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- (71) Applicant: **BAKER HUGHES INCORPORATED**
[US/US]; P.O. Box 4740, Houston, Texas 77210-4740 (US).
- (72) Inventors: **FANG, Sheng**; 10703 Overton Circle, Houston, Texas 77065 (US). **REIDERMAN, Arcady**; 19906 Sky Hollow Lane, Katy, Texas 77450 (US).
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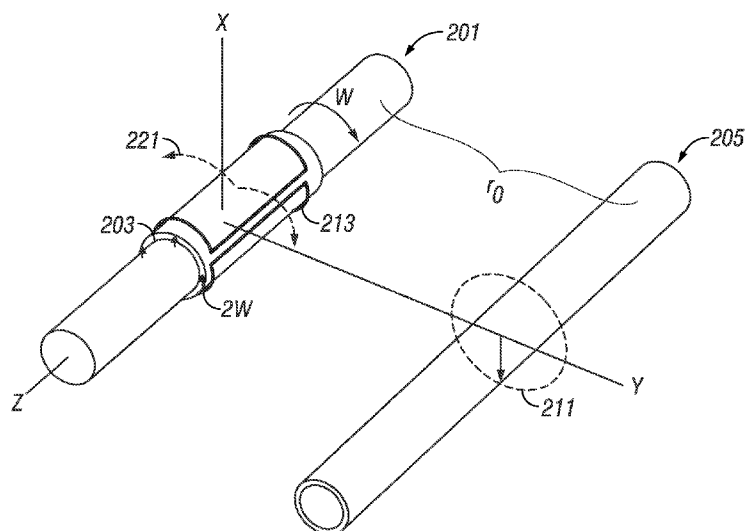


FIG. 2

(57) Abstract: In one aspect an apparatus for determining a distance between a first borehole and a second borehole during drilling of the second borehole is disclosed that in one embodiment includes a magnet on a drilling tool that rotates in the second borehole to induce a primary magnetic field in a magnetic object in the first borehole, a substantially stationary sensor on the drilling tool that detects a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field, and a controller that determines the distance between the first borehole and the second borehole from the detected magnetic field. In another aspect a method of determining a distance between a first borehole and a second borehole, the in one embodiment includes inducing a primary magnetic field in a magnetic object in the first borehole using a rotating magnet in the second borehole, detecting a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field using a substantially stationary sensor in the second borehole, and determining the distance

between the first borehole and the second borehole from the detected magnetic field.

APPARATUS AND METHODS FOR WELL-BORE PROXIMITY MEASUREMENT WHILE DRILLING

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Application No. 13/713960, filed on December 13, 2013, which claims the benefit of U.S. Application No. 13/658599, filed on October 23, 2012, both of which are incorporated herein by reference in their entirety.

BACKGROUND

1. Field of the Disclosure

[0001] This disclosure relates generally to apparatus and methods for determining a distance to a pre-existing wellbore and controlling drilling operations based on the determination.

2. Background of the Art

[0002] In the process of drilling wells (also referred to as wellbores or boreholes) for hydrocarbon production, it is common to drill a second well in a predetermined relationship to an existing well. An example of this may be when a blowout occurred in the existing well. Two approaches may be taken to control the blowout. One method is to use explosives at the surface and snuff out the fire in the burning well. This procedure is fraught with danger and requires prompt control of hydrocarbons flow in the well. The second method is to drill a second borehole to intersect the blowout well and pump drilling mud into the blowout well. This is not a trivial matter. An error of half a degree can result in a deviation of close to 90 feet at a depth of 10,000 feet. A typical borehole is about 12 inches in diameter, a miniscule target compared to the potential error zone.

[0003] Another situation in which accurate placement of a secondary well relative to a preexisting well is desired for secondary recovery operations. For various reasons, such as low formation pressure or high viscosity of hydrocarbons in the reservoir, production under natural conditions of hydrocarbons may be at uneconomically low rates. In such cases, a second borehole is drilled to be substantially parallel to the pre-existing borehole. Fluid such as water, CO₂ is then injected into the formation from the second borehole and the injected fluid drives the hydrocarbons in the formation towards the producing borehole where it may be recovered.

[0004] In the second category are passive ranging techniques that do not require access to the pre-existing well while drilling the second well. The techniques normally

utilize a relatively strong magnetism induced in the casing of the pre-existing well by the Earth's magnetic field. The signal due directly to the earth's magnetic field is a problem, limiting the accuracy of this measurement. Residual magnetism of the casing introduces additional uncertainties.

[0005] The present disclosure discloses apparatus and methods for determining distance from a pre-existing wellbore without accessing the pre-existing well.

SUMMARY

[0006] One embodiment of the disclosure is an apparatus. In one aspect an apparatus for determining a distance between a first borehole and a second borehole during drilling of the second borehole is disclosed that in one embodiment includes a magnet on a drilling tool that rotates in the second borehole to induce a primary magnetic field in a magnetic object in the first borehole, a substantially stationary sensor on the drilling tool that detects a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field, and a controller that determines the distance between the first borehole and the second borehole from the detected magnetic field.

[0007] Another embodiment of the disclosure is a method a method of determining a distance between a first borehole and a second borehole, the in one embodiment includes inducing a primary magnetic field in a magnetic object in the first borehole using a rotating magnet in the second borehole, detecting a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field using a substantially stationary sensor in the second borehole, and determining the distance between the first borehole and the second borehole from the detected magnetic field.

[0008] Examples of certain features of the apparatus and method disclosed herein are summarized rather broadly in order that the detailed description thereof that follows may be better understood. There are, of course, additional features of the apparatus and method disclosed hereinafter that will form the subject of the claims.

BRIEF DESCRIPTION OF THE FIGURES

[0009] For detailed understanding of the present disclosure, references should be made to the following detailed descriptions of the disclosure, taken in conjunction with the accompanying drawings, in which like elements have generally been given like numerals and wherein:

FIG. 1 is a schematic illustration of an exemplary drilling system that includes an apparatus for determining distance between boreholes, according to one embodiment of the disclosure;

FIG. 2 shows a simplified layout of the magnetometer and the coordinate system used for the calculations;

FIG. 3 illustrates azimuthal dependence of the signal in the sensor coil;

FIG. 4 is a schematic illustration of implementation of the rotational magnetometer;

FIG. 5 shows an embodiment that utilizes a pair of additional differentially connected coils synchronously rotating with the magnetic coil;

FIG. 6 shows an embodiment that utilizes switchable magnetic field source;

FIG. 7 shows time diagrams of the switchable magnetic field and the transient responses (corresponds to the embodiment of FIG. 6);

FIG. 8 shows drilling a second borehole in close proximity to a cased production borehole;

FIG. 9 shows an embodiment for a radial magnet-coil arrangement that includes two identical or substantially identical receiver coils symmetrically installed on the surface of the magnet for estimating distance between adjacent wellbore or boreholes;

FIG. 10 shows yet another embodiment of a radial magnet-coil arrangement that includes two coils, each further containing a pair of radial coils, offset equally at two sides of the rotating magnet;

FIG. 11 depicts receiver coil magnetic flux as a function of receiver coil's axial offset as a function of distance between the coil and the casing having a five (5) meter offset;

FIG. 12 shows yet another embodiment of a magnet and coils arrangement wherein that includes three receiver coils placed with equal spacing;

FIG. 13 shows another embodiment of a hybrid configuration of coils that includes six identical or substantially identical receiver coils forming two pairs of axial or three pairs of radial measurements;

FIG. 14 shows an embodiment for a radial magnet-sensor arrangement that includes a rotating magnet and a stationary or substantially stationary sensor for detecting secondary magnetic waves for determining distance and inclination of wellbore relative to another borehole; and

FIG. 15 shows yet another embodiment of a radial magnet-sensor arrangement that includes a magnet and a sensor that rotate at different rotational speeds for determining distance and inclination of a one borehole relative to another borehole.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0010] FIG. 1 shows a schematic diagram of a drilling system 100 with a drillstring 120 carrying a drilling assembly 190 (also referred to as the bottomhole assembly, or ABHA) conveyed in a "wellbore" or "borehole" 126 for drilling the wellbore. The drilling system 100 includes a conventional derrick 111 erected on a floor 112 which supports a rotary table 114 that is rotated by a prime mover such as an electric motor (not shown) at a desired rotational speed. The drillstring 120 includes a tubing such as a drill pipe 122 or a coiled-tubing extending downward from the surface into the borehole 126. The drillstring 20 is pushed into the wellbore 126 when a drill pipe 122 is used as the tubing. For coiled-tubing applications, a tubing injector, such as an injector (not shown), however, is used to move the tubing from a source thereof, such as a reel (not shown), to the wellbore 126. The drill bit 150 attached to the end of the drillstring breaks up the geological formations when it is rotated to drill the borehole 126. If a drill pipe 122 is used, the drillstring 120 is coupled to a drawworks 30 via a Kelly joint 121, swivel, 138 and line 129 through a pulley 123. During drilling operations, the drawworks 130 is operated to control the weight on bit, which is an important parameter that affects the rate of penetration. The operation of the drawworks is well known in the art and is thus not described in detail herein.

[0011] During drilling operations, a suitable drilling fluid 131 from a mud pit (source) 132 is circulated under pressure through a channel in the drillstring 120 by a mud pump 134. The drilling fluid passes from the mud pump 134 into the drillstring 120 via a desurger 136, fluid line 128 and Kelly joint 121. The drilling fluid 131 is discharged at the borehole bottom 151 through an opening in the drill bit 150. The drilling fluid 131 circulates uphole through the annular space 127 between the drillstring 120 and the borehole 126 and returns to the mud pit 132 via a return line 135. The drilling fluid acts to lubricate the drill bit 150 and to carry borehole cutting or chips away from the drill bit 150. A sensor S_1 preferably placed in the line 138 provides information about the fluid flow rate. A surface torque sensor S_2 and a sensor S_3 associated with the drillstring 120 respectively provide information about the torque and rotational speed of the drillstring. Additionally, a sensor (not shown) associated with line 129 is used to provide the hook load of the drillstring 120.

[0012] In one embodiment of the disclosure, the drill bit 150 is rotated by only rotating the drill pipe 122. In another embodiment of the disclosure, a downhole motor 155 (mud motor) is disposed in the drilling assembly 190 to rotate the drill bit 150 and the drill

pipe 122 is rotated usually to supplement the rotational power, if required, and to effect changes in the drilling direction.

[0013] In the embodiment of FIG. 1, the mud motor 155 is coupled to the drill bit 150 via a drive shaft (not shown) disposed in a bearing assembly 157. The mud motor rotates the drill bit 150 when the drilling fluid 131 passes through the mud motor 155 under pressure. The bearing assembly 157 supports the radial and axial forces of the drill bit. A stabilizer 158 coupled to the bearing assembly 157 acts as a centralizer for the lowermost portion of the mud motor assembly.

[0014] In one embodiment of the disclosure, a drilling sensor module 159 is placed near the drill bit 150. The drilling sensor module contains sensors, circuitry and processing software and algorithms relating to the dynamic drilling parameters. Such parameters include bit bounce, stick-slip of the drilling assembly, backward rotation, torque, shocks, borehole and annulus pressure, acceleration measurements and other measurements of the drill bit condition. A suitable telemetry or communication sub 172 using, for example, two-way telemetry, is also provided as illustrated in the drilling assembly 100. The drilling sensor module processes the sensor information and transmits it to the surface control unit 140 via the telemetry system 172.

[0015] The communication sub 172, a power unit 178 and an MWD tool 179 are all connected in tandem with the drillstring 120. Flex subs, for example, are used in connecting the MWD tool 179 in the drilling assembly 190. Such subs and tools form the bottom hole drilling assembly 90 between the drillstring 120 and the drill bit 150. The drilling assembly 190 makes various measurements including the pulsed nuclear magnetic resonance measurements while the borehole 126 is being drilled. The communication sub 172 obtains the signals and measurements and transfers the signals, using two-way telemetry, for example, to be processed on the surface. Alternatively, the signals can be processed using a downhole processor in the drilling assembly 190.

