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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
17 January 2013 (17.01.2013)

(10) International Publication Number
WO 2013/009285 A1

(51) International Patent Classification: *E21B 7/04* (2006.01)

(21) International Application Number: PCT/US2011/043535

(22) International Filing Date: 11 July 2011 (11.07.2011)

(25) Filing Language: English

(26) Publication Language: English

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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *of inventorship (Rule 4.17(iv))*

Published:

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

(54) Title: ROTARY STEERABLE DRILLING SYSTEM AND METHOD

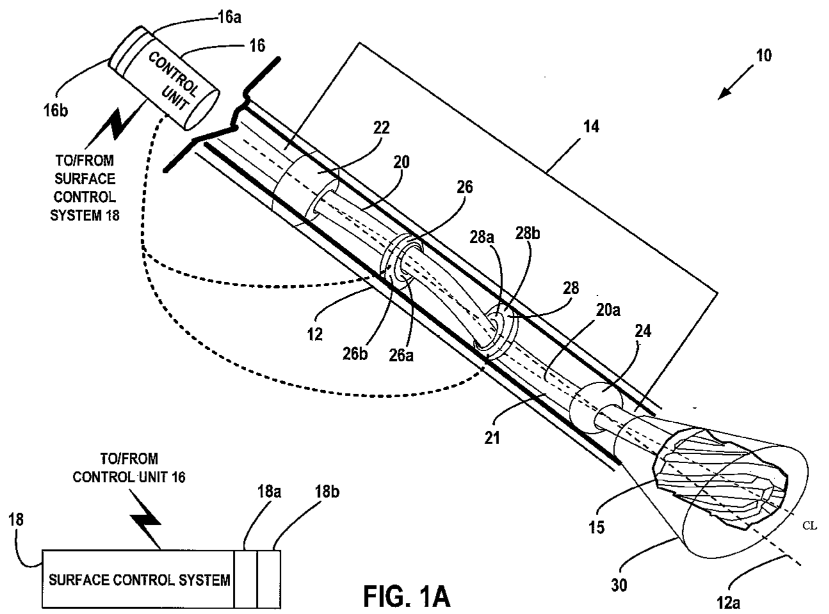

FIG. 1A

(57) Abstract: A drilling system may include an outer sleeve, and a rotary steerable module including a shaft extending within the outer sleeve. The rotary steerable module may further include bearings disposed within the outer sleeve and through which the shaft extends, and cams positioned along the shaft between the bearings. Each cam may include an eccentric ring through which the shaft extends. Each extension of the shaft through one of the eccentric rings defines a bend in the shaft within the outer sleeve, the bend having a bend angle. A method of use and a drilling control apparatus are also provided.

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ROTARY STEERABLE DRILLING SYSTEM AND METHOD

Background

This disclosure generally relates to drilling systems and more particularly, to rotary steerable drilling systems for oil and gas exploration and production operations.

A rotary steerable drilling system allows a drill string to rotate continuously while steering the drill string to a desired target location in a subterranean formation. A rotary steerable drilling system is limited by its maximum dogleg severity, that is, the maximum deflection rate of the drill string (in, for example, angle per linear length) that can be achieved during drilling.

Brief Description of the Drawings

A more complete understanding of this disclosure and advantages thereof may be acquired by referring to the following description taken in conjunction with the accompanying figures, wherein:

Figure 1A is a diagrammatic view of a drilling system according to an exemplary embodiment, the drilling system including a rotary steerable module placed in a reverse double bend configuration, according to an exemplary embodiment.

Figure 1B is an equivalent geometric diagram of the rotary steerable module of Figure 1A, according to an exemplary embodiment.

Figure 2A is a diagrammatic view of the rotary steerable module of Figure 1A, but depicts the rotary steerable module in an accordant double bend configuration, according to an exemplary embodiment.

Figure 2B is an equivalent geometric diagram of the rotary steerable module of Figure 2A, according to an exemplary embodiment.

Figure 3 is an equivalent geometric diagram of a tool option having only a single bend configuration, according to an exemplary embodiment.

Figure 4 is a diagrammatic view of a drilling system including a rotary steerable module that includes a pad, according to an exemplary embodiment.

Figure 5 is a diagrammatic view of a drilling system including a rotary steerable module that includes a pad, according to another exemplary embodiment.

Figure 6 is a diagrammatic view of a drilling system including two rotary steerable modules, according to an exemplary embodiment.

Figure 7 is a diagrammatic view of a drilling system including two rotary steerable modules, according to another exemplary embodiment.

Figure 8 is a flow chart illustration of a method of operating a drilling system, according to an exemplary embodiment.

While this disclosure is susceptible to various modifications and alternative forms, specific exemplary embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure as defined by the appended claims.

Detailed Description

This disclosure generally relates to drilling systems and more particularly, to rotary steerable drilling systems for oil and gas exploration and production operations.

Rotary steerable drilling systems are provided herein that, among other functions, can be used to achieve greater maximum dogleg severities, that is, maximum drill string shaft deflection rates in, for example, angle per linear length.

To facilitate a better understanding of this disclosure, the following examples of certain embodiments are given. In no way should the following examples be read to limit, or define, the scope of the disclosure.

For ease of reference, the terms “upper,” “lower,” “upward,” and “downward” are used herein to refer to the spatial relationship of certain components. The terms “upper” and “upward” refer to components towards the surface (distal to the drill bit or proximal to the surface), whereas the terms “lower” and “downward” refer to components towards the drill bit (proximal to the drill bit or distal to the surface), regardless of the actual orientation or deviation of the wellbore or wellbores being drilled.

In one exemplary embodiment, as illustrated in Figure 1A, a drilling system is generally referred to by the reference numeral 10 and includes an outer housing or sleeve 12 having a center axis 12a. A rotary steerable module 14 is disposed within the outer sleeve 12. A drill bit 15 is positioned proximate to the lowermost or distal end of the outer sleeve 12. A control unit 16 is provided to control the rotary steerable module

14, under conditions to be described below. In one exemplary embodiment, the control unit 16 is connected to, and/or disposed within, the outer sleeve 12. In one exemplary embodiment, the control unit 16 includes one or more measurement-while-drilling (MWD) systems, one or more logging-while-drilling (LWD) systems, and/or any combination thereof. In one exemplary embodiment, the control unit 16 includes one or more processors 16a, a memory or computer readable medium 16b operably coupled to the one or more processors 16a, and a plurality of instructions stored in the computer readable medium 16b and executable by the one or more processors 16a. A surface control unit or system 18 is in two-way communication with the control unit 16. In one exemplary embodiment, the surface control system 18 includes one or more processors 18a, a memory or computer readable medium 18b operably coupled to the one or more processors 18a, and a plurality of instructions stored in the computer readable medium 18b and executable by the one or more processors 18a.

The rotary steerable module 14 includes a flexible lever arm or shaft 20 having a center axis 20a and extending within the outer sleeve 12. As shown in Figure 1A, in one exemplary embodiment, the drill bit 15 is attached to the lowermost or distal end of the shaft 20, and is positioned outside of the outer sleeve 12. In several exemplary embodiments, the shaft 20 is, includes, or is part of, a drill string 21, the lowermost or distal end of which is connected to the drill bit 15. A cantilever bearing 22 is disposed within, and connected to, the outer sleeve 12. A focal bearing 24 is disposed within, and connected to, the outer sleeve 12. The shaft 20 extends through each of the cantilever bearing 22 and the focal bearing 24.

An upper cam 26 is disposed within the outer sleeve 12 and between the cantilever bearing 22 and the focal bearing 24. The upper cam 26 includes an inner eccentric ring 26a through which the shaft 20 extends, and an outer eccentric ring 26b extending about the inner eccentric ring 26a and connected to the outer sleeve 12. The inner eccentric ring 26a is engaged with the shaft 20 and may rotate therewith, relative to each of the outer eccentric ring 26b and the outer sleeve 12, under conditions to be described below. The control unit 16 is operably coupled to the upper cam 26 and controls the rotation of the upper cam 26 about the center axis 12a to any toolface setting and at least the inner eccentric ring 26a to varying degrees of offset from the center. More particularly, the control unit 16 causes at least one of the eccentric rings 26a and 26b to rotate about the center axis 12a to a predetermined angular position, relative to the outer sleeve 12, as shown in Figure 1A. As a result of the extension of the shaft 20 through the inner eccentric ring 26a and the rotation of at least one of the eccentric rings 26a and 26b about the center axis 12a to the predetermined angular position, the shaft 20 bends at the upper cam 26. In one exemplary embodiment, both of the eccentric rings 26a and 26b rotate about the center axis 12a.

A lower cam 28 is disposed within the outer sleeve 12 and between the upper cam 26 and the focal bearing 24. The lower cam 28 includes an inner eccentric ring 28a through which the shaft 20 extends, and an outer eccentric ring 28b extending about the inner eccentric ring 28a and connected to the outer sleeve 12. The inner eccentric ring 28a is engaged with the shaft 20 and may rotate therewith, relative to each of the outer eccentric ring 28b and the outer sleeve 12, under conditions to be described below. The control unit 16 is operably coupled to the lower cam 28 and controls the rotation of the lower cam 28 about the center axis 12a to any toolface setting and at least the inner eccentric ring 28a to varying degrees of offset from the center. More particularly, the control unit 16 can cause at least one of the eccentric rings 28a and 28b to rotate about the center axis 12a to a predetermined angular position, relative to the outer sleeve 12, as shown in Figure 1A. As a result of the extension of the shaft 20 through the inner eccentric ring 28a and the rotation of at least one of the eccentric rings 28a and 28b about the center axis 12a to the predetermined angular position, the shaft 20 bends at the lower cam 28. In one exemplary embodiment, both of the eccentric rings 28a and 28b rotate about the center axis 12a.

