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(54) **Rotary and axial modulation for mud-pulse telemetry**

(57) A mud-pulse telemetry tool (46) carried by a drill collar and comprising a stator (62), positionally fixed relative to the drill collar, and a rotor (64), axially offset from the stator by a gap. A first actuator (58) is operable to cause selective rotation of the rotor relative to the stator. A second actuator (59) is operable to cause selective adjustment of the gap during operation of the mud-pulse telemetry tool within a wellbore. Such telemetry tool may form a pressure pulse generator, operable to generate a pressure wave in drilling mud in the wellbore, and a data encoder, operable to receive data from a data source and vary the pressure wave based on the data such that the pressure wave encodes the data, wherein the pressure pulse generator and the data encoder are collectively operable to modulate the data-encoded pressure wave utilizing at least three different pressure levels.

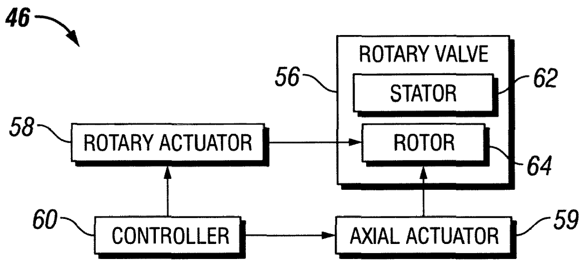

FIG. 2

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Description

Background of the Disclosure

[0001] One or more aspects of the present disclosure relate to well drilling operations and apparatus. During some well drilling operations, downhole apparatus may communicate with surface equipment via mud-pulse telemetry.

[0002] For example, logging-while-drilling (LWD) and measurement-while-drilling (MWD) techniques may be utilized to obtain various measurements via one or more sensors within the wellbore and/or the subterranean formation penetrated by the wellbore. Such measurements may pertain to characteristics of the wellbore (*e.g.*, azimuth and inclination), downhole apparatus (*e.g.*, bit speed), and/or the formations (*e.g.*, density, pressure, and resistivity), for example. The measured data may be communicated to the surface equipment via mud-pulse telemetry, in which drilling fluid or "mud" is utilized as a propagation medium for a pressure wave. That is, data may be communicated to surface by modulating one or more features of the pressure wave to represent the data. For example, variations in the amplitude, frequency, and/or phase of the pressure wave may represent different bits of data. The surface equipment may detect such modulations and, thus, the data encoded thereby.

[0003] The downhole mud-pulse telemetry equipment may comprise a stator and a rotor that is rotationally driven relative to the stator to achieve the modulation. The data to be transmitted to surface is encoded in the pressure wave utilizing two different pressure levels. That is, a minimum pressure corresponds to the rotor permitting fluid flow through the stator, and a maximum pressure corresponds to the rotor preventing fluid flow through the stator. The stator and rotor are axially offset by a predetermined gap that is set at the surface before the equipment is conveyed downhole. The gap sets the maximum pressure of the modulation, and cannot be changed without returning the downhole equipment to surface.

Summary of the Disclosure

[0004] The present disclosure introduces an apparatus that includes a mud-pulse telemetry tool carried by a drill collar. The mud-pulse telemetry tool includes a stator and a rotor axially offset from the stator by a gap. A first actuator of the mud-pulse telemetry tool is operable to cause selective rotation of the rotor relative to the stator. A second actuator of the mud-pulse telemetry tool is operable to cause selective adjustment of a dimension of the gap during operation of the mud-pulse telemetry tool within a wellbore that extends into a subterranean formation.

[0005] The stator, rotor, and first and second actuators may collectively form a pressure pulse generator and a data encoder. The pressure pulse generator may be operable to generate a pressure wave in a drilling fluid disposed in the wellbore, and the data encoder may be operable to receive data from a data source and vary the pressure wave based on the data such that the pressure wave encodes the data. Such pressure pulse generator and data encoder may be collectively operable to modulate the data-encoded pressure wave utilizing at least three pressure levels.

[0006] The present disclosure also introduces a method that includes operating downhole apparatus disposed in a wellbore that extends into a subterranean formation. The downhole apparatus includes a stator and a rotor axially offset from the stator by a gap. Operating the downhole apparatus includes rotating the rotor relative to the stator to generate a pressure wave in a drilling fluid disposed in the wellbore. Operating the downhole apparatus also includes encoding data in the pressure wave. At least one of generating and encoding the pressure wave includes selectively adjusting the gap between the rotor and the stator to modulate the pressure wave utilizing at least three pressure levels.