[0016] The surface control unit or processor 140 also receives signals from other downhole sensors and devices and signals from sensors S_1 - S_3 and other sensors used in the system 100 and processes such signals according to programmed instructions provided to the surface control unit 140. The surface control unit 140 displays desired drilling parameters and other information on a display/monitor 142 utilized by an operator to control the drilling operations. The surface control unit 140 preferably includes a computer or a microprocessor-based processing system, memory for storing programs or models and data, a recorder for recording data, and other peripherals. The control unit 140 is preferably adapted to activate

alarms 144 when certain unsafe or undesirable operating conditions occur. The system also includes a downhole processor, sensor assembly for making formation evaluation and an orientation sensor. These may be located at any suitable position on the bottomhole assembly (BHA). The system further includes a device 180 for determining distance between the wellbore 126 and a pre-existing wellbore, as described in more detail in reference to FIGS. 2-15.

[0017] Turning now to FIG. 2, a permanent magnet 203 is shown on a drill collar section 201 of the secondary well. The magnet is transversely magnetized with the flux direction indicated by 221. The pre-existing well casing is denoted by 205. The coordinate axes x , y , and z are as indicated in FIG. 2. The collar section is provided with a coil 213. The coil rotates synchronously with the magnet, but the magnet-coil combination need not be synchronous with the rotation of the drill collar: this may be done by having the magnet-coil combination on a sleeve. The rotating magnet generates a variable magnetic field at a magnetic object such as the casing 205 of the pre-existing well. This variable magnetic field induces magnetization in the casing that, in turn, generate a variable magnetic flux picked up by the rotating coil 213.

[0018] The magnetic field generated by the magnet at the target well position can be approximated by the point dipole formula:

$$\vec{H}_{MAGNET} = \frac{1}{4\pi} \left[\frac{3(\vec{p}_m \cdot \vec{r})}{r^5} \vec{r} - \frac{\vec{p}_m}{r^3} \right] \quad (1),$$

Where $\vec{p}_m$ is the dipole moment of the magnet, and $\vec{r}$ is the distance from the magnet center to a point on the casing 205. When the magnet 203 rotates in the XY plane with angular velocity ω , then

$$\vec{p}_m = p_m [\cos(\omega t) \vec{e}_x + \sin(\omega t) \vec{e}_y] \quad (2),$$

where $\vec{e}_x$ and $\vec{e}_y$ are unit vectors in the x - and y - directions respectively. The rotating coil sensitivity function (magnetic field produced by the coil driven with a unit current) can be written as:

$$\vec{S}_{COIL} = \frac{A_{COIL}}{p_m} \cdot \vec{H}_{MAGNET} \quad (3).$$

Here $\vec{S}_{COIL}$ is the sensitivity function of the coil and A_{COIL} is the effective area of the coil. The rotating magnet generates variable magnetization in the casing. The magnetization induces a variable magnetic flux in the coil. Based on the principle of reciprocity, the

corresponding voltage can be expressed as:

$$V_{COIL} = \mu_0 \frac{d}{dt} \left[\int_{CASING \text{ VOLUME}} \vec{M}_{CASING}(\vec{r}, t) \cdot \vec{S}_{COIL}(\vec{r}, t) dv \right] \quad (4),$$

where $\vec{M}_{CASING}$ is the magnetization of the casing, and $\vec{S}_{COIL}$ is the coil sensitivity function.

[0019] In eqn. (4) the sensitivity $\vec{S}_{COIL}$ can be considered as a slowly varying function over the cross-sectional area of the casing. Therefore, we can introduce a magnetization average over the cross-sectional area of the casing as:

$$\langle \vec{M}_{CASING} \rangle = \frac{1}{A_{CASING \text{ CROSS_SECTION}}} \cdot \int \vec{M}_{CASING}(\vec{r}, t) ds \approx \chi_{eff_xy} \cdot \vec{H}_{MAGNET_XY}(\vec{r}_a, t) + \chi_{eff_z} \cdot \vec{H}_{MAGNET_Z}(\vec{r}_a, t) \quad (5),$$

Where χ_{eff_xy} and χ_{eff_z} are the effective magnetic susceptibilities in the direction perpendicular and parallel to the casing axis respectively, A_{CASING} is the effective area of the casing, and $\vec{r}_a$ represents points along the axis of the casing. Due to the shape of the casing we can use the following simplification: $\chi_{eff_xy} \ll \chi_{eff_z}$. This then gives, for the coil voltage, the equation:

$$V_{COIL} = \mu_0 \cdot \chi_{eff_z} \cdot A_{CASING} \cdot \frac{A_{COIL}}{p_m} \cdot \frac{d}{dt} \left(\int_{CASING_LENGTH} |H_{MAGNET_Z}(\vec{r}_a, t)|^2 dr_a \right) \quad (6).$$

This then provides the approximate result

$$V_{COIL} = \frac{3\mu_0 \cdot \chi_{eff_z} \cdot A_{CASING} \cdot A_{COIL} \cdot p_m \cdot \omega}{64\pi^2 \cdot r_0^5} \cdot \cos(2\omega \cdot t) \quad (7).$$

Here A_{CASING} is the cross-sectional area of the casing.

[0020] For practical values $\chi_{eff_z}=100$, $A_{CASING} = 2\pi \cdot 10^{-3} \text{ m}^2$, $\omega = 2\pi \cdot 5 \text{ s}^{-1}$, $A_{COIL} = 0.2 \cdot 200 \text{ m}^2$, $p_m = 1000 A \cdot \text{m}^2$, and separation between wells $r_0 = 10 \text{ m}$, the estimated voltage amplitude $V_m = 48 \text{ nV}$. In case the thermal noise in the coil and the preamplifier noise are the only sources of noise the signal-to-noise ratio per 1 second measurement time can be expected to be around 20. If $r_0 = 5 \text{ m}$, then $V_m = 0.75 \text{ } \mu\text{V}$.

[0021] It is important to note from eqn. (7) that the voltage induced in the rotating coil by the rotating magnetization of the casing has a frequency which is twice the rotation frequency of the magnet/coil assembly. This means that the measured proximity signal is relatively easy to separate from a parasitic signal induced in the rotating coil due to the

earth's magnetic field. The parasitic signal has a frequency equal to the magnet/coil rotation frequency.

[0022] The main sources of error in the measurement technique is due to the presence of some second harmonic in the magnet/coil assembly rotation. In this case the earth's magnetic field related signal would appear at the frequency 2ω thus giving a spurious signal at the same frequency as the expected proximity signal. Fortunately, the presence of 2ω - component in the rotation speed can be assessed with an accelerometer and then the data can be used for eliminating the spurious signal from the measurement results. The second harmonic signal is easy to calculate from the accelerometer output, known value and direction of the earth's magnetic field, and measurements of borehole inclination and azimuth. A gyro survey may be needed to get the borehole inclination and azimuth.

[0023] FIG. 3 illustrates azimuthal dependence of the voltage on the rotating coil 213. Using reference voltage

$$V_{REF} \propto \cos(2\omega \cdot t), \quad (8)$$

synchronized with the magnet/coil rotation, the following expression for the voltage on the coil 213 can be written

$$V_{REF} = V_m \cdot \cos[2(\omega \cdot t + \varphi_0)]. \quad (9)$$

Here φ_0 is the azimuth of the casing with respect to the secondary well.

Thus the phase of the signal on the coil 213 is sensitive to the azimuthal position of the casing 205 with respect to the secondary well 201.

[0024] FIG. 4 is a block diagram illustrating an implementation of the rotational magnetometer. The magnetometer comprises a motor 401 rotating the magnet 203 and the coil 213. The signal from the coil 213 transferred to the low noise preamplifier 409 via an adapter (e. g. sliding rings) 407. Provision is made to eliminate parasitic signal 2ω generated by the Earth's magnetic field in presence of rotational disturbances: the signals from rotational accelerometer 411 and the motor driver 403 are used to eliminate parasitic signals from the measurement data. Serving this purpose are also a controller 405, analog-to-digital converters 413, 417, 419, digital signal processor 415 and a variable gain amplifier 419.

[0025] Those versed in the art and having benefit of the present disclosure would recognize that it is sufficient for the coil 213 to be able to responsive to a component of the magnetic flux due to the induced magnetization that is transverse to the z- axis. The configuration of the coil 213 shown in FIG. 2 is not the only arrangement that would provide a suitable signal, but it is one of the better designs. In principle, an inclined planar coil on the

BHA with the coil axis inclined to the z- axis would work. For a coil placed on the magnet 201 the signal would be greatest when the coil axis is transverse to the z- axis. Similarly, the magnet does not have to be a transversally magnetized cylindrical magnet as indicated by 201. The method would also work, albeit less efficiently, using a bar magnet with its magnetization direction having a component parallel to the z- axis. Those versed in the art and having benefit of the present disclosure would recognize also that a longitudinal coil spaced axially apart from the magnet 201 can be used to receive proximity signal originating from variable Z-component of the magnetization of the casing.

[0026] FIG. 5 illustrates an example of embodiment of the technique that utilizes a pair of additional differentially connected coils 217 synchronously rotating with the magnet/coil assembly. The additional coil assembly is sensitive to non-parallel orientation of the wells, i.e., the output will be zero if the two boreholes are parallel. Any differential pair of identical coils placed asymmetrically with respect to the magnet will also be sensitive to the DC magnetization of the casing (gives additional proximity information) and not sensitive to the Earth's magnetic field. This is particularly useful when it is desired to drill the secondary well to intersect the pre-existing well.

[0027] An important feature of the rotational magnetometer described above is that the source of the magnetic field producing variable magnetization in the magnetic casing does not induce any direct signal in the synchronously rotating coil 213. This makes the induction method with the source and the sensor coil placed in one well feasible. Another way to eliminate the direct field signal is to use transient mode of inducing magnetization in the target casing – transient magnetometer.

[0028] FIG. 6 depicts an embodiment of the transient magnetometer. The magnetometer comprises a source of switchable magnetic field 601 having a switching coil 603 and a magnetic core 605. The magnetic field source 601 generates magnetic field (the isolines of the field are shown at 607) at a position of the target casing 205. The magnetic core 605 preferably comprises a magnetic material with residual magnetization. The residual magnetization is used to provide a strong magnetic dipole without the need for a DC current driving the switching coil and causing a significant energy loss if a strong magnetic field needs to be generated (the application of the magnetic material with residual magnetization in a source of a strong switchable magnetic field is described in US patent application Ser. No. 11/037,488). Disclosed therein is a magnetic core having residual magnetization. Switching the current in the coil results in magnetization reversal in the magnetic core and a change in the magnetic dipole moment. After the magnetization reversal is complete the current is

removed and the new vector of magnetic dipole of remains constant (steady-state phase of the antenna dipole) due to magnetic hysteresis of magnetic material employed for the magnetic core. The magnetometer also comprises a longitudinal coil 609 to pickup a variable magnetic flux produced by the casing magnetization transient occurring in response to switching of the magnetization in the magnetic core 605. The magnetometer further comprises a transversal coil 611, the signal induced in this coil is sensitive to the azimuthal position of the casing with respect to the secondary well 201 when the drill collar rotates.

[0029] FIG. 7 shows time diagrams of the switchable magnetic field and the transient responses in the coil 609. The switchable magnetic field 703 is generated by switching polarity of the residual magnetization in the magnetic core 605. The switching polarity is accomplished by driving the switching coil 603 with short pulses of electric current 701.

Decaying signals 705, 707, 709 (transients) in the coil 609 are generated in response to a fast switching off or changing polarity of a “static” magnetic field. The signals are associated with direct coupling between the source and the sensing coil (transient at 705), the signal due to eddy currents in the surrounding rock formations and the conductive collar of the drill string (a conductive body) placed in the well 201 (transient at 707), and casing proximity signal due to variable magnetization of the magnetic casing 205 (transient at 709). It is important for the method that the proximity signal 709 is substantially longer than the undesired signals 705 and 707. It follows from the fact that a time constant of the transient decay is proportional to the effective magnetic permeability of a magnetic conductor. It is to be noted that unlike in the first embodiment, the direction of the magnetic field does not rotate—it only switches polarity. As the coil 609 is also longitudinal, no sinusoidal variation will occur.