In several exemplary embodiments, the upper cam 26 and/or the lower cam 28 may be part of, include, or use, one or more of the annular rotational members and/or harmonic drive mechanisms described in one or more of U.S. Patent Nos. 5,307,885 to Kuwana et al., 5,353,884 to Misawa et al., and 5,875,859 to Ikeda et al., and/or one or more components of such annular rotational members and/or harmonic drive mechanisms. In one exemplary embodiment, the upper cam 26 or the lower cam 28 is, or includes, a drilling direction control device disclosed in U.S. Patent No. 5,353,884 to Misawa et al., and/or includes one or more components of the drilling direction control device such as, for example, one or more harmonic drive mechanisms, double eccentric mechanisms, and annular members. In one exemplary embodiment, the upper cam 26 or the lower cam 28 is, or includes, a drilling-direction control device disclosed in U.S. Patent No. 5,307,885 to Kuwana et al., and/or includes one or more components of the drilling-direction control device such as, for example, one or more harmonic drive mechanisms and rotational discs. In one exemplary embodiment, the upper cam 26 or the lower cam 28 is, or includes, a device for controlling the drilling direction of drills as disclosed in U.S. Patent No. 5,875,859 to Ikeda et al., and/or includes one or more components of the device such as, for example, one or more double eccentric mechanisms and controlling systems.

In one exemplary embodiment, the drilling system 10 is a double bend point-the-bit rotary steerable system, which allows the drill bit 15 to tilt in any direction as indicated by the range of movement 30, under conditions to be described below (e.g., if the distal end portion of the drill string 21 extends horizontally, the drill bit 15 is allowed to tilt up, right, down or left).

In operation, in one exemplary embodiment, the drilling system 10 drills or penetrates directionally into a subterranean ground formation for the purpose of recovering hydrocarbon fluids from the formation. As the drilling system 10 penetrates into the formation directionally, a wellbore is formed (the wellbore is not shown in Figure 1A). During the directional drilling, the rotary steerable module 14 enables the drill string 21, and thus the flexible shaft 20 and the drill bit 15, to rotate continuously and, at the same time, steer the drill string 21 to the desired target location in the formation. The ability to steer on the fly or continuously during drilling is one important aspect of the rotary steerable module 14. By rotating the drill string 21, axial drag is reduced, thereby increasing the amount of weight on bit (WOB) available at the drill bit 15. During the rotation of the drill string 21, the shaft 20 rotates about the center axis 20a, relative to the outer sleeve 12, the cantilever bearing 22, the focal bearing 24, the outer eccentric ring 26b, and the outer eccentric ring 28b, while maintaining the respective bends in the shaft 20 at the cams 26 and 28. During the rotation of the drill string 21, the inner eccentric ring 26a may rotate along with the shaft 20, relative to the outer eccentric ring 26b and the outer sleeve 12. Likewise, the inner eccentric ring 28a may rotate along with the shaft 20, relative to the outer eccentric ring 28b and the outer sleeve 12. During operation, the drilling system 10 operates as a double bend point-the-bit rotary steerable system, allowing the drill bit 15 to tilt in any direction as indicated by the range of movement 30, to the desired direction in order to reach the desired target location in the formation. The tilt of the drill bit 15 is changed using the bending of the shaft 20 at the cams 26 and 28. In several exemplary embodiments, during the directional drilling, the drill bit 15 is rotated by one or more surface rotary drives, steerable motors, mud motors, positive displacement motors (PDMs), electrically-driven motors, and/or any combination thereof.

During operation, in one exemplary embodiment, a control unit 16 positioned in the wellbore communicates with the surface control system 18, sending directional survey information to the surface control system 18 using a telemetry system. In one embodiment, the telemetry system utilizes mud-pulse telemetry. In any event, the control unit 16 may transmit to the surface control system 18 information about the direction, inclination and orientation of the drilling system 10. In one exemplary embodiment, the surface control system 18 controls the rotary steerable module 14 via the control unit 16. During operation, in one exemplary embodiment, the control unit 16 controls the rotary steerable module 14, controlling the rotation of the upper cam 26 and the lower cam 28 to any toolface setting, and controlling the offset of each of the inner eccentric rings 26a and 28a from the center. In one exemplary embodiment, one or both of the control unit 16 and the surface control system 18 are part of a downlink system that allows for automatic steering along a fixed or preprogrammed trajectory towards the desired target location in the formation. In one exemplary embodiment, to control the rotary steerable module 14 using the surface control system 18 and/or the control unit 16, the one or more processors 16a and/or the one or more processors 18a execute the plurality of instructions stored in the computer readable medium 16b and/or the plurality of instructions stored in the computer readable medium 18b.

During operation, the shaft 20 can pivot at the upper cam 26, as well as at the lower cam 28. Due to the cams 26 and 28, and the accompanying pivot actions of the shaft 20 at the cams 26 and 28, wide ranges of dogleg severity (or deflection rate in, for example, angle per linear length) can be achieved. As a result, as shown in Figure 1A, the drill bit 15 has a range of movement 30. As further shown in Figure 1A, the center axis 20a of the shaft 20 is angularly offset from the center axis 12a of the outer sleeve 12 throughout the great majority of the range of movement 30 of the drill bit 15 except when, for example, the center axes 20a and 12a are aligned. Moreover, the shaft 20 can bend negatively, that is, the shaft can pivot in respective opposite directions at the cams 26 and 28, resulting in a reverse double bend configuration as shown in Figure 1A. To achieve an explicit deflection rate, the two bend angles at the cams 26 and 28, respectively, may be in the same plane, and can bend to the accordant or reverse direction (the reverse direction is shown in Figure 1A). As noted above, the control unit 16 controls the rotation of the upper cam 26 and the lower cam 28 to any toolface setting, and controls the offset of each of the inner eccentric rings 26a and 28a from the center. Moreover, forces are applied internally within the outer sleeve 12 using the shaft 20 and the cams 26 and 28. As a result, the bend angle(s) of the shaft 20 can be adjusted on the fly, thereby imparting a side force at the drill bit 15 as desired for building or dropping.

During operation, in one exemplary embodiment and referring to Figure 1B with continuing reference to Figure 1A, bend angles β_1 and β_2 at the cams 28 and 26, respectively, are in the same plane and the rotary steerable module 14 is bent to the reverse direction, that is, placed in the reverse double bend configuration shown in Figure 1A, so that the operational parameters of the drilling system 10 may be analyzed using the equivalent geometrical diagram shown in Figure 1B.

More particularly, the drill bit 15 (point 1 in Figure 1B), the bottom contact at the focal bearing 24 (point 2 in Figure 1B), and the top contact at the cantilever bearing 22 (point 3 in Figure 1B) form three control points (the points 1, 2 and 3) to prescribe a circle, and the curvature of the circle is the reciprocal of its radius. For a double bend configuration, an example of which is shown in Figures 1A and 1B, except $x_1 = 0$, $y_1 = 0$, $x_2 = 0$, other coordinates of the three points 1, 2 and 3 are set forth in Equation (1) below:

$$\begin{cases} y_2 = L_1 \\ x_3 = L_3 \sin\beta_1 + L_4 \sin(\beta_1 + \beta_2) \\ y_3 = L_1 + L_2 + L_3 \cos\beta_1 + L_4 \cos(\beta_1 + \beta_2) \end{cases} \quad (1)$$

Since the configuration shown in Figures 1A and 1B is a reverse double bend configuration, the upper bent angle β_2 is a negative value as it bends to the reverse direction of the lower bent angle β_1. Substituting Equation (1) in the general three point equation and using field units of bend angle and deflection rate yields Equation (2) below:

$$\delta = \frac{200}{L_T}(\lambda_1 \beta_1 + \lambda_2 \beta_2) \ (°/100 \text{ ft}) \quad (2)$$

where:

$$L_S = L_2 + L_3 + L_4\,,\quad L_T = L_1 + L_S\,,\quad \lambda_1 = 1 - \frac{L_2}{L_S}\,,\quad \lambda_2 = \frac{L_4}{L_S}$$

β_1 = Lower bent angle, degrees

β_2 = Upper bent angle, degrees

L_1 = Lower bent angle to bit distance, ft

L_2 = Upper bent angle to lower bent angle distance, ft

L_3 = Upper bent-angle to lower bent-angle distance, ft

L_4 = Top stabilizer to upper bent-angle distance, ft

λ_1 = Influencing factor of lower bent-angle position, dimensionless

λ_2 = Influencing factor of upper bent-angle position, dimensionless

In one exemplary embodiment, referring to Figures 2A and 2B with continuing reference to Figures 1A and 1B, during operation, instead of, or in addition to placing the rotary steerable module 14 in the reverse double bend configuration, the control unit 16 controls the cams 26 and 28 to place the rotary steerable module 14 in an accordant double bend configuration, as shown in Figure 2A. More particularly, the control unit 16 causes at least one of the eccentric rings 26a and 26b to rotate about the center axis 12a to a predetermined angular position, relative to the outer sleeve 12, as shown in Figure 2A. And the control unit 16 causes at least one of the eccentric rings 28a and 28b to rotate about the center axis 12a to a predetermined angular position, relative to the outer sleeve 12. As shown in Figure 2A, the eccentric rings 26a and 26b have been rotated to an angular position that is different than the angular position to which the eccentric rings 26a and 26b have been rotated in Figure 1A.

During operation, in one exemplary embodiment, the bend angles β_1 and β_2 at the cams 28 and 26, respectively, are in the same plane and the rotary steerable module 14 is bent to the accordant direction, that is, placed in the accordant double bend configuration shown in Figure 2A, so that the operational parameters of the drilling system 10 may be analyzed using the equivalent geometrical diagram shown in Figure 2B. Equations (1) and (2) described above are used in connection with the equivalent geometrical diagram of Figure 2B in substantially the same manner as Equations (1) and (2) are used in connection with the equivalent geometrical diagram of Figure 1B, except that the upper bent angle β_2 is a positive value as it bends to the accordant direction of the lower bent angle β_1.

In view of the foregoing, it is clear that the capability of the rotary steerable module 14 to be placed in a single composite double bend configuration, such as the reverse double bend configuration shown in Figures 1A and 1B or the accordant double bend configuration shown in Figures 2A and 2B, provides for a wide range of accordant and reverse bend positions, resulting in multiple bend settings for drilling.

Moreover, as noted above, due to the cams 26 and 28, and the accompanying respective pivot actions of the shaft 20 at the cams 26 and 28, wide ranges of dogleg severity can be achieved. In several exemplary embodiments, using equivalent input parameters, the double bend configuration(s) of the rotary steerable module 14 can achieve a dogleg severity (or deflection rate) that is greater than that of a single bend configuration.