[0007] These and additional aspects of the present disclosure are set forth in the description that follows, and/or may be learned by a person having ordinary skill in the art by reading the materials herein and/or practicing the principles described herein. At least some aspects of the present disclosure may be achieved via means recited in the attached claims.

Brief Description of the Drawings

[0008] The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. 1 is a schematic view of at least a portion of apparatus according to one or more aspects of the present disclosure.

FIG. 2 is a block diagram of at least a portion of the apparatus shown in FIG. 1 according to one or more aspects of the present disclosure.

FIG. 3 is a graph depicting one or more aspects of the present disclosure.

FIG. 4 is a sectional view of a portion of an example implementation of the apparatus shown in FIGS. 1 and 2.

FIG. 5 is a sectional view of the apparatus shown in FIG. 4.

FIG. 6 is a perspective view of a portion of an example implementation of the apparatus shown in FIGS. 4 and 5.

FIG. 7 is a perspective view of a portion of the example implementation of the apparatus shown in FIG. 6.

FIG. 8 is a perspective view of a portion of the example implementation of the apparatus shown in FIGS. 6 and 7.

FIG. 9 is a perspective view of a portion of the example implementation of the apparatus shown in FIG. 6-8.

FIG. 10 is a perspective view of a portion of an example implementation of the apparatus shown in FIGS. 4 and 5.

FIG. 11 is a perspective view of a portion of the example implementation of the apparatus shown in FIG. 10.

FIG. 12 is a perspective view of a portion of the example implementation of the apparatus shown in FIGS. 10 and 11.

FIG. 13 is a block diagram of at least a portion of apparatus according to one or more aspects of the present disclosure.

FIG. 14 is a flow-chart diagram of at least a portion of a method according to one or more aspects of the present disclosure.

Detailed Description

[0009] It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact.

[0010] FIG. 1 is a schematic view of at least a portion of an example implementation of a drilling system 10 according to one or more aspects of the present disclosure. The drilling system 10 is operable to communicate data via mud-pulse telemetry according to one or more aspects introduced herein. While various elements of the drilling system 10 are depicted in FIG. 1 and generally discussed below, a person having ordinary skill in the art will readily appreciate that the drilling system 10 may include other components in addition to, or in place of, those depicted in FIG. 1 and/or described below.

[0011] The drilling system 10 may comprise a drilling rig 12 that supports a drill string 14 disposed within a wellbore 16. A drill bit 18 may be positioned at the downhole end of the drill string 14, and may be configured to cut into one or more subterranean formations 15, thereby extending the wellbore 16 into the formation(s) 15. The drilling system 10 may also comprise or be utilized in conjunction with a casing 20, such as may maintain the structural integrity of the wellbore 16.

[0012] During a drilling operation, various drill cuttings and/or other debris may collect near the bottom of the wellbore 16. The temperature of the drill bit 18 may also increase due to friction between the drill bit 18 and the drilled subterranean formation 15. Accordingly, a drilling fluid 22, commonly referred to as drilling mud, is cycled through the wellbore 16 to remove the debris and/or facilitate cooling of the drill bit 18.

[0013] For example, the mud 22 may be pumped from a reservoir or mud pit 24 and through the wellbore 16 via a pump 26. The pump 26 may route the mud 22 through supply conduits 28 to the drill string 14, as depicted in FIG. 1 by arrows 30. The mud 22 may flow downwardly through the drill string 14 toward the drill bit 18, as depicted in FIG. 1 by arrows 32. The mud 22 may exit the drill string 14 at or near the drill bit 18, such as through one or more ports in the drill bit 18 (not shown). The mud 22 may then return to the surface through an annulus 34 between the circumference of the wellbore 16 and the drill string 14, as depicted in FIG. 1 by arrows 36. The return mud 22 may exit the wellbore 16 via a return conduit 38, which may route the mud 22 back to the reservoir 24, as depicted in FIG. 1 by arrows 40. Accordingly, the mud 22 routed through the wellbore 16 may cool and/or lubricate the drill bit 18 and/or remove debris from the wellbore 16. The debris in the mud 22 returning to the reservoir 24 from the wellbore 16 may settle to the bottom of the reservoir 24 and/or otherwise be removed from the mud 22, thus allowing the mud 22 to be recycled through the wellbore 16 substantially continuously.