[0030] The following expression for the time constant of building up of the average (over the cross-sectional area) magnetization of the casing can be used [see, for example, Polivanov, K.M. *Elektrodinamika veshchestvennykh sred*, 1988]

$$\tau \propto \delta^2 \cdot \mu_0 \cdot \mu \cdot \sigma . \quad (10)$$

Here δ is the wall thickness of the casing, μ is the magnetic permeability, which is about 100 for a typical casing material, and σ is the conductivity of the material of the casing. The process of building up of the magnetic flux in the coil 609 is exponential with the time constant given by eqn.(10). By the time approximately equal to the time constant of the casing magnetization process all other transients will substantially decay. Thus, by measuring the signal in a time window (at 711) starting after a time comparable with the time

constant of building up of the casing magnetization (time window 711) one effectively eliminates all undesired signal. The expected time constant of the direct coupling is of the order of the duration of the pulses 701. In one embodiment, the area within the window is used as a distance indicator. Appropriate calibration is carried out. The processes due to the eddy current in the conductive surroundings are in the range 1-100 μ s. The signal from the magnetic casing should last approximately 10-30ms. Thus practical acquisition window may be positioned between 1ms and 50 ms. Those versed in the art and having benefit of the present disclosure would recognize that it is sufficient that the magnet has a longitudinal component, and the coil is oriented so that is responsive to magnetic flux changes in the longitudinal direction.

[0031] FIG. 8 illustrates an embodiment of the disclosure in secondary recovery operations. A producing wellbore 820 has been drilled into a reservoir interval 801 that contains hydrocarbons. For various reasons, such as low formation pressure or high viscosity of the hydrocarbons in the reservoir, production under natural conditions of hydrocarbons may be at uneconomically low rates. In such cases, a second wellbore 822 is drilled, typically as a side bore from the wellbore 820 so as to be substantially parallel to the main wellbore within the reservoir. The producing wellbore is typically cased with casing 830 that has perforations 834. Fluid, such as water, CO₂ or steam is then injected into the formation through the secondary wellbore 822 and the injected fluid drives the hydrocarbons in the formation towards the producing wellbore 820 where it may be recovered. Such an operation requires careful positioning of the secondary borehole 822 in proximity to the production wellbore 820. This may be done by monitoring the voltage in the coil. As can be seen from eqn. (7), the voltage varies inversely as the fifth power of the distance. Thus, the voltage measurements may be used as either relative distance indicators based on voltage changes, or, with proper calibration, as absolute distance indicators.

[0032] FIG. 9 shows an embodiment for a radial magnet-coil arrangement 900 that includes two identical or substantially identical receiver coils symmetrically installed on the surface of the magnet for estimating distance between adjacent wellbore or boreholes. In this embodiment 900 the coil or coil arrangement 913 includes two coils 913a and 913b that are symmetrically or substantially symmetrically co-located (installed or placed) around or about the centerline of the magnet 203 and/or drill collar 201. The radial magnetic field or flux 221 from the magnet 203 magnetizes the offset well casing 205. The magnetic flux 223 from the casing 205 is received by both coils 913a and 913b. This configuration, in aspects, may

maximize the receiver signal and minimize the size of the rotational magnet/coil assembly. Such a small size magnet/coil assembly may be installed on the drill bit or just above the drill bit and below (downhole) the mud motor. In aspects, such an arrangement is more desirable than attaching the magnet/coil on the drill collar because in high stick-slip situations the rotational speed of the drill collar 201 can induce large parasitic noise. With the magnet/coil assembly on the drill bit, the magnet/coil arrangement can still be rotated at a fairly constant speed using the mud motor. Pulling the drill bit a little uphole or back can be useful because the drill bit is then not in contact with bottom of the borehole. The configuration 900 continuously provided the distance between the drill collar 201 and the casing 205 while drilling the second borehole, which measurement may be used to monitor placement of the second borehole with respect to the first borehole.

[0033] To estimate the distance between the drill collar 201 and the casing 205 (r_1 from center of the drill collar 201 to the center of the casing), signals from both the coils 913a and 913b are measured. Differential signals between coils 913a and 913b are obtained while rotating the drill collar 201. Due to the fact that the earth's magnetic field is spatially homogeneous while the signal from the rotating magnetization of the casing is spatially inhomogeneous, the parasitic signal from the earth's magnetic field is substantially removed from the differential signals, leaving a significant portion of signal from the rotating magnetization of the casing for further processing. A controller downhole and/or at the surface may be utilized for processing the coil signals for determining the distance between the boreholes. The controller may be a microprocessor based circuit and includes memory devices and programmed instructions for determining the distance. Such circuits are known in the art and are thus not described in detail herein. The distance from the center of the coil 913 to the center of the casing is shown as " r "₂ while the distance between the surfaces of the drill collar and the casing is shown as " d ."

[0034] FIG. 10 shows yet another embodiment of a radial magnet-coil arrangement 1000 that includes two coils, each coil further containing a pair of coils, radially symmetrically offset at two sides of the rotating magnet 203. In the embodiment 1000, a first coil 1015 containing a first pair of identical or substantially identical coils 1015a and 1015b are placed a distance " d_1 " from the center of magnet 203 away from one end 203a and a second coil 1017 containing a second pair of coils 1017a and 1017b are placed at the distance d_1 away from the second end 203b of magnet 203. The coils 1017a and 1017b are identical or substantially identical to coils 1015a and 1015b. Thus in the embodiment 1000, there are two pairs of radial coils, offset equally at two sides of the rotating magnet. The magnet/coil

configuration 1000 provides two distance-to-casing measurements (one corresponding to each pair) whose differentials may be utilized to estimate the distances and also determine the angle of the drill collar 201 with respect to the casing 205. Therefore, this configuration may be utilized intermittently when drilling is temporarily stopped (for example when drill pipe sections are being added) to determine the angle between the drill collar 201 and the casing 205 or the inclination of the drill collar 201 relative to the casing 205. The determined angle or relative angle or the inclination may then be utilized to steer or guide the next drilling section, i.e. till the next angle or inclination measurements. When the receiver coils 1015 and 1017 are axially offset from the magnet 203, the signal in the receiver coils 1015a, 1015b, 1017a and 1017b will generally be less than signals in the receiver coils 913a and 913b because the receiver coil voltage is now dependent also on the axial offset. This means the efficiency of this configuration will decrease as the axial offset increases.

[0035] As shown by the magnetic flux lines 221 and 223 in FIGS. 9 and 10, the magnetic field from the magnetized casing 205 is inhomogeneous not only radially from the casing 205 but also axially along the direction parallel to the casing 205. FIG. 11 shows an exemplary graph 1100 of the magnetic flux 1110 at the receiver 215 or 217 as a function of the receiver axial offset 1120, i.e. (in this case two meters) between the receiver and the rotating magnet 203 shown in FIG. 10, wherein the distance between the drill collar 201 and the casing 205 (the casing offset) is five (5) meters. For example, the receiver magnetic flux at zero axial offset 1112 is $3.60\text{e-}11$ Webb, while the receiver magnetic flux at two (2) meters axial offset 1114 is $2.49\text{e-}11$ Webb. Therefore, by taking differential signals between a pair of receivers at these two locations provides almost 31% of the remaining casing signal, which is significantly greater than the remaining signal (3.75%) for the radial signal.

[0036] FIG. 12 shows an exemplary axial coil configuration 1200. In the particular configuration of FIG. 12, three identical or substantially identical receiver coils 1213, 1215 and 1217 are installed on the drill collar 201 with equal spacing d_2 . The middle coil 1213 is collocated with the rotating magnet 203, while coil 1215 is offset on one side of the magnet 203 and coil 1217 on the other side. Two sets of differential signals between coil pairs 1215/1213, and 1213/1217 may be generated and utilized for determining the distance as well as the relative angle between the drill collar 201 and the casing 205.

[0037] An advantage of the axial configuration 1200 of FIG. 12 is that there is no physical limitation on the axial offset between the coils, while for the radial design the offset is limited by the diameter of the drill collar so the effectiveness of the radial gradiometer cannot be made very high. A disadvantage may be that the bending/twisting/vibration of the

drill collar may introduce relatively strong parasitic noise when the coils are axially separated. As a result, it may be more difficult to balance the magnetic moments of the coils for the axial configuration than for the radial configuration.

[0038] FIG. 13 shows an exemplary hybrid coil configuration 1300. In the particular configuration of FIG. 13, three identical or substantially identical receiver coils 1313, 1315 and 1317 are installed on the drill collar 201 with equal spacing d_3 . Each such coil arrangement is shown to include a pair of two identical or substantially identical coils. For example, coil 1313 includes a pair 1313a and 1313b, coil 1315 includes a pair 1315a and 1315b and coil 1317 includes a pair 1317a and 1317b. The middle coil 1313 is collocated with the rotating magnet 203, while coil 1315 is offset on one side of the magnet 203 and coil 1317 on the other side. Two sets of differential signals between coil pairs 1315/1313, and 1313/1317 may be generated and utilized for determining the distance as well as the relative angle between the drill collar 201 and the casing 205. These measurements provide measurements for both the radial and axial configurations. For example, when differential signals are obtained, coil pairs 1313a and 1313b, 1315a and 1315b and 1317a and 1317b may be viewed as three radial configurations as shown in FIG. 9. However, when signals from each pair are combined, the three coil 1313, 1315 and 1317 would function as an axial configuration as, shown in FIG. 12.

[0039] Although coils, such as coils 1015, 1017, 1313, 1315 and 1317 are shown to include two coils, more than two coils and suitable differential measurements may be utilized for the purposes of this disclosure. Also, the spacing from the magnet to the coils may be different. Additionally, the hybrid and other configurations provide more options and combinations of measurements so that the tool performance may be optimized for a particular drilling environment. Additionally, the embodiments discussed thus show the use of coils as detectors, magnetometers may also be used to detect the secondary magnetic field and the signals do detected may be processed to determine the distance between boreholes and the inclination a borehole.

[0040] In the coil configurations shown in FIGS. 2 and 5, the rotating magnet from a second borehole produces a time varying magnetic field in a first borehole. A coil in the second borehole is then used to produce a signal responsive to a magnetic flux resulting from the magnetization of the casing from the first borehole. Since the signal induced by the rotating magnetization of the casing has a frequency which is twice the rotation frequency of the magnet/coil assembly, the measured proximity signal is separated from a parasitic signal induced in the rotating coil due to the earth's magnetic field, which has a frequency equal to

the magnet/coil rotation frequency. However, in often the rotational speed of the magnet/coil assembly is not perfectly stable and therefore the parasitic signal from the earth's magnetic field may have spectral component at twice the rotation frequency of the magnet/coil assembly. Such parasitic signal cannot be removed by a frequency-domain filter and may remain as a major source of noise in the final result.

[0041] The coil configurations shown in FIGS. 9, 10, 12 and 13 may reduce the parasitic signal from the earth's magnetic field and therefore improve the signal-to-noise ratio of the measurement. In these configurations, the receiver coils with substantially equal magnetic moments are installed either radially-symmetrical or axially offset along the drill collar. The magnetic moments of the receiver coils may be stabilized at (near) identical through surface or down-hole real-time calibration. Differential signal between a pair of receivers is processed for estimating the distance and the angle between two boreholes or objects. Since the earth's magnetic field is spatially homogeneous, the parasitic signal from the earth's magnetic field in the two substantially identical receiver coils should be substantially equal and therefore cancel out. However, the signal induced by the rotating magnetization of the casing will not entirely cancel out because it is spatially inhomogeneous. Therefore, by taking the differential measurement, the noise from the earth's magnetic field is substantially removed, but a significant portion of the signal from the magnetized casing still remains for processing. The signal-to-noise ratio of the final measurement is thus improved.

[0042] An example of improvement in the signal to noise ratio is provided below. When the receiver coils are collocated with the rotating magnet, the approximate result of the receiver voltage takes the following form:

$$V_{tot}(t) = V_e \sin(\omega t) + V_c \sin(2\omega t + \varphi_0), \text{ where} \quad (11)$$

$$V_e = \omega A_{COIL} B_e, \text{ and}$$

$$V_c = \frac{45\mu_0 \cdot \chi_{eff_z} \cdot A_{CASING} \cdot A_{COIL} \cdot p_m \cdot \omega}{2048\pi \cdot r_1^{2.5} \cdot r_2^{2.5}} \quad (12)$$

Wherein:

V_e is the amplitude of signal from the spatially homogeneous magnetic field of the Earth B_e ;

V_c is the amplitude of signal from the rotating magnetization of the target casing from the permanent magnet in the well being drilled, which has a strong spatial gradient;

φ_0 is the angle between the Earth's magnetic field vector and the vector pointing from the well being drilled to the target casing, projected on the plane that is perpendicular to the surface of the receiver coils;

μ_0 is the vacuum permeability;

χ_{eff_z} is the effective magnetic susceptibility of the casing;

A_{CASING} is the cross-sectional area of the casing;

A_{COIL} is the area of the receiver coil;

p_m is the magnetic moment of the rotating magnet;

ω is the angular frequency of the magnet/coil assembly;

r_1 is the distance between the rotating magnet and the casing;

r_2 is the distance between the casing and the receiver coil.