For example, a well needs a dogleg severity (or deflection rate) of 15.75 degrees per 100 ft. The available tool options are set forth below, each of which has a maximum bend of 1.5 degrees. The maximum deflection rate for each option in the accordant direction is determined as set forth below.

Referring to Figure 3, the equivalent geometric diagram of a tool option having only a single bend configuration is shown, and the tool option is generally referred to by the reference numeral 36. The tool option 36 includes the outer sleeve 12, the drill bit 15, the shaft 20, the cantilever bearing 22, the focal bearing 24, and the lower cam 28. L_1 and L_2 of the tool option 36 of Figure 3 represent the same dimensions as L_1 and L_2 of the rotary steerable module 14 of Figure 2B. L_3 of the tool option 36 of Figure 3 represents the dimension from the lower cam 28 to the cantilever bearing 22, whereas L_3 of the rotary steerable module 14 of Figure 2B represents the dimension from the lower cam 28 to the upper cam 26. The tool option 36 of Figure 3 does not include L_4, whereas the rotary steerable module 14 of Figure 2B includes L_4, which as noted above represents the dimension from the upper cam 26 to the cantilever bearing 22.

In the example, for the tool option 36 having the single bend configuration as shown in Figure 3, L_1 = 3 ft, L_2 = 3 ft, and L_3 = 10 ft (L_4 is omitted or is considered to be zero). Using Equations (1) and (2) above, and the foregoing input parameters including a maximum bend of 1.5 degrees, the maximum deflection rate is calculated as follows:

$$\delta = \frac{200}{18}(0.7692 \times 1.5) = 14.42 \text{ (°/100 ft)}$$

Therefore, the maximum dogleg severity or deflection rate is 14.42 degrees per 100 ft for the tool option 36 having the single bend configuration as shown in Figure 3. Therefore, the single bend configuration shown in Figure 3 cannot achieve the desired dogleg severity of 15 degrees per 100 ft.

In the example, for the rotary steerable module 14 having the accordant double bend configuration of Figure 2B, L_1 = 3 ft, L_2 = 3 ft, L_3 = 10 ft, and L_4 = 5 ft. Using Equations (1) and (2) above, and the foregoing input parameters including a maximum bend of 1.5 degrees, the maximum deflection rate is calculated as follows:

$$\delta = \frac{200}{21}(0.833 \times 1.5 + 0.277 \times 1.5) = 15.87 \text{ (°/100 ft)}$$

Therefore, the maximum dogleg severity or deflection rate is 15.87 degrees per 100 ft for the rotary steerable module 14 having the accordant double bend configuration as shown in Figure 2B. Thus, the accordant double bend configuration shown in Figure 2B can achieve the desired dogleg severity of 15 degrees per 100 ft, whereas the single bend configuration shown in Figure 3 cannot achieve the desired dogleg severity.

In one exemplary embodiment, as illustrated in Figure 4, a drilling system is generally referred to by the reference numeral 38 and includes the drill bit 15, the outer sleeve 12, and a rotary steerable module 40, a portion of which is disposed within the outer sleeve 12 and a portion of which is disposed outside of the outer sleeve 12. More particularly, the rotary steerable module 40 includes all of the components of the rotary steerable module 14, which components are given the same reference numerals and are disposed within the outer sleeve 12. The rotary steerable module 40 further includes a pad 42, which is connected to the outer sleeve 12 so that at least a portion of the pad 42 is positioned outside of the outer sleeve 12. The pad 42 is disposed between the focal bearing 24 and the drill bit 15. In one exemplary embodiment, the pad 42 is, includes, or is part of, a side cutting structure. In one exemplary embodiment, the drilling system 38 is a double bend push-the-bit rotary steerable system, which can be placed in either a reverse double bend configuration or an accordant double bend configuration. In several exemplary embodiments, the location of the pad 42, relative to the outer sleeve 12, may be varied. In several exemplary embodiments, the rotary steerable module 40 of the drilling system 38 may include one or more additional pads carried by the outer sleeve 12, each of which may be substantially identical to the pad 42.

In operation, in one exemplary embodiment, the drilling system 38 drills or penetrates into a subterranean ground formation for the purpose of recovering hydrocarbon fluids from the formation. As the drilling system 38 penetrates into the formation, a wellbore 44 is formed. During the drilling, the rotary steerable module 40 enables the drill string 21, and thus the flexible shaft 20 and the drill bit 15, to rotate continuously. The pad 42 interacts with the formation in which the wellbore 44 is being formed, thereby causing a side force to be generated, which side force deviates or pushes the drill bit 15 in a desired direction. In one exemplary embodiment, the pad 42 acts as a pivot for the deflection of the drill bit 15. The placement of the pad 42 and any additional pad(s), relative to the outer sleeve 12, enables the drill bit 15 to be steered in a controlled manner.

In several exemplary embodiments, during operation, the drilling system 38 operates as a double bend push-the-bit rotary steerable system. During operation, the rotary steerable module 40 of the system 38 may be placed in a reverse double bend configuration, as shown in Figure 4. Alternatively, during operation, instead of a reverse double bend configuration, the rotary steerable module 40 of the system 38 may be placed in an accordant double bend configuration.

In one exemplary embodiment, as illustrated in Figure 5, a drilling system is generally referred to by the reference numeral 46 and includes the drill bit 15, the outer sleeve 12, and a rotary steerable module 48, a portion of which is disposed within the outer sleeve 12 and a portion of which is disposed outside of the outer sleeve 12. More particularly, the rotary steerable module 48 includes all of the components of the rotary steerable module 14, which components are given the same reference numerals and are disposed within the outer sleeve 12. The rotary steerable module 48 further includes the pad 42, which is connected to the outer sleeve 12 so that at least a portion of the pad 42 is positioned outside of the outer sleeve 12. In the rotary steerable module 48, the pad 42 is disposed along the outer sleeve 12 so that the pad 42 is positioned above the cantilever bearing 22, that is, so that the cantilever bearing 22 is positioned between the pad 42 and the upper cam 26.

In one exemplary embodiment, the drilling system 46 is a double bend push-the-bit rotary steerable system, which can be placed in either a reverse double bend configuration or an accordant double bend configuration. In several exemplary embodiments, the location of the pad 42, relative to the outer sleeve 12, may be varied. In several exemplary embodiments, the rotary steerable module 48 of the drilling system 38 may include one or more additional pads connected to the outer sleeve 12, each of which may be substantially identical to the pad 42.

In operation, in one exemplary embodiment, the drilling system 46 drills or penetrates into a subterranean ground formation for the purpose of recovering hydrocarbon fluids from the formation. As the drilling system 46 penetrates into the formation, a wellbore 50 is formed. During the drilling, the rotary steerable module 48 enables the drill string 21, and thus the flexible shaft 20 and the drill bit 15, to rotate continuously. The pad 42 interacts with the formation in which the wellbore 50 is being formed, thereby causing a side force to be generated, which side force deviates or pushes the drill bit 15 in a desired direction. In one exemplary embodiment, the pad 42 acts as a pivot for the deflection of the drill bit 15. The placement of the pad 42 and any additional pad(s), relative to the outer sleeve 12, enables the drill bit 15 to be steered in a controlled manner.

In several exemplary embodiments, during operation, the drilling system 46 operates as a double bend push-the-bit rotary steerable system. During operation, the rotary steerable module 48 of the system 46 may be placed in a reverse double bend configuration, as shown in Figure 5. During operation, instead of a reverse double bend configuration, the rotary steerable module 48 of the system 46 may be placed in an accordant double bend configuration.

In one exemplary embodiment, as illustrated in Figure 6, a drilling system is generally referred to by the reference numeral 52 and includes two rotary steerable modules as described herein. More specifically, the drilling system 52 includes a drill bit 15, an outer sleeve 12 having sections 12a and 12b, a rotary steerable module 14, and a rotary steerable module 40. The module 14 is disposed within the section 12a of the outer sleeve 12. The module 14 is also disposed between the drill bit 15 and the module 40, a portion of which is disposed within the section 12b of the outer sleeve 12. At least a portion of the pad 42 of the module 40 is disposed outside of, and carried by, the section 12b of the outer sleeve 12.

A connector 54 including an internal threaded connection (not shown) is connected to the upper end of the module 14. A connector 56 is connected to the lower end of the module 40. The connector 56 includes an external threaded connection (not shown), which is engaged with the internal threaded connection of the connector 54, thereby connecting the module 40 to the module 14. The sections 12a and 12b, the connector 54, and the connector 56 together form at least a portion of the outer sleeve 12. A connector 57 extends within at least the connectors 54 and 56, and connects the respective shafts 20 of the modules 14 and 40. The connector 57 and the respective shafts 20 of the modules 14 and 40 form at least a portion of the drill string 21, the lowermost end of which is connected to the drill bit 15.

In operation, in one exemplary embodiment, the drilling system 52 operates as a double bend hybrid rotary steerable system. More particularly, the module 40 of the drilling system operates as a double bend push-the-bit rotary steerable system, while the module 14 operates as a double bend point-the-bit rotary steerable system. The overall coherence of the drilling system 52 achieves a desired toolface vector.

During operation, in one exemplary embodiment, the module 14 is placed either in an accordant double bend configuration or in a reverse double bend configuration. Likewise, the module 40 is placed either in an accordant double bend configuration or in a reverse double bend configuration.

In several exemplary embodiments, another module substantially identical to one of the modules 14, 40 and 48 is connected to the upper end of the module 40. In several exemplary embodiments, one or more modules, each of which is substantially identical to one of the modules 14, 40 and 48, are connected to each other end-to-end, with the lowermost module connected to the module 40. In several exemplary embodiments, in the drilling system 52, either the module 14 or the module 40 is replaced with the module 48.

In one exemplary embodiment, as illustrated in Figure 7, a drilling system is generally referred to by the reference numeral 58 and includes two rotary steerable modules as described herein. More specifically, the drilling system 58 includes a drill bit 15, an outer sleeve 12 having sections 12a and 12b, a rotary steerable module 40, and a rotary steerable module 14. The module 40 is disposed between the drill bit 15 and the module 14. A portion of the module 40 is disposed within the section 12a of the outer sleeve 12. At least a portion of the pad 42 of the module 40 is disposed outside of, and carried by, the section 12a of the outer sleeve 12. The module 14 is disposed within the section 12b of the outer sleeve 12.