[0014] Various additional components and tools may also be provided in the wellbore 16, such as components configured to facilitate MWD or LWD operations. Such additional components may comprise one or more data sources 42. For example, the data sources 42 may be or comprise various instruments and/or sensors operable to measure information relevant to drilling operations and/or the subterranean formation 15. Non-limiting examples of such information include position data, orientation data, pressure data, resistivity data, and gamma ray data, although the use of sensors to measure other parameters is also within the scope of the present disclosure.

[0015] Data collected from the one or more data sources 42 may be electronically transmitted to an assembly that comprises an encoder 44 and a modulator 46, which may cooperate to generate and vary aspects of a pressure wave to represent the data from the one or more data sources 42, as discussed in greater detail below. The pressure wave propagates through the mud 22 in the drill string 14 and the supply conduit 28 (which may include a standpipe of the drilling rig 12), as depicted in FIG. 1 by arrows 50. One or more pressure transducers and/or other sensors 52 at the surface of the drilling system 10 detect variations in the pressure wave.

[0016] One or more computers, processors, controllers, and/or other surface equipment 54 may process the detected variations, such as to reconstruct the original data from the one or more data sources 42. For example, the surface equipment 54 may be operable to execute one or more programs stored within a local and/or other memory, such as to correlate the wave modulations with sequences of bits of digital data corresponding to the data originally obtained by the one or more data sources 42. The surface equipment 54 may also facilitate control and/or monitoring of other aspects of the drilling system 10. For example, the surface equipment 54 may facilitate control of the pump 26.

[0017] FIG. 2 is a block diagram of at least a portion of an example implementation of the modulator 46 shown in FIG. 1 according to one or more aspects of the present disclosure. The modulator 46 comprises or operates in conjunction with a rotary valve 56 that comprises a stator 62 and a rotor 64. The modulator 46 also comprises or operates in conjunction with a rotary actuator 58 and an axial actuator 59. The rotary actuator 58 is operable to selectively rotate the rotor 64 relative to the stator 62 around an axis of rotation, such as by applying a mechanical, electrical, electromechanical, electromagnetic, hydraulic, and/or other force to the rotor 64. Such force may drive rotation of the rotor 64, or the force may be a braking force impeding rotation of the rotor 64, such as in implementations in which the rotor 64 is driven by a turbine in response to the flow of mud 22. The axial actuator 59 is operable to selectively translate the rotor 64 axially along the axis of rotation, relative to the stator 62, such as by applying a mechanical, electrical, electromechanical, electromagnetic, hydraulic, and/or other force to the rotor 64.

[0018] A controller 60 selectively provides control signals to the rotary actuator 58 and the axial actuator 59. The modulator 46 may comprise at least a portion of the controller 60, or the controller 60 may form at least a portion of another component of the downhole apparatus being utilized in conjunction with the modulator 46.

[0019] The controller 60 drives the rotary actuator 58 to rotate the rotor 64 with respect to the stator 62 to selectively inhibit the flow of mud 22 through the rotary valve 56 and thereby generate pressure pulses forming the pressure wave described above. For example, the stator 62 and the rotor 64 may include complimentary openings that allow mud 22 to flow through the rotary valve 56 when oriented in an "open" position, and that prevent such flow when oriented in a "closed" position. The selective inhibition of the flow of mud 22 may result in a continuous pressure wave, having a period proportional to the rate of interruption, and that propagates from the rotary valve 56 towards the surface through the mud 22.

[0020] The controller 60 drives the axial actuator 59 to translate the rotor 64 with respect to the stator 62 and thereby adjust an axial offset or gap between the rotor 64 and the stator 62. The gap may be adjusted in this manner to adjust the pressure of the pulses generated via operation of the rotary actuator 58. Thus, the pressure of the pulses generated via operation of the rotary actuator 58 may be varied via operation of the axial actuator 59. FIG. 3 is a graph depicting various pressure pulses of a pressure wave 68 that may be achieved via such rotary and axial actuation of the rotor 64 relative to the stator 62. The pressure wave 68 comprises a minimum pressure and a maximum pressure. The minimum pressure 69 remains substantially constant regardless of the position of the rotor 64 relative to the stator 62, but the maximum pressure varies as a function of the gap between the rotor 64 and the stator 62. For example, a maximum pressure pulse 70 may correspond to the rotary actuator 58 positioning the rotor 64 in the closed position while the axial actuator 59 minimizes the gap axially separating the rotor 64 from the stator 62. The minimum gap may be about 0.01 inches (or about 0.25 mm), although other values are also within the scope of the present disclosure. Another pressure pulse 72 may correspond to the rotary actuator 58 positioning the rotor 64 in the open position after the axial actuator 59 has increased the gap between the rotor 64 and the stator 62. The maximum gap may be about 0.10 inches (or about 2.54 mm), although other values are also within the scope of the present disclosure.