Assume that the magnet 203 is symmetric around the drill collar 201 so r_1 does not vary during rotation. If the distance between the center of the drill collar 201 and the casing 205 is five (5) meters, the diameter of the drill collar is 15 centimeters, then r_2 varies approximately in the range of 5 ± 0.075 m as the receiver coil rotates with the drill collar. In the radial configuration, two substantially identical coils mounted on opposite sides of the drill collar in a radially symmetric manner, and signals from the two coils are differentially combined.

According to Equation 12, the residual V_c from the variation in r_2 is approximately $\frac{2.5d}{2r_2} \sim 3.75\%$ of V_c from a single coil. Assume that the magnetic moments of the receiver coils are calibrated to be differed within 1%, then the amplitude of the differential V_e signal from the homogeneous earth's magnetic field is now only 1% of that from a single coil. In summary, for this particular case, by using the gradiometer-type of measurement, the signal-to-noise ratio can be improved by a factor around 3.75. In the axial configuration, the difference in the voltages of two coils may be expressed as:

$$v(t) = V_{COIL1}(t) - V_{COIL2}(t) = \omega A_{rec} (B_c(l_1) - B_c(l_2)) \sin(2\omega t + \phi_0) \quad (13)$$

Where, l is the axial offset between the magnet and the receiver coil. Equation 13 shows that the signals due to the earth's magnetic field is removed by differentiating the measurements of the two coil signals, while a significant part of the casing signal remains for processing. The signal amplitude at different axial offset l can be determined from FIG. 11 (assuming for example $r_1 = r_2 = 5m$).

[0043] The signal-to-noise ratio may be further improved by better calibration of the receiver coil moments, and by using a drill collar with a greater diameter. It is also possible to implement an asymmetric magnet so r_1 varies in phase with r_2 during rotation, but this generally leads to a smaller total moment of the magnet and therefore a reduction of signal strength.

[0044] FIG. 14 shows an embodiment for a radial magnet-sensor arrangement 1400 for estimating distance between adjacent wellbore or boreholes. The arrangement 1400 may

be on a drill collar 1410 of a downhole tool, such as drilling assembly 190, FIG. 1, used for drilling a wellbore or may be in the form of a sub of the drilling assembly. A magnetic member 1450, such as a metallic casing, in a preexisting wellbore is shown proximate the sub 1400. Referring to FIGS. 1 and 9, the sub 1400 includes a magnet 1420 placed around a member 1410 of the sub 1400. In one configuration, the magnet 1420 may be a permanent magnet placed around the member 1410 that generates uniform magnetic field 1422 that is induced the magnetic member 1450 when the drilling assembly (190, FIG. 1) is used to drill the wellbore. In one configuration, the magnet 1420 rotates when the sub 1400 rotates with the drilling assembly (190, FIG. 1). In another embodiment, the magnet 1420 may be rotated independent of the drilling assembly rotation at a desired rotational speed that may be differ from the rotational speed of the sub 1400. The magnet 1420, in one embodiment, may be rotated by an electrically- or hydraulically-operated motor. The magnet 1420, when rotated independent of the sub 1400, is referred to herein as a detachable or detached magnet. When the magnet 1420 rotates, it produces the uniform magnetic field 1422 (P_m) around the member 1410, which induces a primary magnetic field in the magnetic member 1450. The sub 1400 further includes a sensor 1430 associated with the sub 1400. In one aspect, sensor 1430 may include one or more magnetometers 1430a-1430n placed around the member 1410. In one configuration, sensors 1430a-1430n may be equally spaced. Any suitable number of sensors (for example 2-16) may be utilized. In one configuration, sensor 1430 or sensors 1430a-1430n may be placed on a non-rotating sleeve around member 1410 so that the sensors are stationary or substantially stationary relative to the rotation of the magnet 1420. In another configuration, sensor 1430 or the sensors 1430a-1430n may rotate relative to the magnet 1420 at a selected rotational speed that is different from the rotational speed of the magnet 1420. The sensor 1430 or sensors 1430a-1430n may be rotated by any suitable device, including electrically- or hydraulically-operated motor. In another aspect, a secondary or bucking magnet 1440 having a magnetic field P_b may be placed between the magnet 1420 and sensor 1430 or sensors 1430a-1430n oriented in a manner to reduce or substantially cancel the effect of the magnetic field P_m on the sensor 1430 or sensors 1430a-1430n. The distance between the sensor 1430 and the bucking magnet is shown as r_b , while the distance between the magnet 1420 and the sensor 1430 is shown as r .

During drilling, in one embodiment, the magnet 1420 rotates, while the sensor 1430 or sensors 1430a-1430n remain stationary or substantially stationary relative to the magnet 1420. Sensor 1430 or sensors 1430a-1430n receive secondary magnetic field 1424 responsive to the primary magnetic field induced in the casing 1450 and provide signals representative of

the received secondary magnetic field. The secondary magnetic field B_θ received at a particular sensor may be designated by its relative location, such as B_0 , B_{90} , etc.

[0045] FIG. 15 shows an embodiment that utilizes electrical coils 1530a-1530n that provide electrical voltages V_θ (V_0 , V_{90} , etc.) corresponding to the received secondary magnetic field. Any suitable number of equispaced coils may be provided around the drill coil. The coils may be stationary, substantially stationary or rotate at a rotational speed that differs from the rotational speed of the magnet 1420. As in the configuration shown in FIG. 14, the magnet 1420 induces a primary magnetic field 1422 in the casing 1450. The coils 1530a-1530n provide voltage signals corresponding to secondary magnetic field 1424. The voltage signals are processed by a downhole and/or surface controller to estimate the distance D between the drilling assembly 1500 and the preexisting well 1450. In aspects, the distance D may be determined as follows.

[0046] The bucked magnetic response for a rotating magnet and stationary sensor may be derived as follows:

$$B_0 = A \cos(\omega t + \theta - 2\psi) + (A + B_{bucking}^{residual}) \cos(\omega t - \theta) + B_L \cos(\theta - \phi) + B_r(\theta) \quad (14)$$

$$0^\circ \leq \theta \leq 360^\circ$$

where $A = \frac{45\mu_0(\mu_r-1)p_m A_{casing}}{4096\pi D^5}$

and wherein:

A_{casing} is the cross area of magnetic casing,

μ_r is casing magnetic permeability

p_m is moment of permanent magnet

D is distance to casing

B_L is lateral earth magnetic field

$B_{bucking}^{residual}$ is residual effect from imperfect bucking

$B_r(\theta)$ is magnetic fields from residual magnetic charge distribution on casing

θ is azimuth angle of receiver moment direction

ψ is direction angle from a first borehole to a second borehole

ϕ is direction angle of earth magnetic field

In the above derivation, it is assumed that a bucking magnet cancels or bucks out the direct magnetic field from the primary magnet while the casing signal from the bucking magnet is small enough and can be neglected.

[0047] The data received at evenly distributed times t_i may be processed as follows:

$$B_{\theta_j}^{t_i} = A \cos(\omega t_i + \theta_j - 2\psi) + (A + B_{bucking}^{residual}) \cos(\omega t_i - \theta_j) + B_L \cos(\theta_j - \phi) + B_r(\theta_j) \quad (15)$$

where $\theta_j = \{0^\circ \ 45^\circ \ 90^\circ \ 135^\circ \ 180^\circ \ 225^\circ \ 270^\circ \ 315^\circ\}$

Using a matrix-vector format:

$$\vec{B} = M \cdot \vec{S}$$

where

$$\vec{B} = (B_{\theta_j}^{t_i} - B_{\theta_j}^{t_{i-1}}), \quad I = 1, 2, \dots N$$

M

$$= (\cos(\omega t_i + \theta_j) - \cos(\omega t_{i-1} + \theta_j) \quad \sin(\omega t_i + \theta_j) - \sin(\omega t_{i-1} + \theta_j) \quad \cos(\omega t_i - \theta_j) - \cos(\omega t_{i-1} - \theta_j))$$

$$\vec{S} = (s_1 \ s_2 \ s_3)^T = (A \cos 2\psi \ A \sin 2\psi \ C)^T$$

The solution vector is then may be solved as follows:

$$\vec{S} = (M^T \cdot M)^{-1} \cdot M^T \cdot \vec{B}$$

Then, we have $A = \sqrt{s_1^2 + s_2^2}$

$$\psi = \frac{1}{2} \tan^{-1} \frac{s_2}{s_1}$$

Further, the distance D can be determined from A.

[0048] The bucked voltage response for a rotating magnet and stationary coils mat be expressed as:

$$V_\theta = V_s \sin(\omega t + \theta - 2\psi) + (V_s + V_{bucking}^{residual}) \sin(\omega t + \theta) \quad (16)$$

$$0^\circ \leq \theta \leq 360^\circ$$

Wherein

$$V_s = \frac{45\mu_0(\mu_r - 1)p_m A_{casing} A_{coil}}{4096\pi D^5}$$

and wherein:

ω is angular frequency of rotation

μ_r is casing magnet permeability

p_m is moment of permanent magnet

A_{casing} is cross-section area of casing

A_{coil} is cross-section area of coil

D is distance to casing.

$V_{bucking}^{residual}$ is residual effect from imperfect bucking

The data processing relating to voltage signals to determine the distance may be performed as

follows:

$$V_{\theta_j}^{t_i} = V_s \sin(\omega t_i + \theta_j - 2\psi) + (V_s + V_{bucking}^{residual}) \sin(\omega t_i - \theta_j) \quad (17)$$

where $\theta_j = \{0^\circ \ 90^\circ\}$

$t_i \ \{i = 1 \dots N\}$ are evenly distributed in a matrix-vector format

$$\vec{V} = M \cdot \vec{S}$$

where

$$\vec{V} = (V_{\theta_j}^{t_i})$$

$$M = \begin{pmatrix} \sin(\omega t_i + \theta_j) & -\cos(\omega t_i + \theta_j) & \sin(\omega t_i - \theta_j) \end{pmatrix}$$

$$\vec{S} = (s_1 \ s_2 \ s_3)^T = (V_s \cos 2\psi \ V_s \sin 2\psi \ C)^T$$

The solution vector can be solved as follows:

$$\vec{S} = (M^T \cdot M)^{-1} \cdot M^T \cdot \vec{V}$$

Then, we have $V_s = \sqrt{s_1^2 + s_2^2}$

$$\psi = \frac{1}{2} \tan^{-1} \frac{s_2}{s_1}$$

Further D can be determined from V_s .

[0049] The processing of the data may be performed by a downhole processor to give corrected measurements substantially in real time. Implicit in the control and processing of the data is the use of a computer program on a suitable machine readable medium that enables the processor to perform the control and processing. The machine-readable medium may include ROMs, EPROMs, EEPROMs, Flash Memories and Optical disks.

[0050] While the foregoing disclosure is directed to the preferred embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.

CLAIMS

1. A method of determining a distance between a first borehole and a second borehole, the method comprising:
 - inducing a primary magnetic field in a magnetic object in the first borehole using a rotating magnet in the second borehole;
 - detecting a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field using a substantially stationary sensor in the second borehole;
 - and
 - determining the distance between the first borehole and the second borehole from the detected magnetic field.
2. The method of claim 1 further comprising determining an orientation of the second borehole relative to the first borehole using the detected magnetic field.
3. The method of claim 1 further comprising providing a bucking magnet between the rotating magnet and the substantially stationary sensor to reduce an effect of direct magnetic field from the rotating magnet on the substantially stationary sensor.
4. The method of claim 1, wherein the sensor is selected from a group consisting of: a magnetometer; and a coil.
5. The method of claim 1, wherein the sensor includes a plurality of sensors placed circumferentially spaced apart on a drilling tool in the second borehole.
6. The method of claim 1, wherein the sensor or magnet is detachably placed around a drilling tool.
7. The method of claim 1 further comprising rotating the rotating magnet at a plurality of rotational angles.
8. The method of claim 1 further comprising drilling the second borehole relative to the first borehole using the determined distance.
9. An apparatus for determining a distance between a first borehole and a second borehole during drilling of the second borehole, comprising:
 - a magnet on a drilling tool that rotates in the second borehole to induce a primary magnetic field in a magnetic object in the first borehole;
 - a substantially stationary sensor on the drilling tool that detects a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field; and
 - a controller that determines the distance between the first borehole and the second borehole from the detected magnetic field.