The connector 54 is connected to the upper end of the module 40. The connector 56 is connected to the lower end of the module 14. The connector 56 is engaged with the connector 54, thereby connecting the module 14 to the module 40. The sections 12a and 12b, the connector 54, and the connector 56 together form at least a portion of the outer sleeve 12. The connector 57 extends within at least the connectors 54 and 56, and connects the respective shafts 20 of the modules 14 and 40. The connector 57 and the respective shafts 20 of the modules 14 and 40 together form at least a portion of the drill string 21, the lowermost end of which is connected to the drill bit 15.

In operation, in one exemplary embodiment, the drilling system 58 operates as a double bend hybrid rotary steerable system. More particularly, the module 40 of the drilling system operates as a double bend push-the-bit rotary steerable system, while the module 14 operates as a double bend point-the-bit rotary steerable system. The overall coherence of the drilling system 58 achieves a desired toolface vector.

During operation, in one exemplary embodiment, the module 14 is placed either in an accordant double bend configuration or in a reverse double bend configuration. Likewise, the module 40 is placed either in an accordant double bend configuration or in a reverse double bend configuration.

In several exemplary embodiments, another module substantially identical to one of the modules 14, 40 and 48 is connected to the upper end of the module 14. In several exemplary embodiments, one or more modules, each of which is substantially identical to one of the modules 14, 40 and 48, are connected to each other in tandem end-to-end, with the lowermost module connected to the module 14. As a result, wider angles may be achieved. In several exemplary embodiments, in the drilling system 58, either the module 14 or the module 40 is replaced with the module 48.

As shown in Figures 6 and 7, the modular aspect of each of the drilling systems 52 and 58 ensures the significant benefit of optimizing the selection of modules for the desired wellbore path, providing a topology that can be made coherent to achieve the desired toolface vector.

In several exemplary embodiments, with continuing reference to Figures 1-7, each of the drilling systems 10, 38, 46, 52 and 58 is not based on a single fixed bend angle, which would result in only one inclination, but instead permits multiple combinations of bends to achieve multiple inclinations. The multiple combinations may have desired ranges based on the respective inner diameters of the cams 26 and 28. Each of the drilling systems 10, 38, 46, 52 and 58 can be utilized in continuous drilling operations while still achieving enhanced steering control, thereby yielding accurate well placement, better hole quality and better hole cleaning.

In one exemplary embodiment, as illustrated in Figure 8, a method of operating any one of the drilling systems 10, 38, 46, 52 and 58 is generally referred to by the reference numeral 60. The method 60 includes a step 62, at which a first bend is placed in a shaft within an outer sleeve, wherein the first bend has a first bend angle, and wherein the shaft and the outer sleeve have first and second center axes, respectively. Before, during or after the step 62, at step 64, a second bend is placed in the shaft within the outer sleeve, wherein the second bend has a second bend angle. At step 66, the shaft is rotated, relative to the outer sleeve, about the first center axis while maintaining the first and second bends in the shaft within the outer sleeve. In one exemplary embodiment, as shown in Figure 8, the step 62 includes a step 62a, at which at least one of a first eccentric ring and a second eccentric ring is rotated about the second center axis to a first angular position within the outer sleeve, wherein the shaft extends through the first eccentric ring, and the second eccentric ring extends about the first eccentric ring within the outer sleeve. In one exemplary embodiment, as shown in Figure 8, the step 64 includes a step 64a, at which at least one of a third eccentric ring and a fourth eccentric ring is rotated about the second center axis to a second angular position with the outer sleeve, wherein the shaft extends through the third eccentric ring, and the fourth eccentric ring extends about the third eccentric ring within the outer sleeve.

In several exemplary embodiments, the method 60 may be implemented in whole or in part by a computer. In several exemplary embodiments, the plurality of instructions stored on the computer readable medium 16b, the plurality of instructions stored on the computer readable medium 18b, a plurality of instructions stored on another computer readable medium, and/or any combination thereof, may be executed by a processor to cause the processor to carry out or implement in whole or in part the method 60, and/or to carry out in whole or in part the above-described operation of one or more of the drilling systems 10, 38, 46, 52 and 58. In several exemplary embodiments, such a processor may include the one or more processors 16a, the one or more processors 18a, one or more additional processors, and/or any combination thereof.

An example of a drilling system has been described that includes an outer sleeve; and a first rotary steerable module, comprising a first shaft extending within the outer sleeve; a first bearing disposed within the outer sleeve and through which the first shaft extends; a second bearing disposed within the outer sleeve and through which the first shaft extends, wherein the second bearing is spaced from the first bearing along the first shaft; a first cam disposed within the outer sleeve so that the first cam is positioned along the first shaft between the first and second bearings, the first cam comprising a first eccentric ring through which the first shaft extends; and a second eccentric ring extending about the first eccentric ring; wherein the extension of the first shaft through the first eccentric ring defines a first bend in the first shaft within the outer sleeve, the first bend having a first bend angle; and a second cam disposed within the outer sleeve so that the second cam is positioned along the first shaft between the first cam and the second bearing, the second cam comprising a third eccentric ring through which the first shaft extends; and a fourth eccentric ring extending about the third eccentric ring; wherein the extension of the first shaft through the second eccentric ring defines a second bend in the first shaft within the outer sleeve, the second bend having a second bend angle.

An example of a drilling method has been described that includes extending a shaft within an outer sleeve, wherein the shaft and the outer sleeve have first and second center axes, respectively; placing a first bend in the shaft within the outer sleeve, the first bend having a first bend angle; placing a second bend in the shaft within the outer sleeve, the second bend having a second bend angle; and rotating, relative to the outer sleeve, the shaft about the first center axis while maintaining the first and second bends in the shaft within the outer sleeve.

An example of a drilling control apparatus has been described that includes a computer readable medium; and a plurality of instructions stored on the computer readable medium and executable by a processor, the plurality of instructions comprising instructions that cause the processor to place a first bend in a shaft within an outer sleeve, wherein the first bend has a first bend angle, and wherein the shaft and the outer sleeve have first and second center axes, respectively; instructions that cause the processor to place a second bend in the shaft within the outer sleeve, wherein the second bend has a second bend angle; and instructions that cause the processor to rotate, relative to the outer sleeve, the shaft about the first center axis while maintaining the first and second bends in the shaft within the outer sleeve.

It is understood that variations may be made in the foregoing without departing from the scope of the disclosure.

Any spatial references such as, for example, “upper,” “lower,” “above,” “below,” “between,” “bottom,” “vertical,” “horizontal,” “angular,” “upwards,” “downwards,” “side-to-side,” “left-to-right,” “left,” “right,” “right-to-left,” “top-to-bottom,” “bottom-to-top,” “top,” “bottom,” “bottom-up,” “top-down,” etc., are for the purpose of illustration only and do not limit the specific orientation or location of the structure described above.

While the foregoing has been described in relation to a drill string and is particularly desirable for addressing dogleg severity concerns, those skilled in the art with the benefit of this disclosure will appreciate that the drilling systems of this disclosure can be used in other drilling applications without limiting the foregoing disclosure.

Claims

What is claimed is:

1. A drilling system, comprising:

an outer sleeve; and

a first rotary steerable module, comprising:

a first shaft extending within the outer sleeve;

a first bearing disposed within the outer sleeve and through which the first shaft extends;

a second bearing disposed within the outer sleeve and through which the first shaft extends, wherein the second bearing is spaced from the first bearing along the first shaft;

a first cam disposed within the outer sleeve so that the first cam is positioned along the first shaft between the first and second bearings, the first cam comprising:

a first eccentric ring through which the first shaft extends; and

a second eccentric ring extending about the first eccentric ring;

wherein the extension of the first shaft through the first eccentric ring defines a first bend in the first shaft within the outer sleeve, the first bend having a first bend angle; and

a second cam disposed within the outer sleeve so that the second cam is positioned along the first shaft between the first cam and the second bearing, the second cam comprising:

a third eccentric ring through which the first shaft extends; and

a fourth eccentric ring extending about the third eccentric ring;

wherein the extension of the first shaft through the third eccentric ring defines a second bend in the first shaft within the outer sleeve, the second bend having a second bend angle.

2. The drilling system of claim 1, wherein the first bend within the outer sleeve bends in a first angular direction; and

wherein the second bend within the outer sleeve bends in a second angular direction that is the reverse of the first angular direction.

3. The drilling system of claim 1, wherein the first and second bends within the outer sleeve bend in the same angular direction.

4. The drilling system of claim 1, wherein the first shaft has a center axis and is rotatable about the center axis within, and relative to, the outer sleeve.

5. The drilling system of claim 1, wherein the outer sleeve and the first shaft have first and second center axes, respectively;
wherein the drilling system further comprises a drill bit connected to the first shaft, the drill bit having a range of movement defined at least in part by the first and second bend angles; and
wherein the second center axis is angularly offset from the first center axis within the range of movement of the drill bit.

6. The drilling system of claim 1, wherein the first rotary steerable module comprises a pad connected to the outer sleeve, wherein at least a portion of the pad is positioned outside of the outer sleeve.

7. The drilling system of claim 1, wherein the outer sleeve has a center axis; and wherein the drilling system further comprises:
a control unit operably coupled to each of the first and second cams, the control unit comprising:
a processor;
a computer readable medium operably coupled to the processor; and
a plurality of instructions stored on the computer readable medium and executable by the processor, wherein the plurality of instructions comprises:
instructions that cause the processor to rotate at least one of the first and second eccentric rings about the center axis to a first angular position, relative to the outer sleeve; and

instructions that cause the processor to rotate at least one of the third and fourth eccentric rings about the center axis to a second angular position, relative to the outer sleeve.

8. The drilling system of claim 7, wherein the second angular position is different than the first angular position; and

wherein the first and second bend angles are dependent upon the first and second angular positions, respectively.