[0021] The maximum and/or minimum gap lengths between the rotor 64 and the stator 62 may vary across the myriad implementations within the scope of the present disclosure. The maximum and/or minimum gap lengths may be predetermined, such as in implementations in which the maximum and/or minimum gap lengths are set at the surface prior to introducing the modulator 46 and associated downhole apparatus into the wellbore. The maximum and/or minimum gap lengths may also be determined while the modulator 46 and associated downhole apparatus are disposed at one or more depths within the wellbore, such as during telemetry startup and/or calibration operations. Factors that may contribute to the maximum and/or minimum gap lengths may include density, flow rate, and/or other parameters associated with the mud 22, and dimensions, responsiveness (e.g., lag), and/or other parameters associated with the modulator 46 and/or other components of the associated downhole apparatus, as well as the amount and/or type of data to be transmitted to surface via operation of the modulator 46 and associated downhole apparatus. The pressure differential between the pressure pulses 70 and 72 may range between about 5% and about 20%, such as in implementations in which the pressure differential is about 10%, although other values are also within the scope of the present disclosure.

[0022] Conventional mud-pulse telemetry systems have shown to present bandwidth limitations because, for example, data encoding in the pressure wave was limited to two pressure levels, namely a maximum pressure and a minimum pressure. However, the availability of one or several additional pressure levels according to one or more aspects of the present disclosure can increase data bandwidth, by introducing at least a third pressure level to be utilized when data is encoded in the resulting pressure wave.

[0023] The axial actuator 59 may also be selectively operable for utilization with more than two gap lengths, such that multiple intermediate pressure levels may be available for data encoding. For example, as depicted in the example shown in FIG. 3, pressure pulses 74 at additional pressure levels between those of the maximum pressure pulse 70 and the intermediate pressure pulse 72 may be possible in some implementations within the scope of the present disclosure, assuming the surface equipment 54 is able to discern the pressure differences between each of the pressure pulses 70, 72, and 74.

[0024] FIGS. 4 and 5 are cross-sectional views of an example implementation of the modulator 46 shown in FIGS. 1 and 2, designated herein by reference numeral 146. The modulator 146 comprises a stator 162, a rotor 164, a rotary actuator 158, and an axial actuator 159, which at least functionally correspond to the stator 62, the rotor 64, the rotary actuator 58, and the axial actuator 59, respectively, of the modulator 46 shown in FIGS. 1 and 2 and described above.

[0025] The modulator 146 is carried within a drill collar 102, whether separately or in combination with associated downhole apparatus. The stator 162 is coupled to or otherwise positionally fixed relative to the drill collar 102. The rotor 164 is positionally fixed relative to a shaft 104. The operational stage depicted in FIG. 4 corresponds to the maximum pressure level 72 shown in FIG. 3, such that the axial offset or gap 147 between the rotor 164 and the stator 162 is the maximum gap. For example, the axial offset or gap 147 depicted in FIG. 4 may be about 0.10 inches (or about 2.54 mm), although other values are also within the scope of the present disclosure.

[0026] FIG. 5 is a sectional view of the modulator 146 shown in FIG. 4 in which the axial actuator 159 has extended the output feature 118, thus sliding the bearings 106 in the recess 108 away from the axial actuator 159. Accordingly, the shaft 104 has likewise translated in an uphole direction, such that the end 105 of the shaft extends further into the recess 163 of the stator 162, and the gap 147 has substantially decreased. The configuration depicted in FIG. 5 may correspond to one of the pressure levels 70 or 74 shown in FIG. 3. For example, in an implementation in which the configuration depicted in FIG. 5 corresponds to the pressure level 70 shown in FIG. 3, the width of the gap 147 depicted in FIG. 5 may be about 0.01 inches (or about 0.25 mm), although other values are also within the scope of the present disclosure.