10. The apparatus of claim 9, wherein the controller determines an orientation of the second borehole relative to the first borehole using the detected magnetic field.

11. The apparatus of claim 9 further comprising a bucking magnet between the rotating magnet and the substantially stationary sensor that reduces an effect of direct magnetic field from the rotating magnet on the substantially stationary sensor.

12. The apparatus of claim 9, wherein the sensor is selected from a group consisting of: a magnetometer; and a coil.

13. The apparatus of claim 9, wherein the sensor includes a plurality of sensors placed circumferentially spaced apart on the drilling tool.

14. The apparatus of claim 9, wherein one of the sensor and the magnet is detachably placed around a drilling tool.

15. The apparatus of claim 9, wherein the magnet is configured to rotate at a plurality of rotational angles.

16. The apparatus claim 9 further comprising an additional sensor placed spaced apart from the sensor for detecting the secondary magnetic field from the magnetic object responsive to the induced primary magnetic field and wherein the controller:

determines the distance between the first borehole and the second borehole from the magnetic field detected by the additional sensor; and

determines an orientation of the second borehole with respect to the first borehole from the distances determined from the magnetic fields detected by the sensor and the additional sensor.

17. A method of determining a distance between a first borehole and a second borehole, the method comprising:

inducing a primary magnetic field in a magnetic object in the first borehole using a magnet in the second borehole rotating at a first rotational speed;

detecting a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field using a magnetometer in the second borehole rotating at same rotational seed; and

determining the distance between the first borehole and the second borehole from the detected magnetic field.

18. An apparatus for determining a distance between a first borehole and a second borehole, the method comprising:

a drilling tool having a magnet configured to rotate at a first rotating speed for inducing a primary magnetic field from the second borehole into a magnetic object in the first borehole;

a sensor on the drilling tool rotating at a second rotating speed for detecting a secondary magnetic field from the magnetic object responsive to the induced primary magnetic field, wherein the first rotational speed and second rotational speed are different; and

a controller that determines the distance between the first borehole and the second borehole from the detected magnetic field.

19. The apparatus of claim 18, wherein the sensor is selected from a group consisting of a: magnetometer and coil.

20. The apparatus of claim 18, wherein the sensor includes a plurality of circumferentially spaced apart sensors on the drilling tool.

21. The apparatus of claim 18, wherein one of the magnet and the sensor is detachably placed on the drilling tool.

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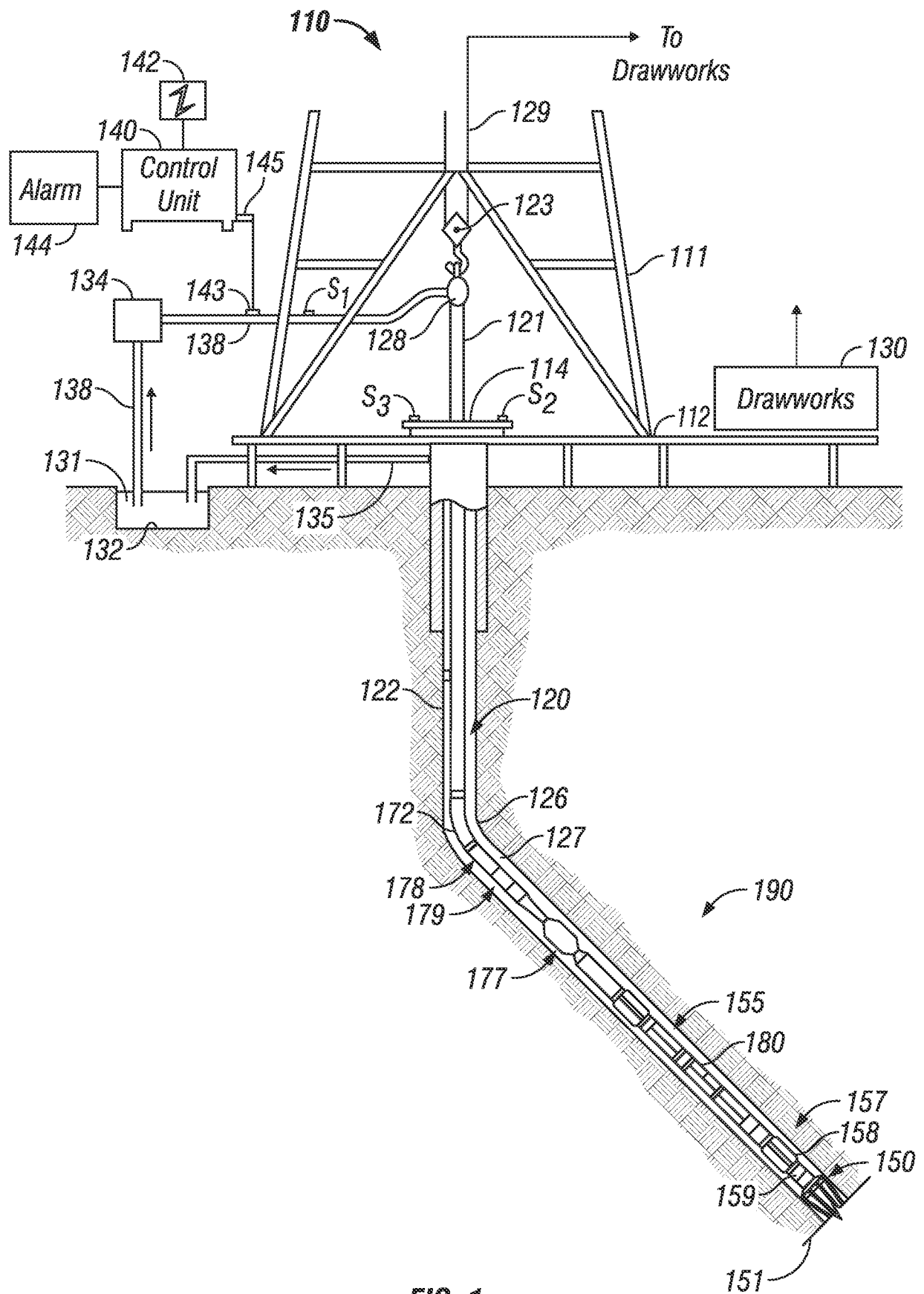


FIG. 1

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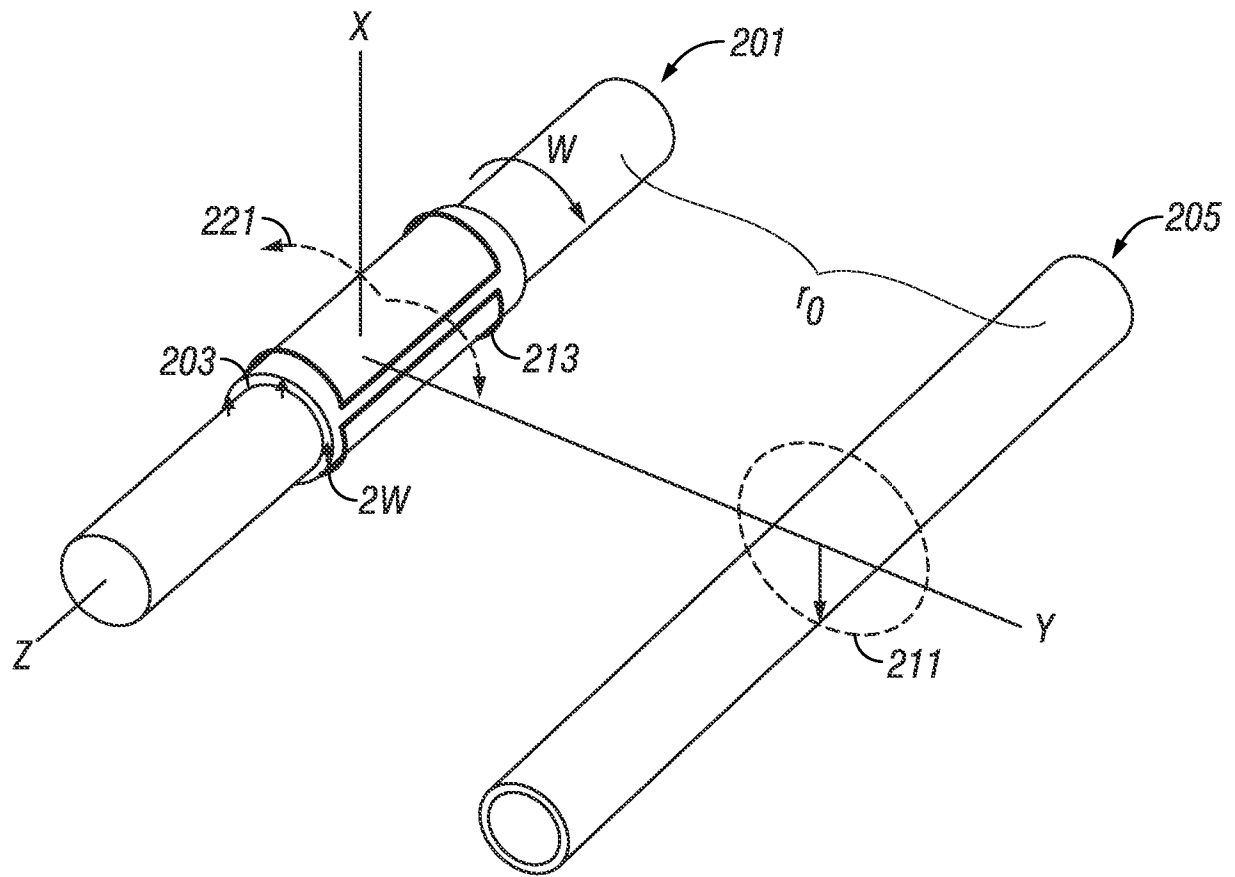