9. The drilling system of claim 7, wherein the outer sleeve comprises a first section and a second section connected thereto;

wherein the first shaft, the first and second bearings, and the first and second cams of the first rotary steerable module are disposed within the first section of the outer sleeve; and

wherein the drilling system further comprises a second rotary steerable module connected to the first rotary steerable module, the second rotary steerable module comprising:

a second shaft connected to the first shaft and extending within the second section of the outer sleeve;

a third bearing disposed within the second section of the outer sleeve and through which the second shaft extends;

a fourth bearing disposed within the second section of the outer sleeve and through which the second shaft extends, wherein the second bearing is spaced from the first bearing along the second shaft;

a third cam disposed within second section of the outer sleeve so that the third cam is positioned along the second shaft between the third and fourth bearings; and

a fourth cam disposed within the second section of the outer sleeve so that the fourth cam is positioned along the first shaft between the third cam and the fourth bearing.

10. The drilling system of claim 9, wherein at least one of the first and second rotary steerable modules comprises a pad carried by one of the first and second

sections of the outer sleeve, and wherein at least a portion of the pad is positioned outside of the outer sleeve.

11. A drilling method, comprising:

extending a shaft within an outer sleeve, wherein the shaft and the outer sleeve have first and second center axes, respectively;

placing a first bend in the shaft within the outer sleeve, the first bend having a first bend angle;

placing a second bend in the shaft within the outer sleeve, the second bend having a second bend angle; and

rotating, relative to the outer sleeve, the shaft about the first center axis while maintaining the first and second bends in the shaft within the outer sleeve.

12. The drilling method of claim 11, wherein placing the first bend in the shaft within the outer sleeve comprises:

extending the shaft through a first eccentric ring about which a second eccentric ring extends within the outer sleeve; and

rotating at least one of the first and second eccentric rings about the second center axis to a first angular position within the outer sleeve to thereby place the first bend in the shaft within the outer sleeve.

13. The drilling method of claim 12, wherein placing the second bend in the shaft within the outer sleeve comprises:

extending the shaft through a third eccentric ring about which a fourth eccentric ring extends within the outer sleeve;

rotating at least one of the third and fourth eccentric rings about the second center axis to a second angular position within the outer sleeve to thereby place the second bend in the shaft within the outer sleeve;

14. The drilling method of claim 13, wherein the second angular position is different than the first angular position; and

wherein the first and second bend angles are dependent upon the first and second angular positions, respectively.

15. The drilling method of claim 14, wherein the first bend within the outer sleeve bends in a first angular direction; and
wherein the second bend within the outer sleeve bends in a second angular direction that is the reverse of the first angular direction.

16. The drilling method of claim 11, wherein the drilling method further comprises attaching a drill bit to the shaft, the drill bit having a range of movement defined at least in part by the first and second bend angles; and
wherein the first center axis is permitted to be angularly offset from the second center axis within the range of movement of the drill bit.

17. A drilling control apparatus, comprising:
a computer readable medium; and
a plurality of instructions stored on the computer readable medium and executable by a processor, the plurality of instructions comprising:
instructions that cause the processor to place a first bend in a shaft within an outer sleeve, wherein the first bend has a first bend angle, and wherein the shaft and the outer sleeve have first and second center axes, respectively;
instructions that cause the processor to place a second bend in the shaft within the outer sleeve, wherein the second bend has a second bend angle; and
instructions that cause the processor to rotate, relative to the outer sleeve, the shaft about the first center axis while maintaining the first and second bends in the shaft within the outer sleeve.

18. The drilling control apparatus of claim 17, wherein the instructions that cause the processor to place the first bend in the shaft within the outer sleeve comprise:
instructions that cause the processor to rotate at least one of a first eccentric ring through which the shaft extends, and a second eccentric ring extending about the first eccentric ring within the outer sleeve, about the second center axis to a first angular position within the outer sleeve.

19. The drilling control apparatus of claim 18, wherein the instructions that cause the processor to place the second bend in the shaft within the outer sleeve comprise:

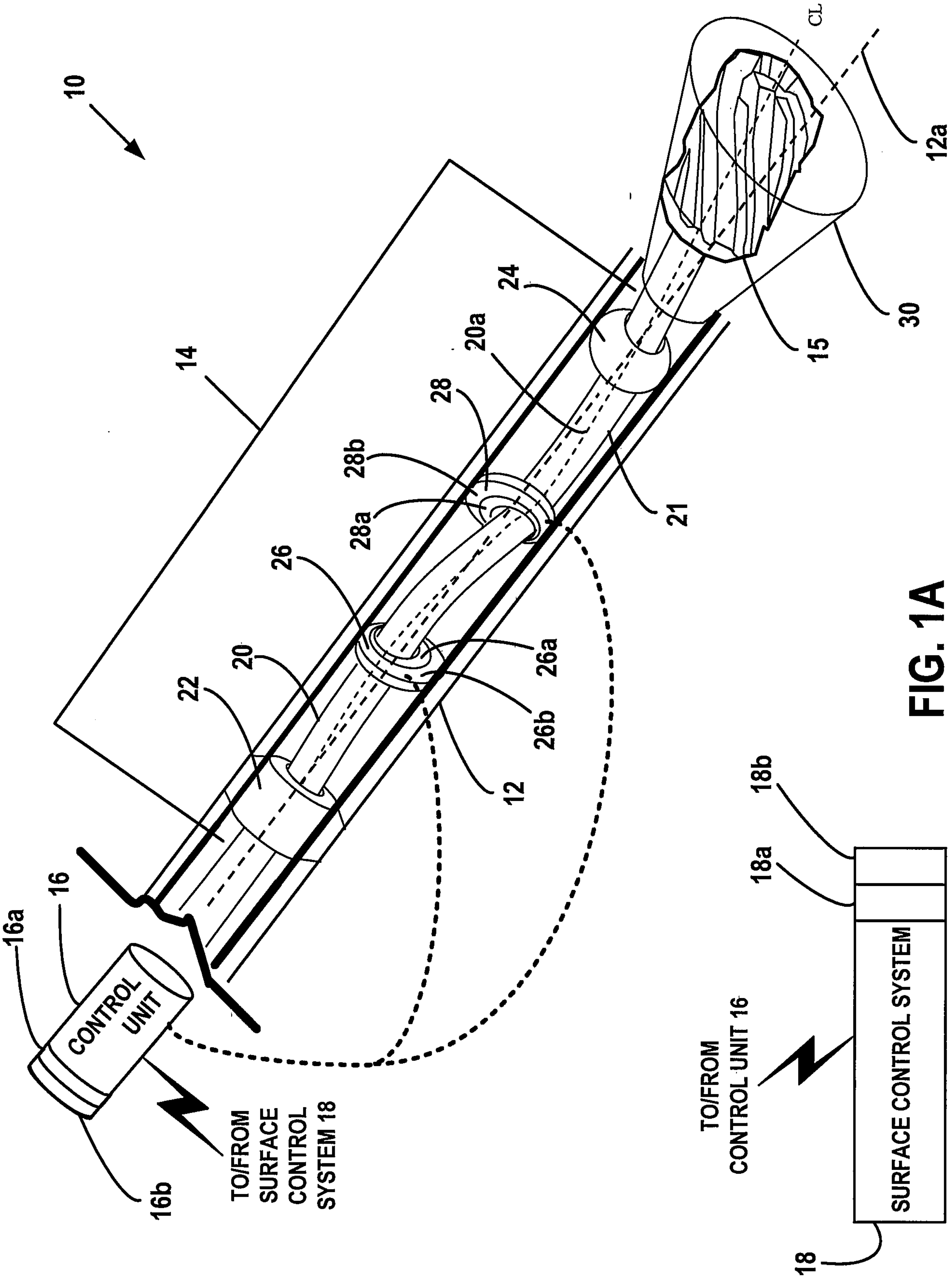
instructions that cause the processor to rotate at least one of a third eccentric ring through which the shaft extends, and a fourth eccentric ring extending about the third eccentric ring within the outer sleeve, about the second center axis to a second angular position within the outer sleeve;

wherein the second angular position is either the same as, or different than, the first angular position; and

wherein the first and second bend angles are dependent upon the first and second angular positions, respectively.

20. The drilling control apparatus of claim 19, wherein the first bend within the outer sleeve bends in a first angular direction; and

wherein the second bend within the outer sleeve bends in a second angular direction that is either the reverse of, or the same as, the first angular direction.


10
14
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12a
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15
28
28b
21
28a
26
26a
26b
20
22
12
16a
16
CONTROL UNIT
16b
TO/FROM SURFACE CONTROL SYSTEM 18
18b
18a
TO/FROM CONTROL UNIT 16
SURFACE CONTROL SYSTEM
18