[0027] The shaft 104 is rotatably supported within the drill collar 102, such as by one or more bearings 106 received within a recess 108 of a chassis 110. For example, the bearings 106 may comprise a stack of thrust bearings, wherein an inner race of the bearings 106 may be positionally fixed relative to the shaft 104, and an outer race of the bearings 106 may be rotatably coupled with the inner race and slidable within the recess 108 of the chassis 110. As described below, the sliding of the bearings 106 within the recess 108 of the chassis 110 may be in response to operation of the axial actuator 159.

[0028] The chassis 110 is coupled to or otherwise positionally fixed relative to the drill collar 102. The shaft 104 may extend at least partially into the chassis 110 in a manner permitting rotation relative to the chassis 110.

[0029] A fastener 112 may retain the bearings 106 relative to the shaft 104, such as in conjunction with a shoulder, member, and/or other feature 114 protruding radially from the shaft 104. The fastener 112 may be a locknut threaded to the shaft 104, although other means for securing the bearings 106 to the shaft 104 are also within the scope of the present disclosure.

[0030] An uphole end 105 of the shaft 104 may also be mechanically supported or otherwise received within a corresponding recess 163 of the stator 162. Although not depicted in FIG. 4, one or more bearings may support the uphole end 105 of the shaft 104 within the recess 163 of the stator 162. The recess 163 may also be sized sufficiently larger than the end 105 of the shaft 104 so that the shaft end 105 may rotate within but not contact the recess 163.

[0031] The rotor 164 may be coupled to the shaft 104 by threads, fasteners, welding, interference/press fit, and/or other means. Such coupling may utilize a shoulder, member, and/or other feature 120 protruding radially from the shaft 104. The radially protruding features 114 and 120 are depicted in FIG. 4 as being outwardly opposing faces of a portion of the shaft 104 having an enlarged diameter. However, other arrangements for positionally fixing the rotor 164 and/or the bearings 106 to the shaft 104 are also within the scope of the present disclosure.

[0032] As described above, the rotary actuator 158 may be or comprise a mechanical, electrical, electromechanical, electromagnetic, hydraulic, and/or other type of actuator selectively operable to drive rotation of the shaft 104 and, thus, the rotor 164 around a rotational axis 116. However, the rotary actuator 158 may instead apply a braking force to the rotor 164, such as in implementations in which the rotor 164 is driven by a turbine (not shown) in response to the flow of mud. The rotary actuator 158 may be received within a recess 124 of the chassis 110, although other means for assembling the rotary actuator 158 within the modulator 146 are also within the scope of the present disclosure.

[0033] The axial actuator 159 may be or comprise a mechanical, electrical, electromechanical, electromagnetic, hydraulic, and/or other type of actuator and/or motive force selectively operable to translate the rotor 164 axially along the rotational axis 116 of the shaft 104 and rotor 164, thereby adjusting the gap 147 in a direction substantially parallel with the rotational axis 116 of the rotor 164. The axial actuator 159 may be received within a recess 126 of the chassis 110 and/or otherwise positionally fixed relative to the chassis 110.

[0034] Operation of the axial actuator 159 may generate a force imparted to the bearings 106. The bearings 106 may be slidable within the recess 108 of the chassis 110. Thus, operation of the axial actuator 159 may translate the bearing 106, and thus the shaft 105 and the rotor 164, relative to the chassis 110, thereby adjusting the width of the gap 147.

[0035] An output shaft, member, linkage, and/or other feature 118 may extend from the axial actuator 159 and/or between the axial actuator 159 and the bearings 106. Operation of the axial actuator 159 may extend and retract the feature 118, and such motion may be imparted to the rotor 164 through the bearings 106 and the shaft 104. However, other means for transferring the motive force of the axial actuator 159 to the rotor 164, including via various mechanical and/or other features collectively connecting the rotor 164 to the axial actuator 159, are also within the scope of the present disclosure.

[0036] The modulator 146 may also comprise a biaser 122 operable to resist closure of the gap 147. For example, the biaser 122 may comprise one or more compression springs, Bellville springs, and/or other substantially elastic members operable to axially urge the bearings 106 towards the axial actuator 159, thus enlarging the gap 147. The bearings 106 may instead or also be coupled to the bearings 106 and/or otherwise arranged such that retraction of the output feature 118 causes or encourages the bearings 106 to slide in the recess 108 towards the axial actuator 159, thus widening the gap 147.

[0037] FIG. 6 is a perspective view of an example implementation of the axial actuator 159 shown in FIGS. 4 and 5, designated herein by reference numeral 259. The axial actuator 259 comprises a linear motive source 230 and a linkage assembly 232.