FIG. 2

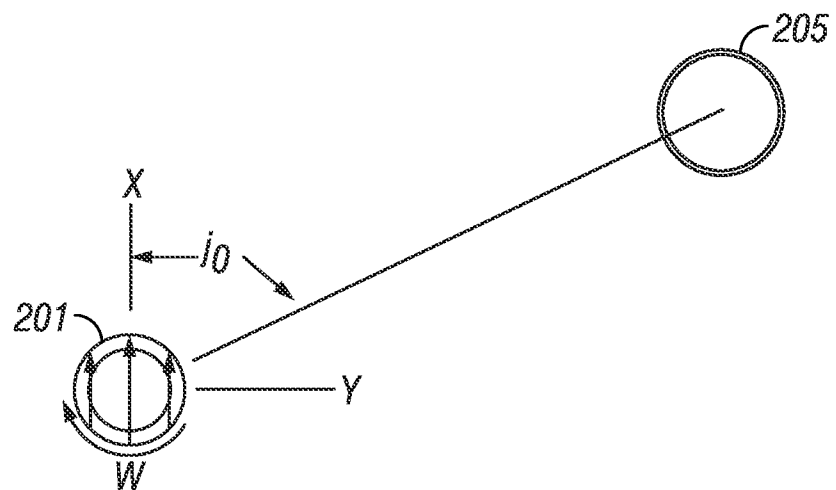
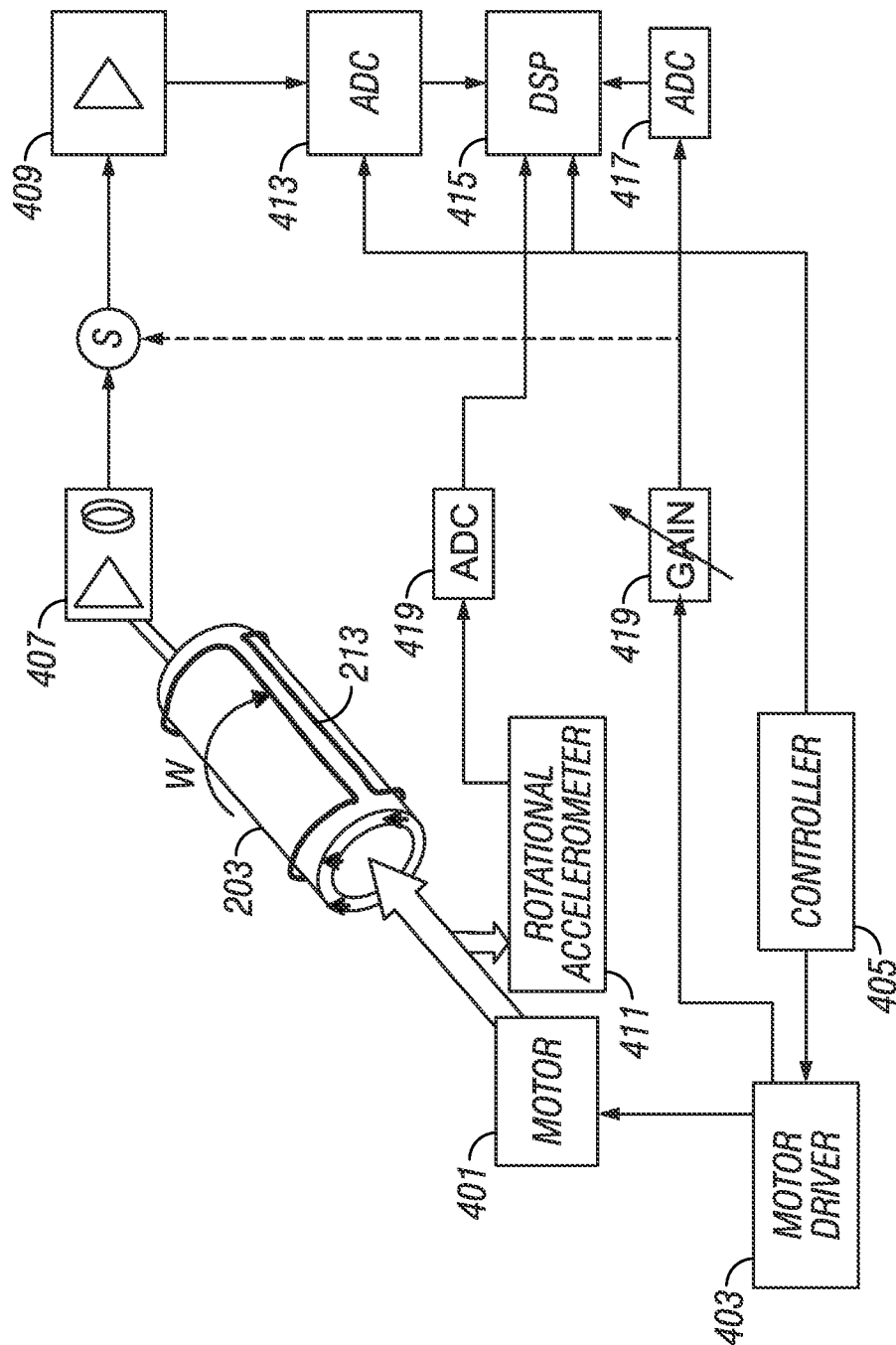


FIG. 3

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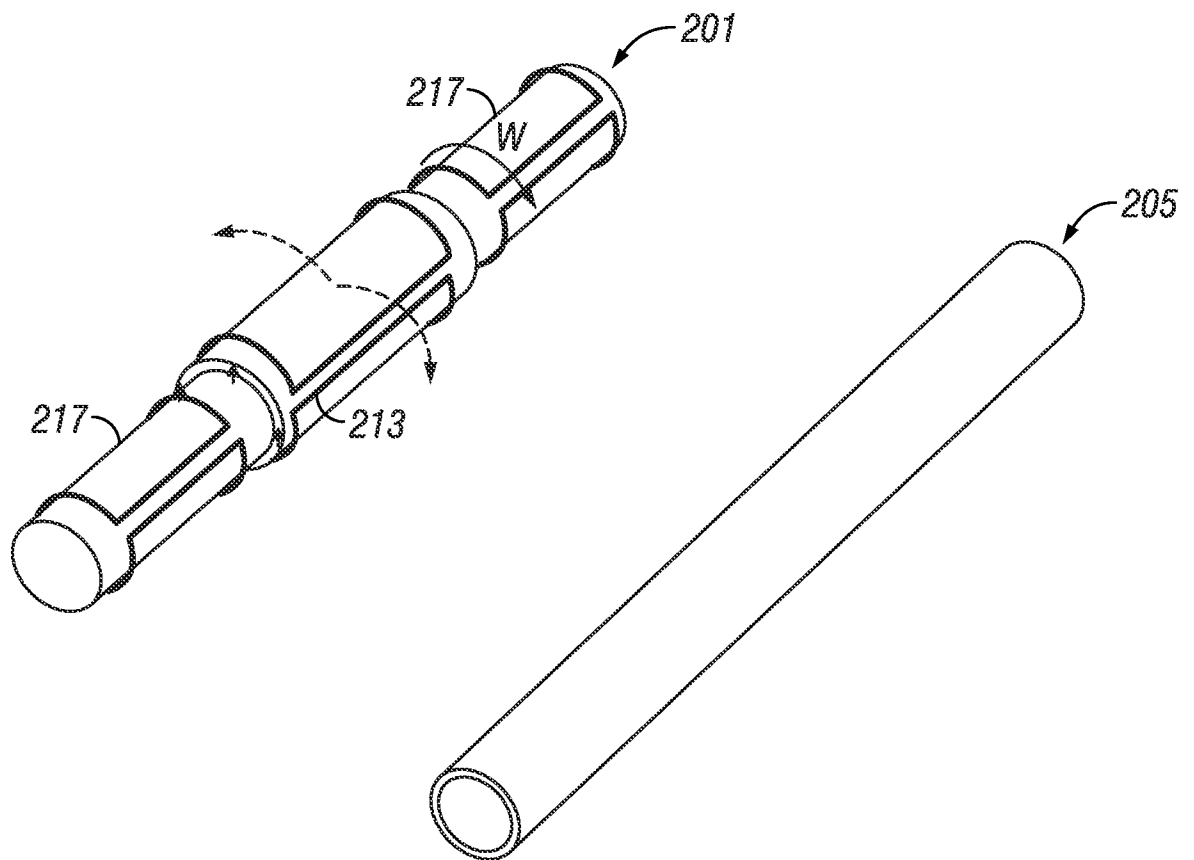