FIG. 1A

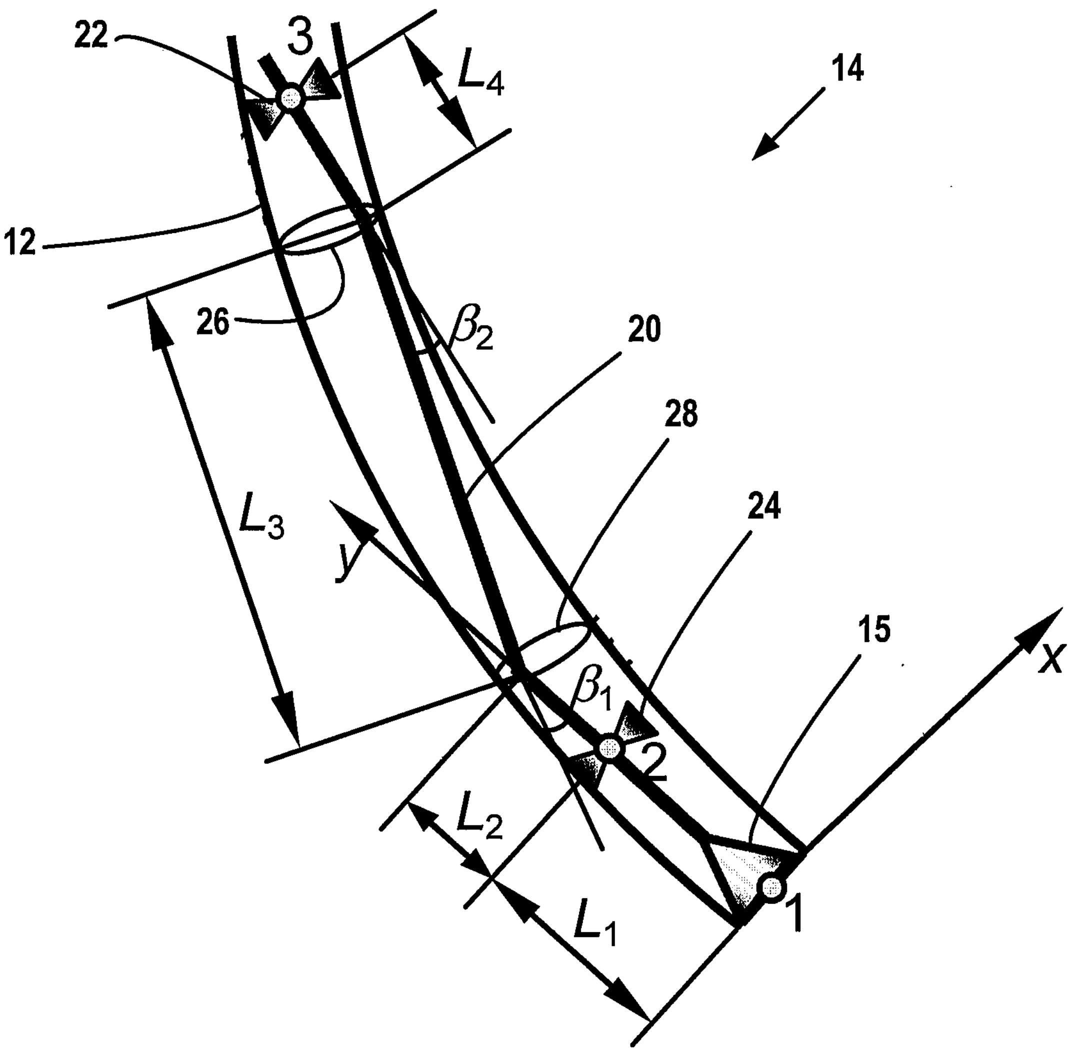

FIG. 1B

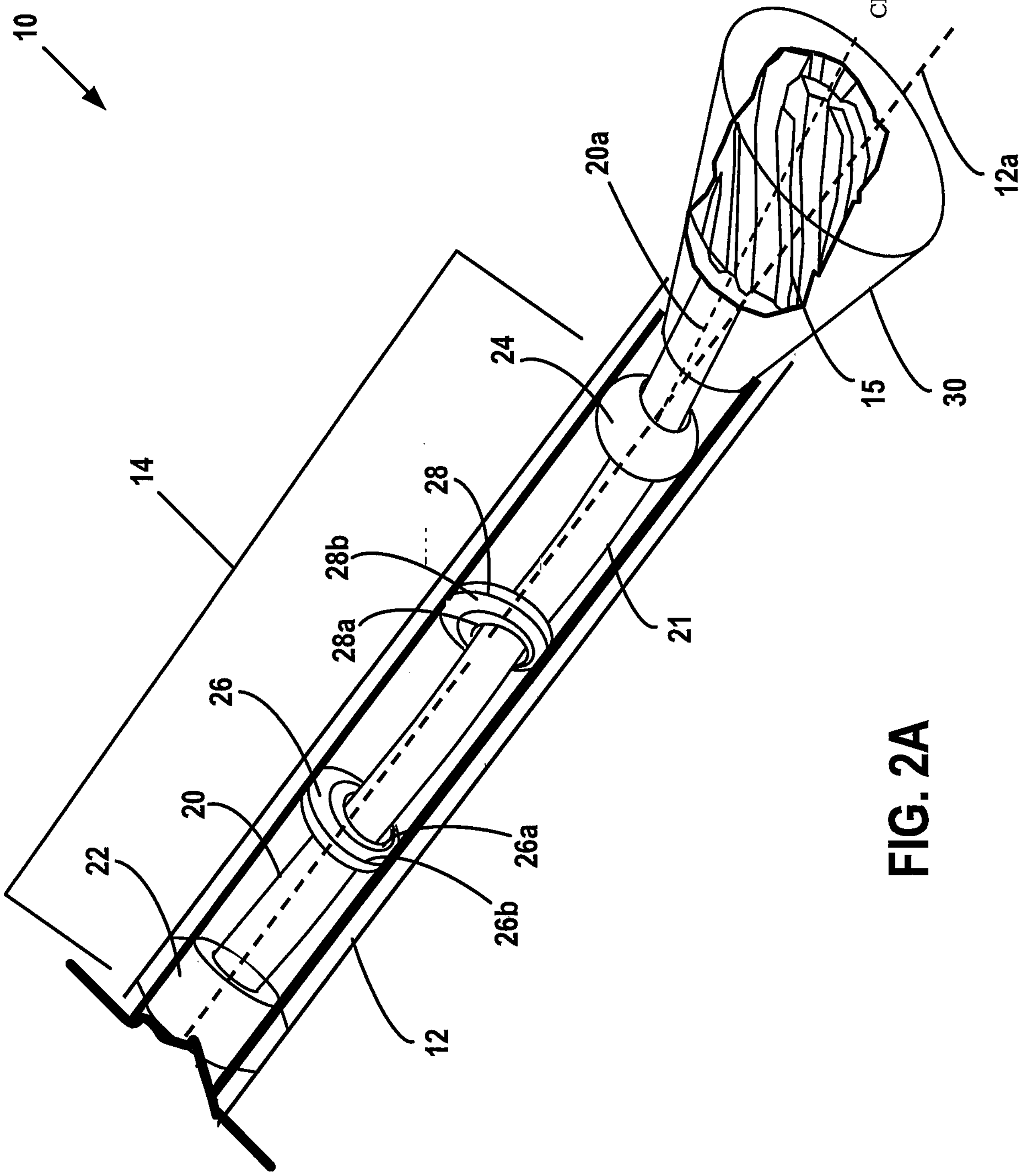

FIG. 2A

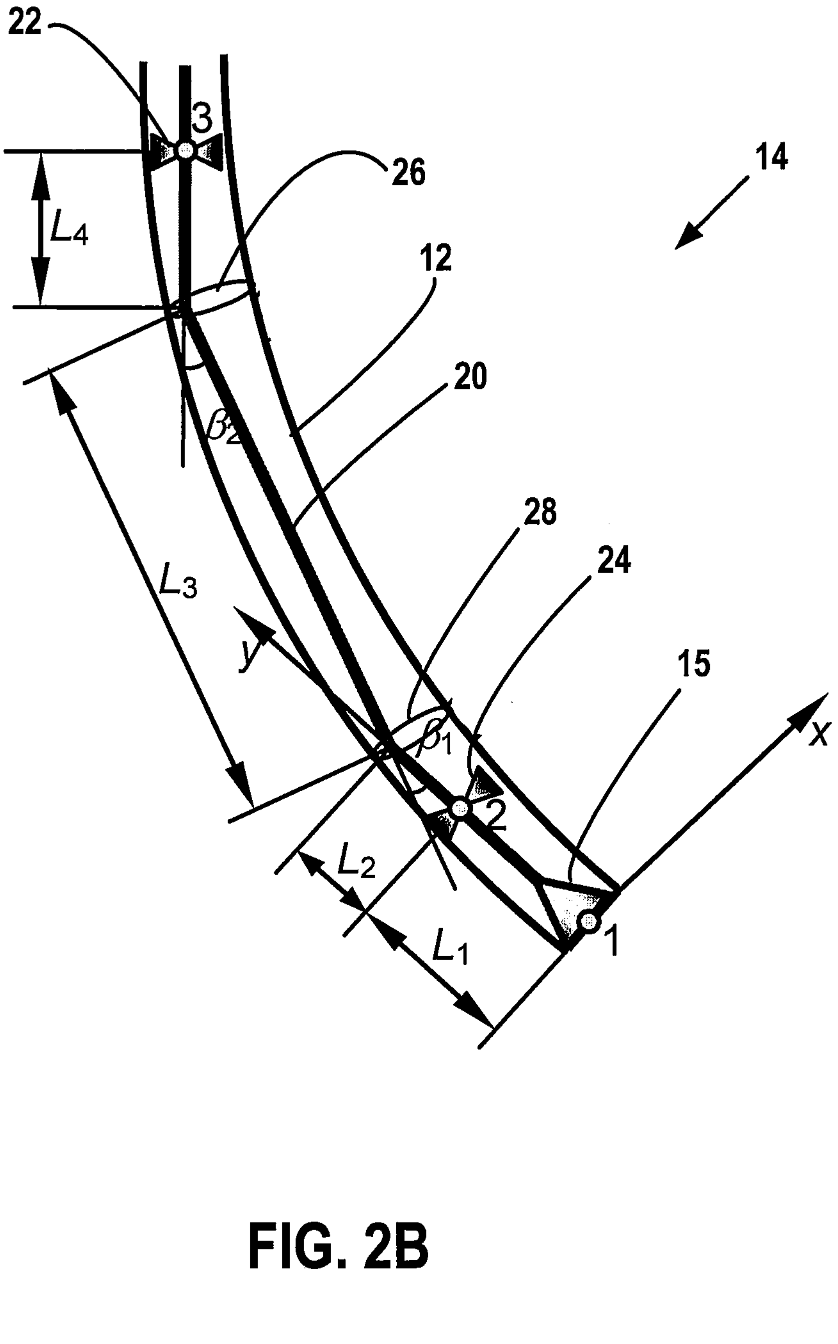

FIG. 2B

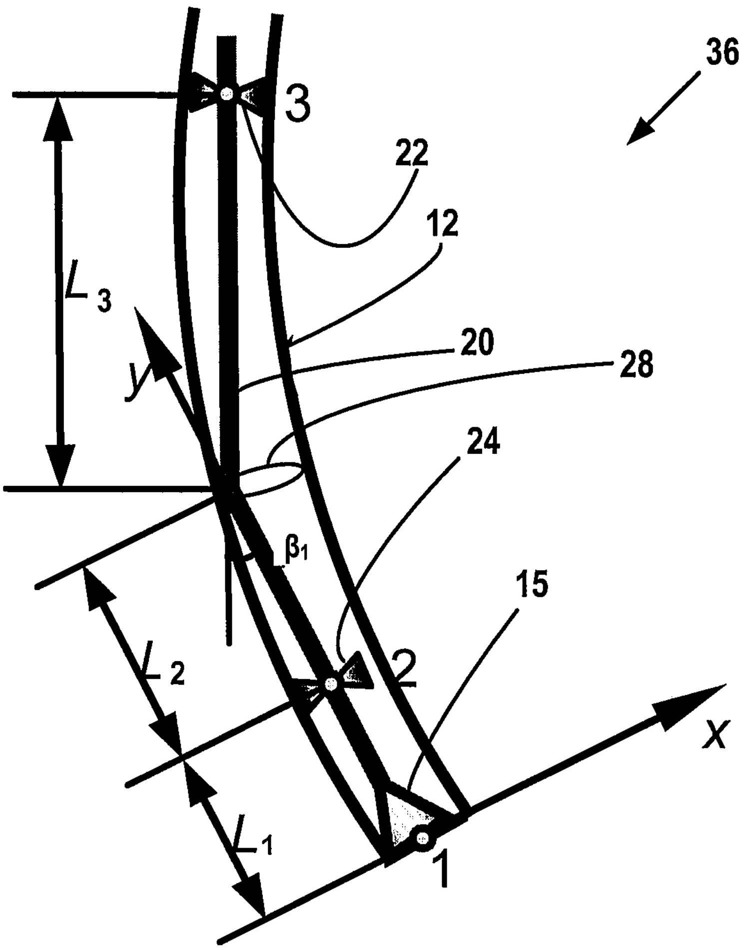

FIG. 3

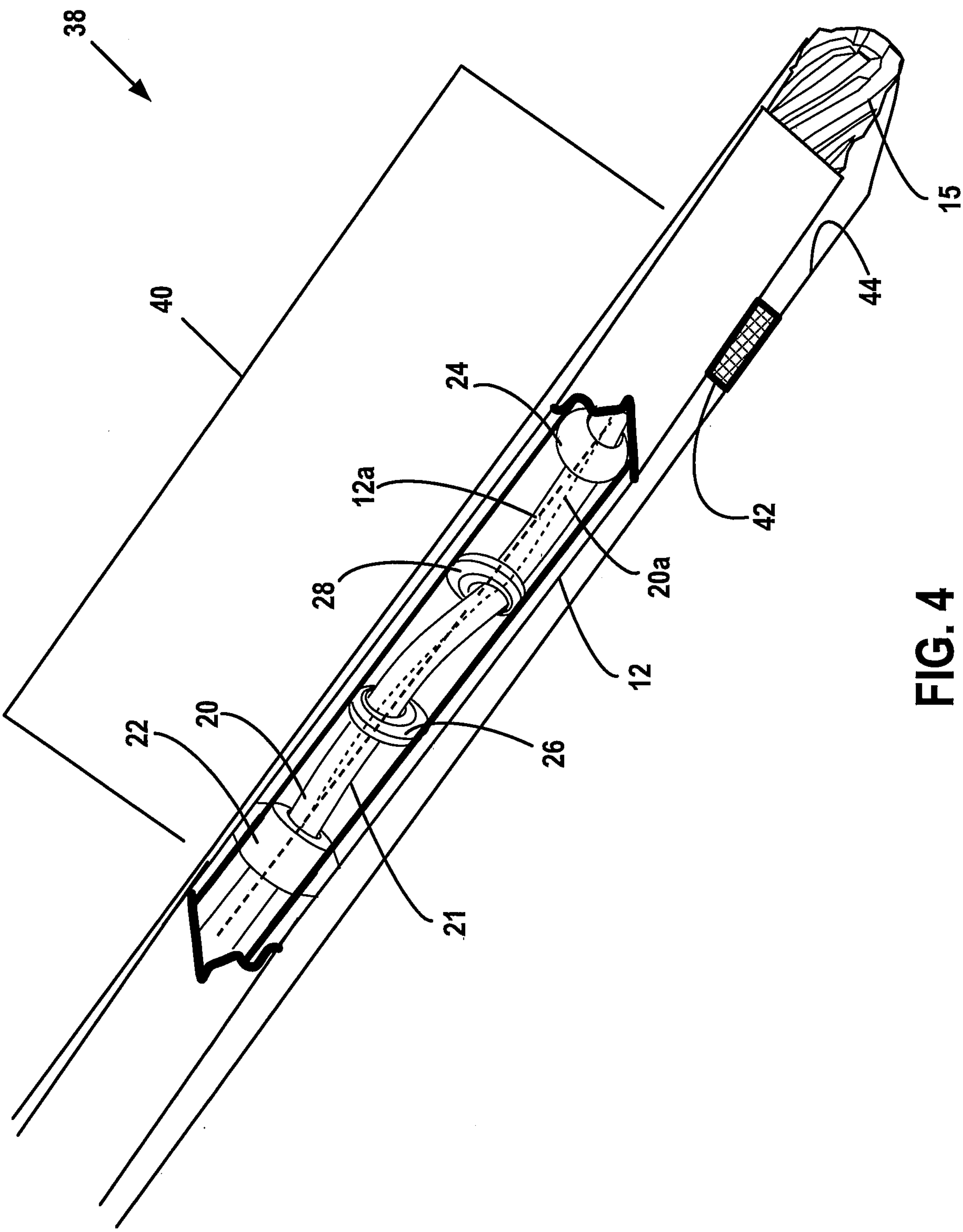

FIG. 4

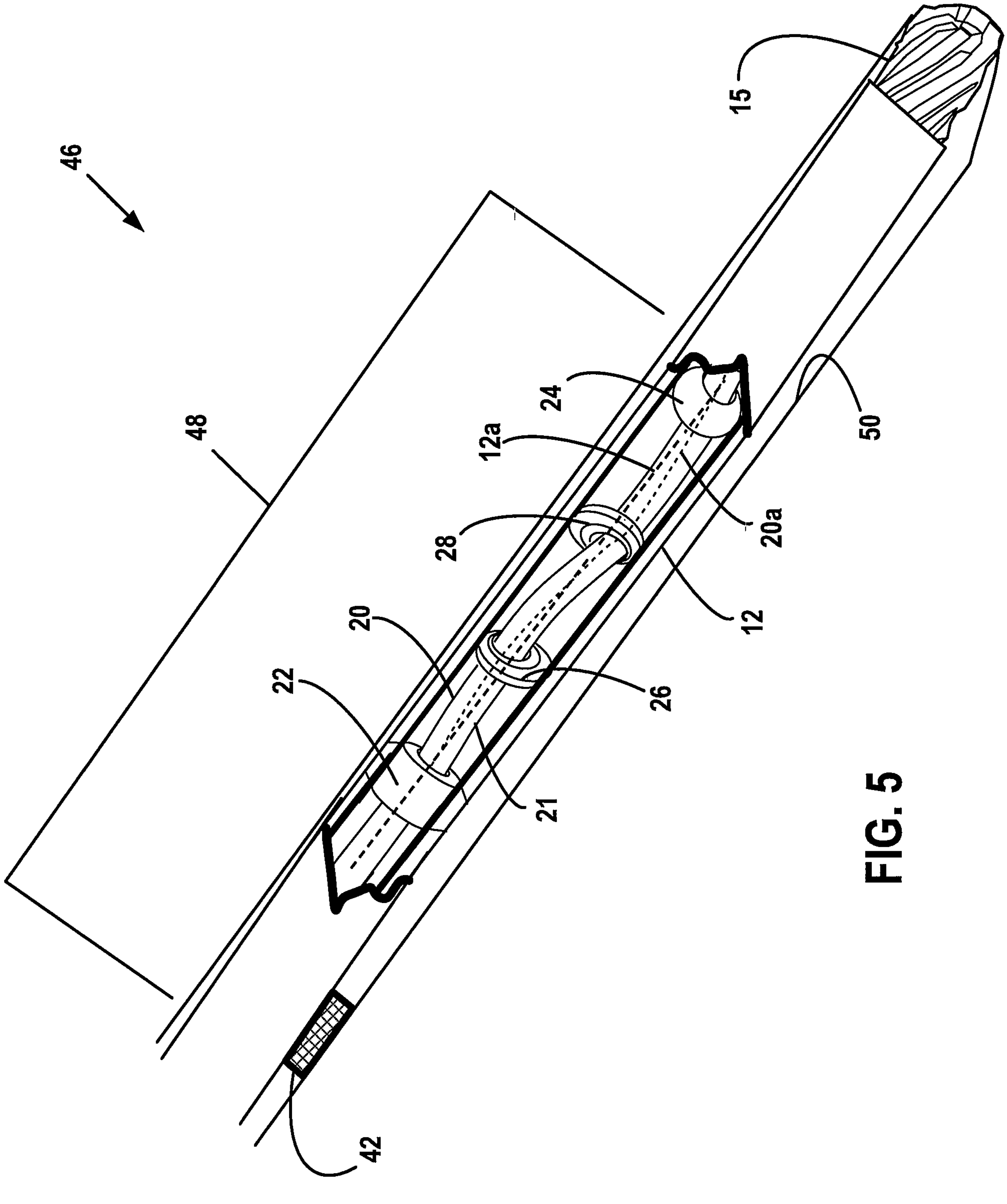

FIG. 5

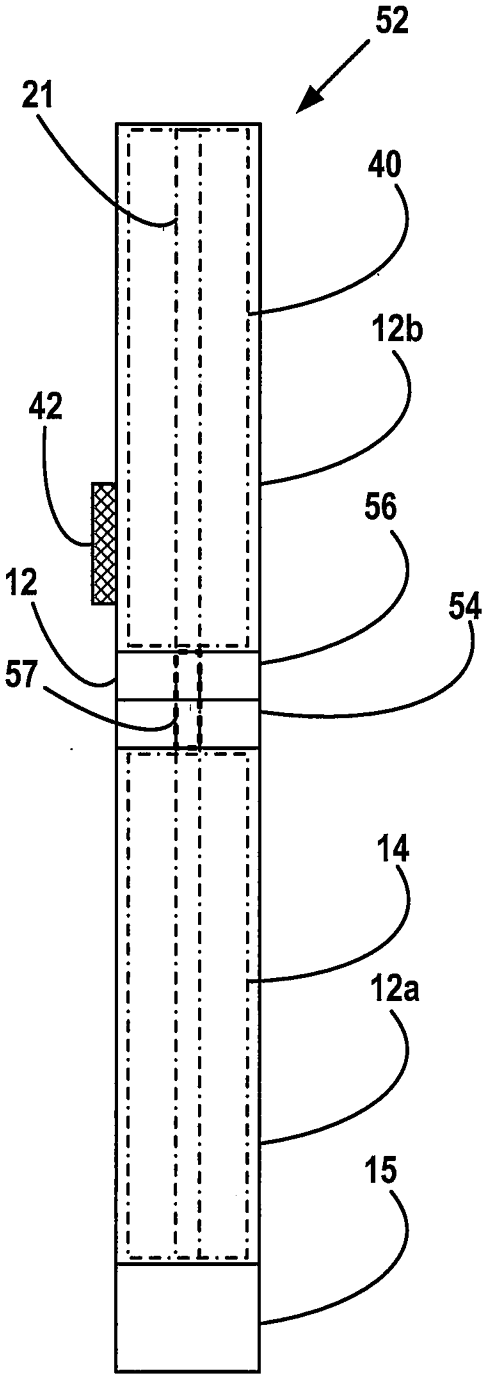
52
21
40
12b
42
56
12
54
57
14
12a
15

FIG. 6

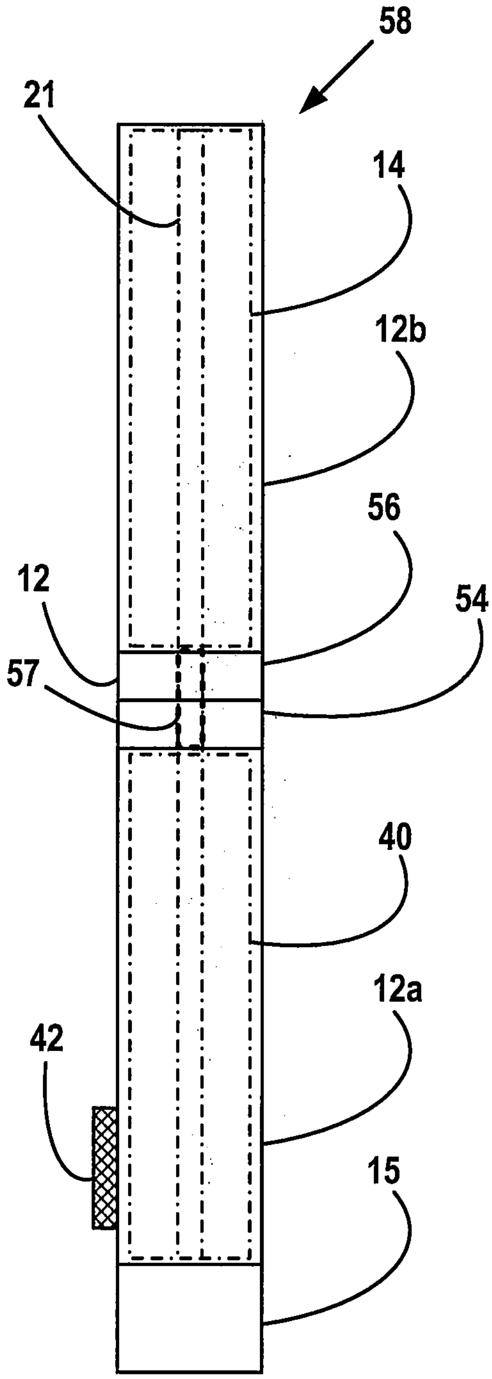
58
21
14
12b
56
12
54
57
40
12a
42
15

FIG. 7

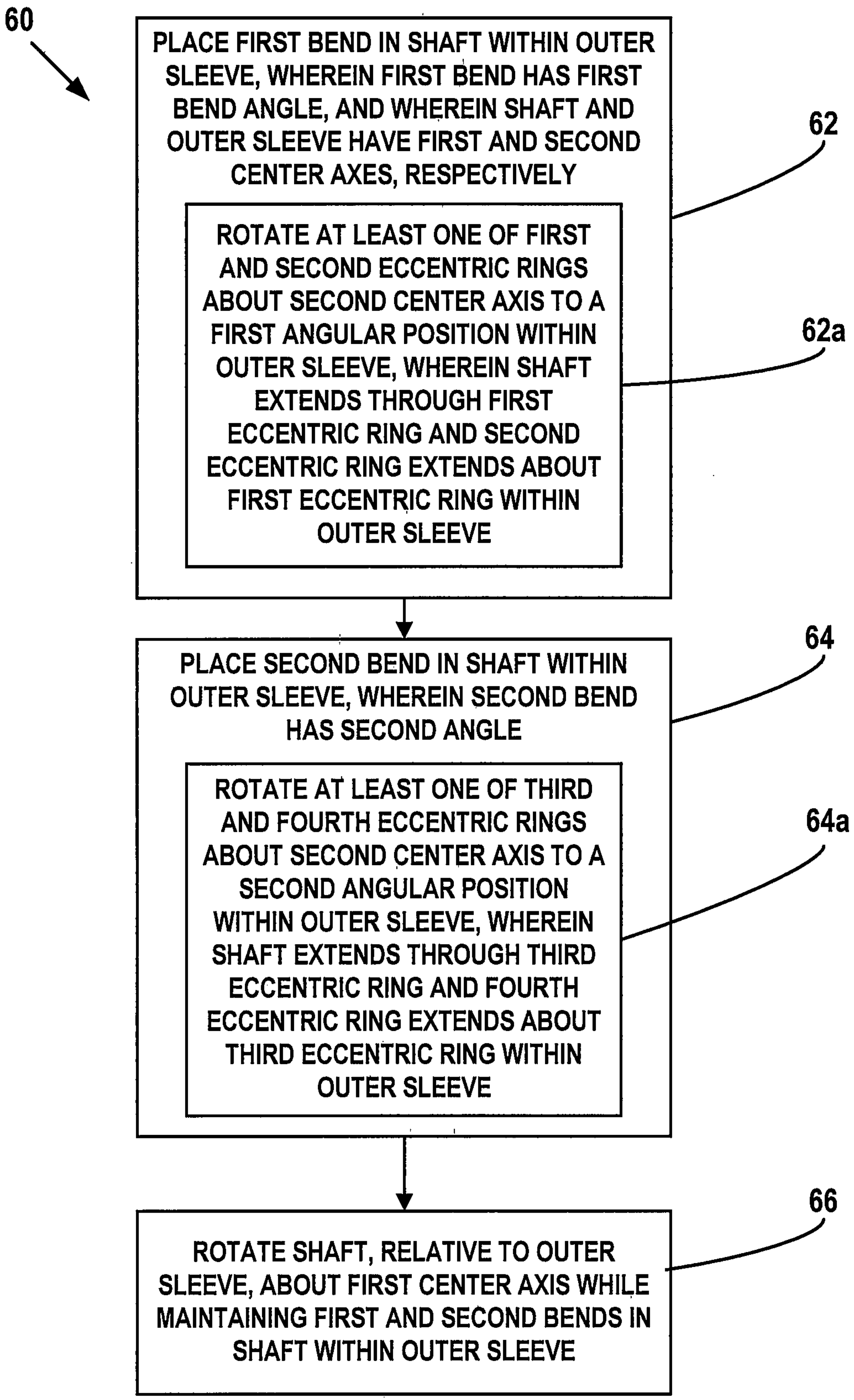
60
PLACE FIRST BEND IN SHAFT WITHIN OUTER SLEEVE, WHEREIN FIRST BEND HAS FIRST BEND ANGLE, AND WHEREIN SHAFT AND OUTER SLEEVE HAVE FIRST AND SECOND CENTER AXES, RESPECTIVELY
62
ROTATE AT LEAST ONE OF FIRST AND SECOND ECCENTRIC RINGS ABOUT SECOND CENTER AXIS TO A FIRST ANGULAR POSITION WITHIN OUTER SLEEVE, WHEREIN SHAFT EXTENDS THROUGH FIRST ECCENTRIC RING AND SECOND ECCENTRIC RING EXTENDS ABOUT FIRST ECCENTRIC RING WITHIN OUTER SLEEVE