[0038] The motive source 230 comprises a substantially cylindrical housing 234 and an output feature (e.g., shaft) 236 reciprocally driven in opposing lateral directions, which are substantially parallel to the longitudinal axis 235 of the housing 234. The motive source 230 may comprise a motor and/or actuator (not shown) disposed within the housing 234 and selectively operable to electrically, electromechanically, electromagnetically, hydraulically, or otherwise drive the output feature 236 in a linearly reciprocating manner.

[0039] The linkage assembly 232 comprises a bearing seat 238 and a linkage arm 240. The linkage arm 240 may be a yoke or other Y-shaped member, with an open end 242 rotatably coupled to pivot pins and/or other portions 239 of the bearing seat 238, and the other end 244 rotatably coupled to the output feature 236 of the motive source 230. The linkage assembly may also comprise a ball joint 246 rotatably coupling the end 244 of the linkage arm 240 to the output feature 236 of the linear motive source 230. This type of coupling with the Y-shaped member may transmit the motion between the motive source 230 and the bearing 106 in a way that may aid in ensuring an adequate distribution of stress. However, other types of mechanical coupling may also or instead be utilized.

[0040] FIG. 7 is a perspective view of the example axial actuator 259 shown in FIG. 6 assembled with the shaft 104 and bearings 106 shown in FIGS. 4 and 5. The shaft 104 extends through the bearing seat 238, such that an uphole-facing surface 241 of the bearing seat 238 (see FIG. 6) abuts a downhole end of the stack of bearings 106.

[0041] FIGS. 8 and 9 are sectional views of at least a portion of an example implementation of the modulator 146 shown in FIGS. 4 and 5, designated herein by reference number 346. The modulator 346 comprises the axial actuator 259 shown in FIGS. 6 and 7. The example implementation depicted in FIGS. 8 and 9 also comprises a stator 262, a rotor 264, and a rotary actuator (not shown), which at least functionally correspond to the stator 62, the rotor 64, and the rotary actuator 58, respectively, of the modulator 46 shown in FIGS. 1 and 2, and/or the stator 162, the rotor 164, and the rotary actuator 158, respectively, of the modulator 146 shown in FIGS. 4 and 5.

[0042] The modulator 346 may also comprise a wear sleeve 350 received within a corresponding recess 352 of the drill collar 102. The wear sleeve 352 may comprise a material that is stronger and/or more durable than that of the drill collar 102, and/or otherwise more resistant to wear and erosion resulting from mud and debris flowing past the stator 262 and the rotor 264.

[0043] The modulator 346 may also comprise a face seal 354 fluidly isolating the bearings 106 and other internal components from the flow of mud. A shield 356 may aid in maintaining the integrity of such seal. The face seal 354 and shield 356 may rotate with the rotor 264 and shaft 104. The modulator 346 also comprises an example implementation of the chassis 110 shown in FIGS. 4 and 5, designated herein by reference number 358.

[0044] FIGS. 8 and 9 also depict the motive source 230, which may be positionally fixed relative to the chassis 358, such as within a recess 360 of the chassis 358. Another recess 362 of the chassis 358 may be sufficiently large to allow movement of the linkage assembly 232 and output feature of the motive source 230 (in response to operation of the motive source 230).

[0045] FIGS. 8 and 9 also illustrate the biaser 122 (described above with respect to FIGS. 4 and 5) urging the bearings 106 in a downhole direction. The biaser 122 may operate in cooperation with the linkage assembly 232 to slide the bearings 106, and thus the shaft 104 and the rotor 264, relative to the stator 262 and the chassis 358. For example, in FIG. 8, the motive source 230 has been operated to extend the bearings 106, and thus the shaft 104 and the rotor 264, in an uphole direction towards the stator 262, resulting in a minimum gap 347. In FIG. 9, the motive source 230 has been operated to retract the bearings 106, and thus the shaft 104 and the rotor 264, in a downhole direction away from the stator 262, resulting in a maximum gap 347.

[0046] The operation of the biaser 122 and/or the linkage assembly 232, perhaps including the cooperation thereof, may include contact between the linkage arm 240 and a point, line, or area 364 of the recess 362 and/or other recess of the chassis 358 in which the linkage assembly 232 is disposed. Such contact may, for example, be utilized as a fulcrum through which motion of the output feature of the motive source 230 may be imparted to the bearings 106 (by the uphole-facing surface 241 of the bearing seat 238).