FIG. 5

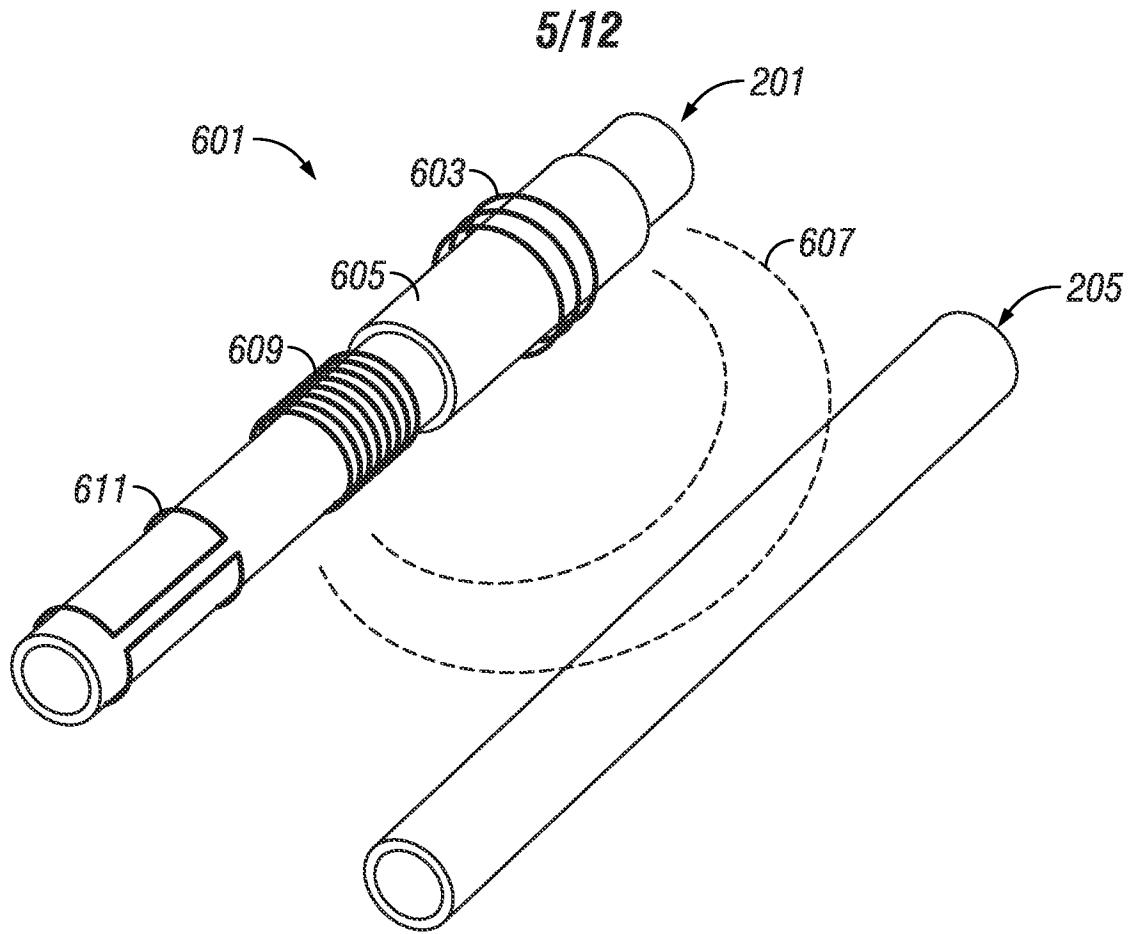


FIG. 6

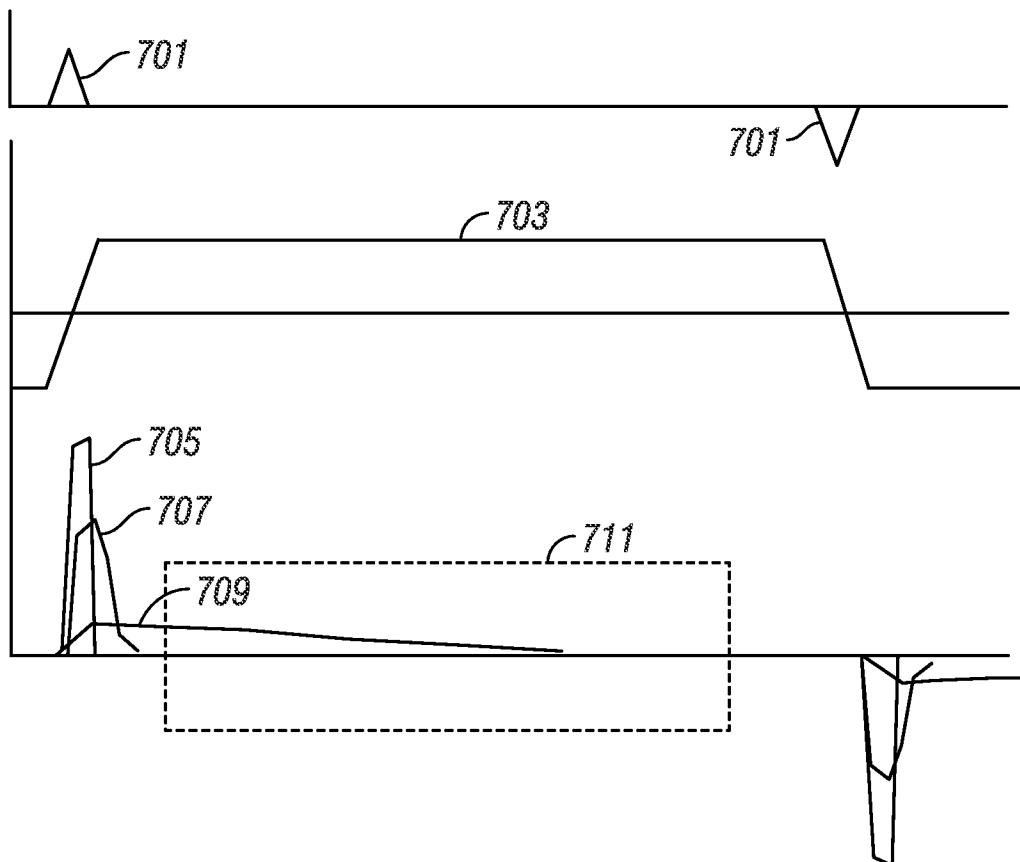


FIG. 7

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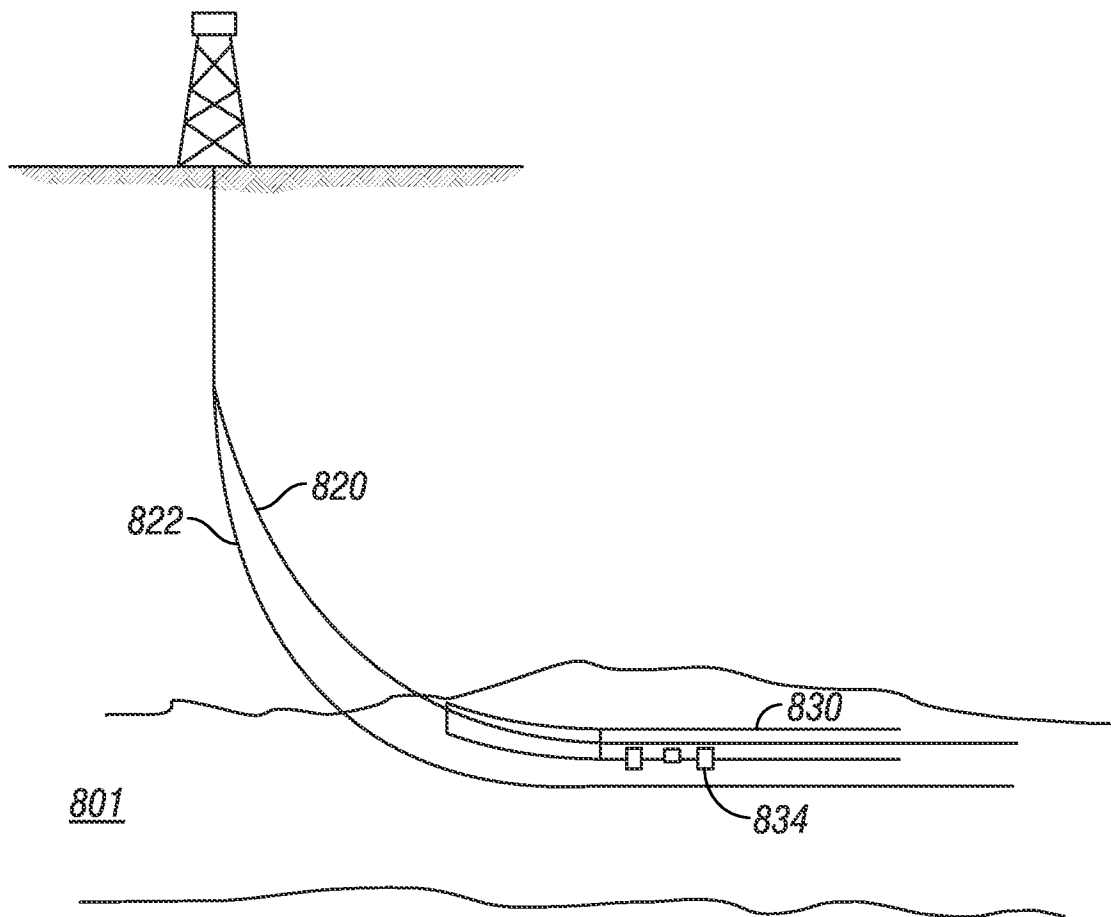


FIG. 8

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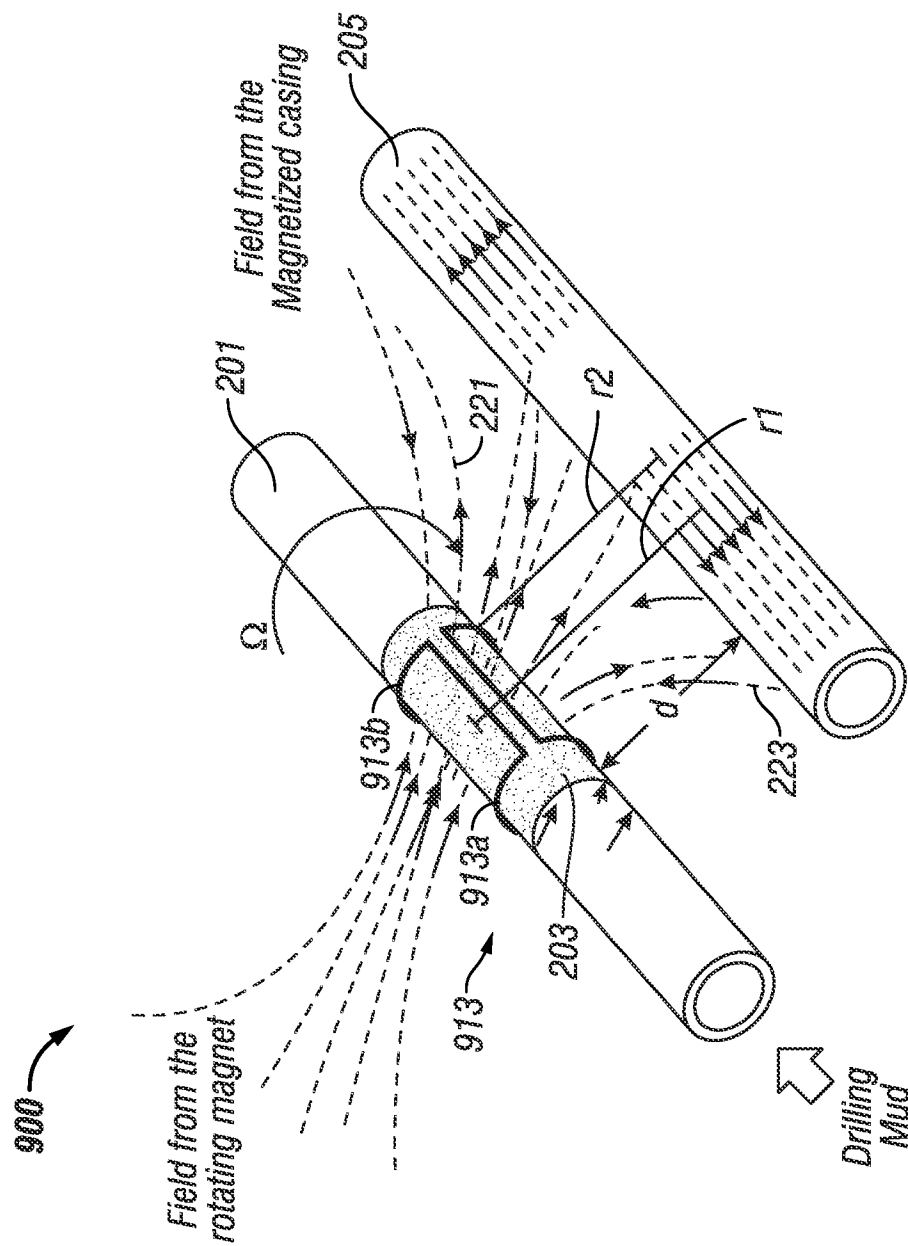


FIG. 9

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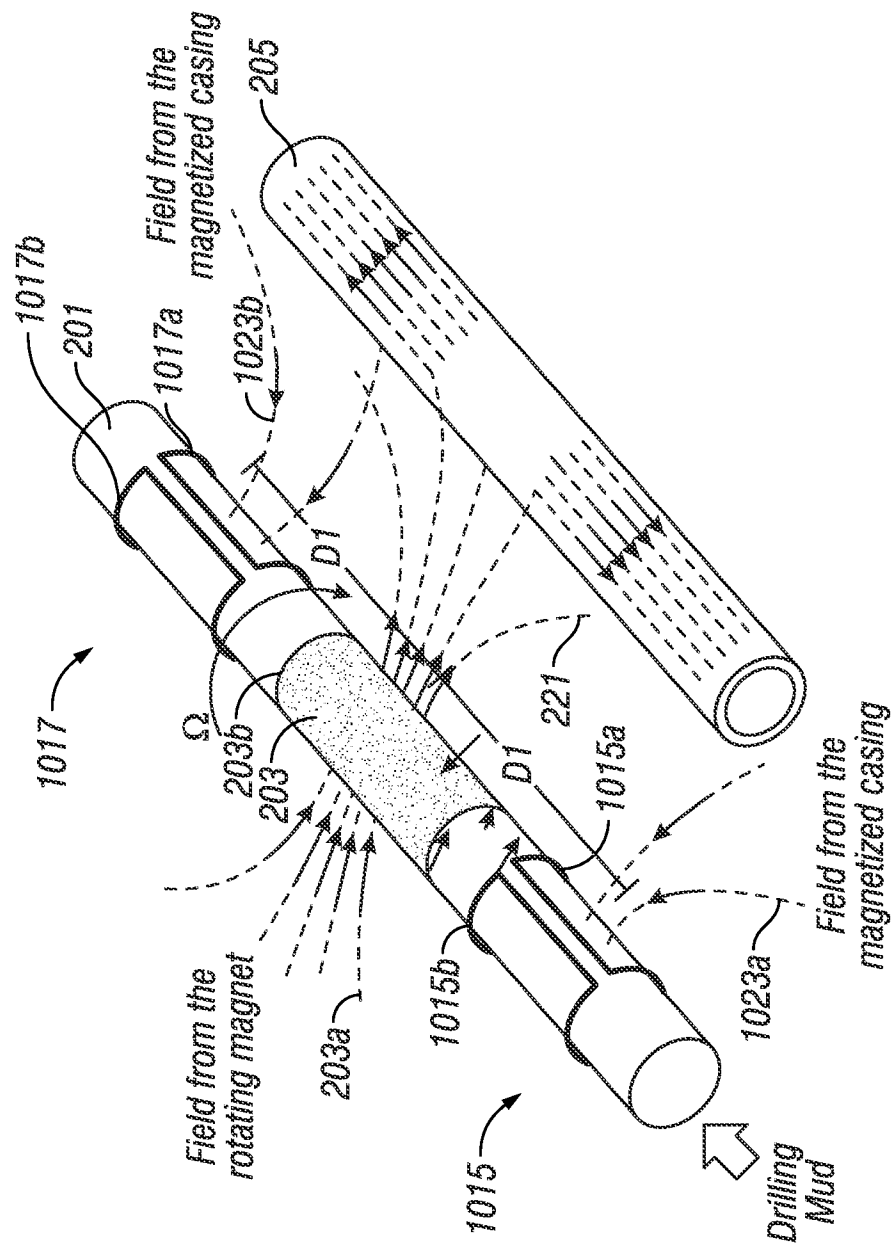