62a
PLACE SECOND BEND IN SHAFT WITHIN OUTER SLEEVE, WHEREIN SECOND BEND HAS SECOND ANGLE
64
ROTATE AT LEAST ONE OF THIRD AND FOURTH ECCENTRIC RINGS ABOUT SECOND CENTER AXIS TO A SECOND ANGULAR POSITION WITHIN OUTER SLEEVE, WHEREIN SHAFT EXTENDS THROUGH THIRD ECCENTRIC RING AND FOURTH ECCENTRIC RING EXTENDS ABOUT THIRD ECCENTRIC RING WITHIN OUTER SLEEVE
64a
ROTATE SHAFT, RELATIVE TO OUTER SLEEVE, ABOUT FIRST CENTER AXIS WHILE MAINTAINING FIRST AND SECOND BENDS IN SHAFT WITHIN OUTER SLEEVE
66

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/043535

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - E21B 7/04 (2011.01)
USPC - 175/73
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)
IPC(8) - E21B 7/04, 7/08 (2011.01)
USPC - 166/384; 175/22, 61, 73, 75, 231, 325.1, 398

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
ECLA - E21B 7/06K

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2005/0236187 A1 (CHEN et al) 27 October 2005 (27.10.2005) entire document	11-12, 16 --- 1-8, 13-15, 17-20
Y	US 3,049,185 A (HERBOLD) 14 August 1962 (14.08.1962) entire document	1-8, 13-15, 19-20
Y	US 2002/0043372 A1 (CARGILL et al) 18 April 2002 (18.04.2002) entire document	7-8, 17-20
A	US 6,234,259 B1 (KUCKES et al) 22 May 2001 (22.05.2001) entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐

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

Date of the actual completion of the international search	Date of mailing of the international search report
28 November 2011	08 DEC 2011

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