[0047] FIG. 10 is a perspective view of another example implementation of the axial actuator 159 shown in FIGS. 4 and 5, designated herein by reference numeral 459. The axial actuator 459 comprises a rotary motive source 430, a rotating cam 410, and a stationary cam 420.

[0048] FIG. 11 is a perspective view of the axial actuator 459 shown in FIG. 10 in a different position (and viewed from a different perspective relative to FIG. 10). FIG. 12 is a perspective view of at least a portion of an example implementation of the modulator 146 shown in FIGS. 4 and 5, designated herein by reference numeral 446. The example implementation depicted in FIG. 12 also comprises the stator 262, the rotor 264, the rotary actuator (not shown), and the chassis 358 shown in FIGS. 8 and 9 and/or otherwise described above. The example implementation depicted in FIG. 12 may be substantially similar to the example implementation depicted in FIGS. 8 and 9, but substituting the axial actuator 459 shown in FIGS. 10 and 11 for the axial actuator 259 shown in FIGS. 6-9. The following description refers to at least FIGS. 10-12, collectively.

[0049] The rotary motive source 430 is positionally fixed relative to the internal chassis 358. An output feature (e.g., shaft) 432 of the rotary motive source 430 is rotationally driven about an axis of rotation 434 that is substantially parallel to the rotational axis 116 of the rotor 264.

[0050] The rotating cam 410 is rotationally driven around the rotational axis 116 by the rotary motive source 430, and comprises an undulating surface 412. The stationary cam 420 is rotationally fixed between the rotating cam 410 and the bearings 116, and comprises an undulating surface 422 abutting the undulating surface 412 of the rotating cam 410. Rotation of the rotating cam 410 relative to the stationary cam 420 varies a stack height 470 of the rotating and stationary cams 410 and 420 between a minimum stack height 470 shown in FIG. 10 and a maximum stack height 470 shown in FIG. 11. The minimum stack height 470 shown in FIG. 10 may be about 0.10 inches (0.25 cm) less than the maximum stack height 470 shown in FIG. 11.

[0051] The rotary motive source 430 may comprise a substantially cylindrical housing 434. The rotary motive source 430 may drive the output feature 432 in a clockwise or counter-clockwise direction, or both clockwise and counter-clockwise in a reciprocating manner. The rotary motive source 430 may comprise a motor and/or actuator (not shown) disposed within the housing 434 and selectively operable to electrically, electromechanically, electromagnetically, hydraulically, or otherwise rotationally drive the output feature 432. The output feature 432 may comprise a gear and/or other feature 438 operable to impart rotation to the rotating cam 410, such as by meshing with a corresponding gear and/or other portion 414 of the rotating cam 410. The gear train thus formed by the feature 438 of the rotary motive source 430 and the portion 414 of the rotating cam 410 may also include additional gears (not shown) and/or other means for transferring rotational motion of the output feature 432 to the rotating cam 410.

[0052] FIG. 12 also illustrates the biaser 122 (described above with respect to FIGS. 4 and 5) urging the bearings 106 in a downhole direction. The biaser 122 may operate in cooperation with the axial actuator 459 to slide the bearings 106, and thus the shaft 104 and the rotor 264, relative to the stator 262 and the chassis 358. A thrust bearing 490 may also be utilized between the rotating cam 410 and the chassis 358 (as shown in FIG. 12) and/or between the rotating cam 410 and the bearings 106 (not shown).

[0053] In FIG. 10, the rotary motive source 430 has been operated to rotate the rotating cam 410 relative to the stationary cam 420 so that the undulating surface 412 of the rotating cam 410 meshes or fits within the undulating surface 422 of the stationary cam 420. Thus, the stack height 470 is minimized, corresponding to a maximum width of the gap between the rotor 264 and the stator 262. This results in a pressure pulse corresponding to the pressure pulse/level 70 shown in FIG. 3. In FIG. 11, the rotary motive source 430 has been operated to rotate the rotating cam 410 relative to the stationary cam 420 so that the undulating surface 412 of the rotating cam 410 does not fit within the undulating surface 422 of the stationary cam 420. Thus, the stack height 470 is maximized, corresponding to a minimum width of the gap between the rotor 264 and the stator 262. This results in a pressure pulse corresponding to the pressure pulse/level 72 or 74 shown in FIG. 3.