FIG. 10

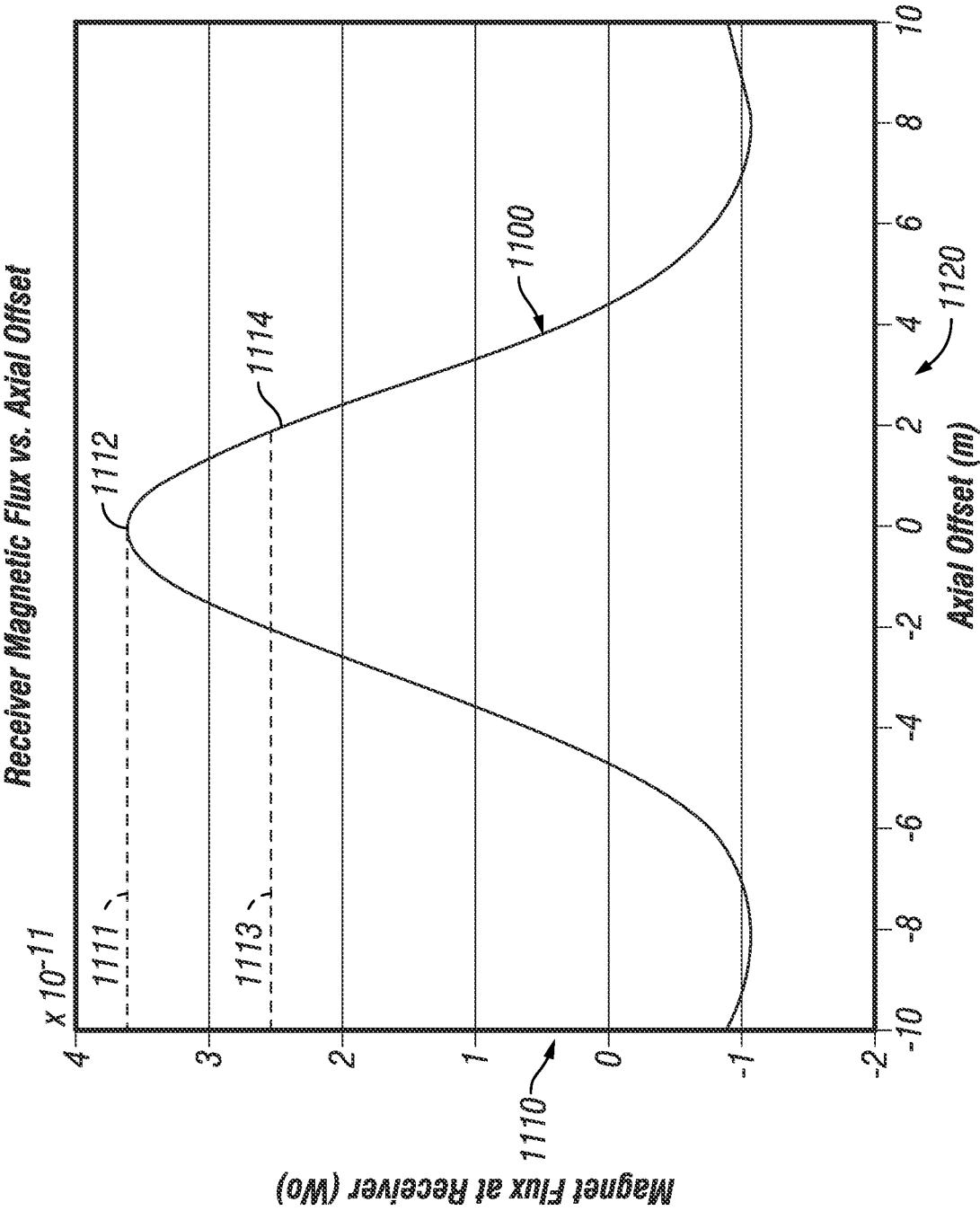
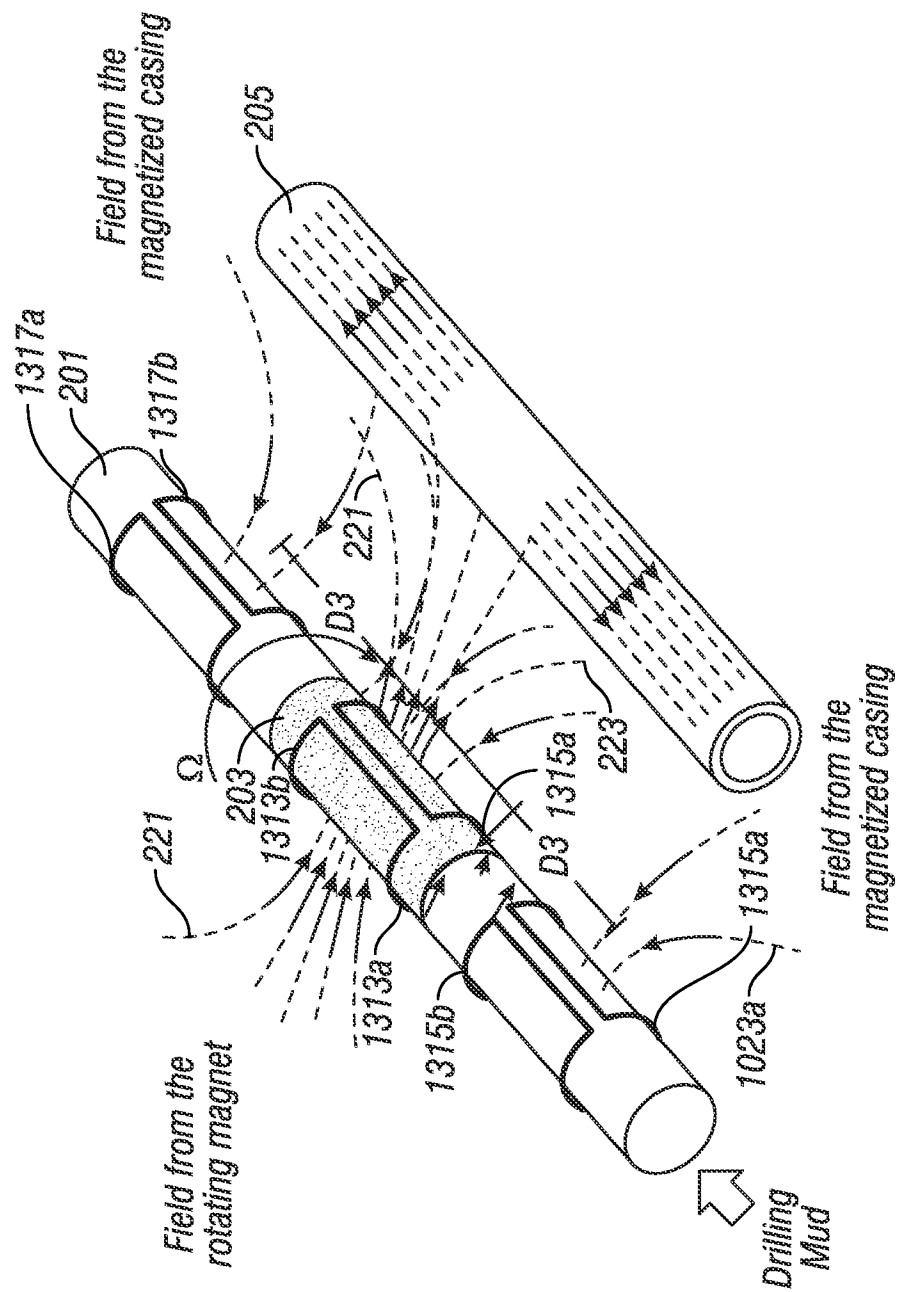


FIG. 11

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49.13

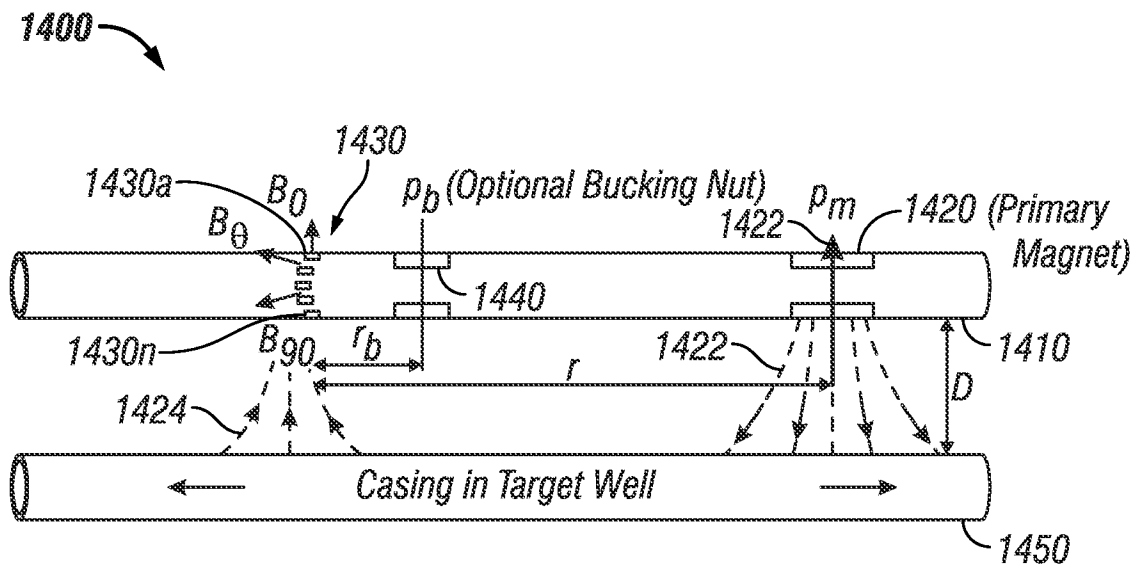


FIG. 14

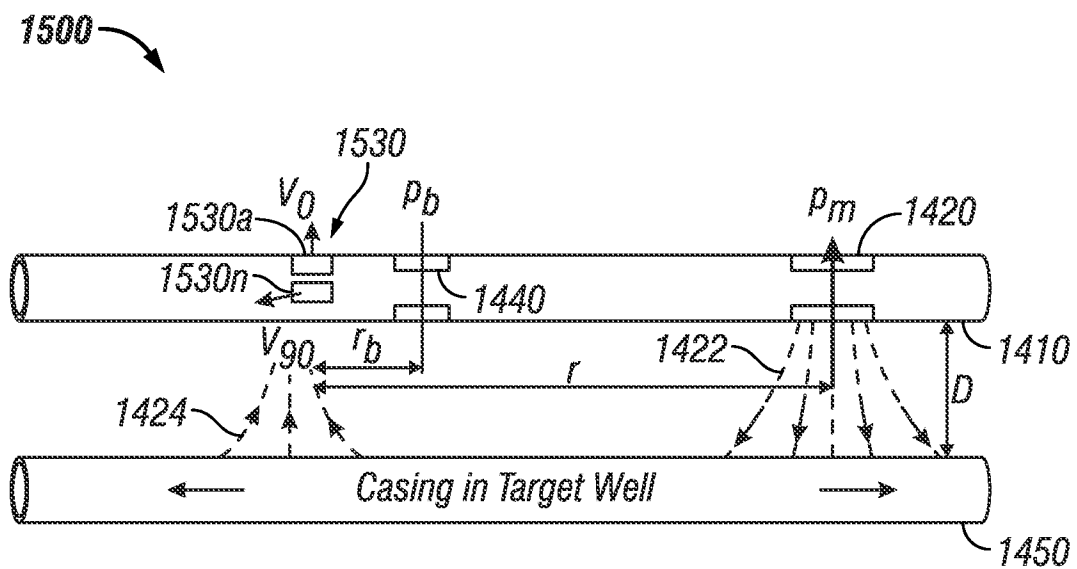


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/073105**A. CLASSIFICATION OF SUBJECT MATTER****E21B 47/092(2012.01)i, E21B 43/16(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 47/092; E21B 47/02; G01V 3/26; E21B 47/18; E21B 47/022; G01V 3/08; E21B 43/16

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: determine, distance, rotating magnet, stationary sensor, magnetic field, and magnetometer

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008-0018334 A1 (REIDERMAN, AREADY) 24 January 2008 See abstract, paragraphs [0011]-[0052] and claims 1,6,13.	17
A		1-16, 18-21
A	US 2007-0278008 A1 (KUCKES et al.) 06 December 2007 See paragraphs [0024]-[0033] and figures 1-5.	1-21
A	US 2005-0247484 A1 (BRUNE et al.) 10 November 2005 See abstract and paragraphs [0008]-[0022].	1-21
A	US 2009-0260879 A1 (CLARK et al.) 22 October 2009 See abstract, paragraphs [0030]-[0035] and figures 1-3.	1-21
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Further documents are listed in the continuation of Box C.



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Name and mailing address of the ISA/KR

International Application Division
Korean Intellectual Property Office
189 Cheongsu-ro, Seo-gu, Daejeon Metropolitan City, 302-701,
Republic of Korea

Facsimile No. +82-42-472-7140

Authorized officer

LEE, Jong Kyung

Telephone No. +82-42-481-3360



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