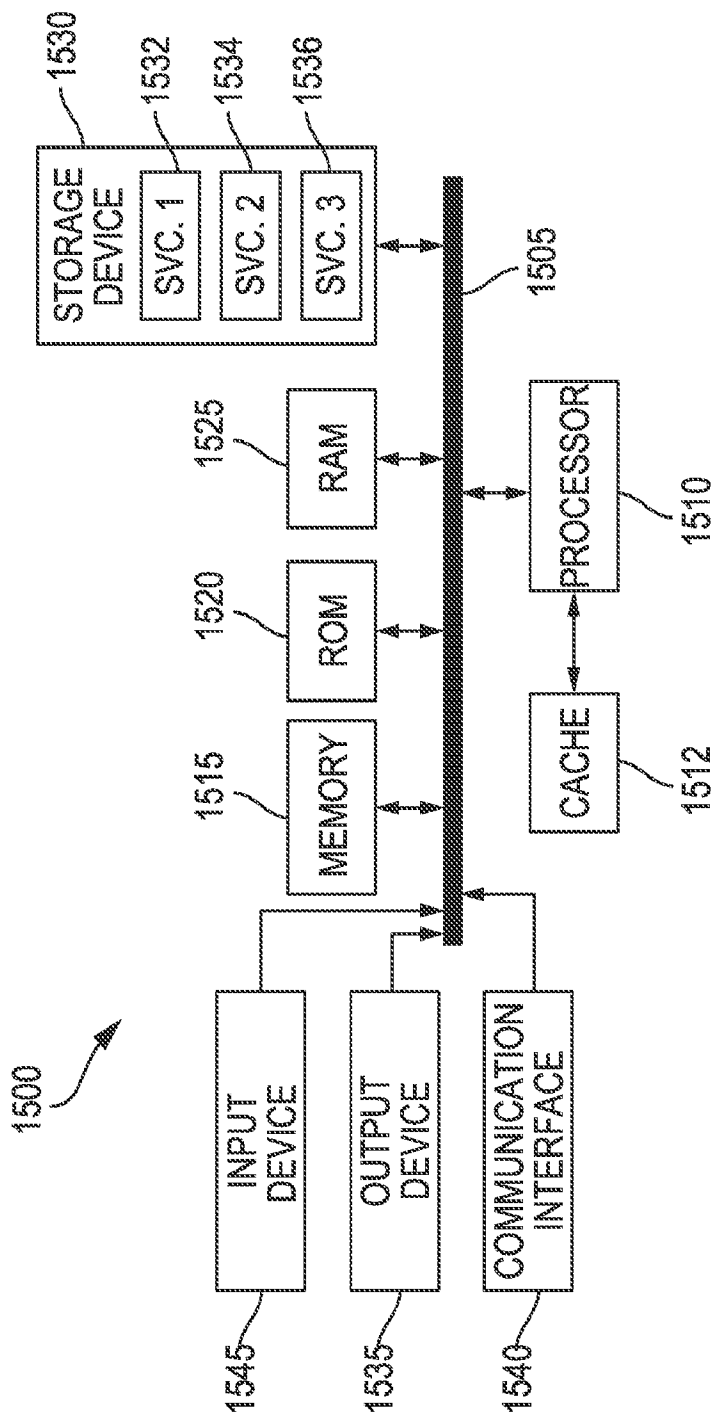


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2023/036571

A. CLASSIFICATION OF SUBJECT MATTER**G01V 3/30(2006.01)i; G01V 3/12(2006.01)i; E21B 47/12(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)

G01V 3/30(2006.01); E21B 47/00(2006.01); E21B 47/08(2006.01); E21B 47/10(2006.01); G01N 27/72(2006.01);
G01N 27/82(2006.01); G01V 3/26(2006.01); G01V 3/28(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: well tubular, integrity, transmitter station, receiver station, coil, axial depth, azimuth,
radial depth, electromagnetic shield, true azimuth**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 3137737 B1 (HALLIBURTON ENERGY SERVICES, INC.) 09 November 2022 (2022-11-09) paragraphs [0015]-[0018], [0021]-[0024], [0028], [0032]-[0036], [0042], [0052], [0063]-[0064], claim 7, and figures 1-2, 4A-5F, 10	1-13,16,18-20
Y		14-15,17
Y	US 6087830 A (BRANDLY et al.) 11 July 2000 (2000-07-11) column 16, lines 35-48 and figure 6	14-15
Y	US 2006-0202700 A1 (BAROLAK et al.) 14 September 2006 (2006-09-14) paragraphs [0052]-[0056] and figure 10	17
A	US 2017-0191361 A1 (HALLIBURTON ENERGY SERVICES, INC.) 06 July 2017 (2017-07-06) paragraphs [0017]-[0052] and figures 1-7	1-20
A	US 11016216 B2 (HALLIBURTON ENERGY SERVICES, INC.) 25 May 2021 (2021-05-25) claims 1-20 and figures 1-9	1-20

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

* Special categories of cited documents:

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“D” document cited by the applicant in the international application

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“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

22 February 2024

Date of mailing of the international search report

22 February 2024

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/US2023/036571

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