[0054] FIG. 13 is a schematic view of at least a portion of apparatus according to one or more aspects of the present disclosure. The apparatus is or comprises a processing system 1300 that may execute example machine-readable instructions to implement at least a portion of one or more of the methods and/or processes described herein, and/or to implement a portion of one or more of the example downhole tools described herein. The processing system 1300 may be or comprise, for example, one or more processors, controllers, special-purpose computing devices, servers, personal computers, personal digital assistant ("PDA") devices, smartphones, internet appliances, and/or other types of computing devices. Moreover, while it is possible that the entirety of the processing system 1300 shown in FIG. 13 is implemented within downhole apparatus, such as the encoder 44, the modulator 46, for instance for controlling the rotary and/or axial modulator 58, 59, other downhole apparatus shown in one or more of FIGS. 1-12, and/or other downhole apparatus, it is also contemplated that one or more components or functions of the processing system 1300 may be implemented in wellsite surface equipment, perhaps including the surface equipment 54 depicted in FIG. 1 and/or other surface equipment, for instance for processing pressure waves received from the downhole tool.

[0055] The processing system 1300 may comprise a processor 1312 such as, for example, a general-purpose programmable processor. The processor 1312 may comprise a local memory 1314, and may execute coded instructions 1332 present in the local memory 1314 and/or another memory device. The processor 1312 may execute, among other things, machine-readable instructions or programs to implement the methods and/or processes described herein. The programs stored in the local memory 1314 may include program instructions or computer program code that, when executed by an associated processor, enable surface equipment and/or downhole controller and/or control system to perform tasks as described herein. The processor 1312 may be, comprise, or be implemented by one or a plurality of processors of various types suitable to the local application environment, and may include one or more of general-purpose computers, special purpose computers, microprocessors, digital signal processors ("DSPs"), field-programmable gate arrays ("FPGAs"), application-specific integrated circuits ("ASICs"), and processors based on a multi-core processor architecture, as non-limiting examples. Of course, other processors from other families are also appropriate.

[0056] The processor 1312 may be in communication with a main memory, such as may include a volatile memory 1318 and a non-volatile memory 1320, perhaps via a bus 1322 and/or other communication means. The volatile memory 1318 may be, comprise, or be implemented by random access memory (RAM), static random access memory (SRAM), synchronous dynamic random access memory (SDRAM), dynamic random access memory (DRAM), RAMBUS dynamic random access memory (RDRAM) and/or other types of random access memory devices. The non-volatile memory 1320 may be, comprise, or be implemented by read only memory, flash memory and/or other types of memory devices. One or more memory controllers (not shown) may control access to the volatile memory 1318 and/or the non-volatile memory 1320.

[0057] The processing system 1300 may also comprise an interface circuit 1324. The interface circuit 1324 may be, comprise, or be implemented by various types of standard interfaces, such as an Ethernet interface, a universal serial bus (USB), a third generation input/output (3GIO) interface, a wireless interface, and/or a cellular interface, among others. The interface circuit 1324 may also comprise a graphics driver card. The interface circuit 1324 may also comprise a communication device such as a modem or network interface card to facilitate exchange of data with external computing devices via a network (*e.g.,* Ethernet connection, digital subscriber line ("DSL"), telephone line, coaxial cable, cellular telephone system, satellite, *etc.*).

[0058] One or more input devices 1326 may be connected to the interface circuit 1324. The input device(s) 1326 may permit a user to enter data and commands into the processor 1312. The input device(s) 1326 may be, comprise, or be implemented by, for example, a keyboard, a mouse, a touchscreen, a track-pad, a trackball, an isopoint, and/or a voice recognition system, among others.

[0059] One or more output devices 1328 may also be connected to the interface circuit 1324. The output devices 1328 may be, comprise, or be implemented by, for example, display devices (*e.g.,* a liquid crystal display or cathode ray tube display (CRT), among others), printers, and/or speakers, among others.

[0060] The processing system 1300 may also comprise one or more mass storage devices 1330 for storing machine-readable instructions and data. Examples of such mass storage devices 1330 include floppy disk drives, hard drive disks, compact disk (CD) drives, and digital versatile disk (DVD) drives, among others. The coded instructions 1332 may be stored in the mass storage device 1330, the volatile memory 1318, the non-volatile memory 1320, the local memory 1314, and/or on a removable storage medium 1334, such as a CD or DVD. Thus, the modules and/or other components of the processing system 1300 may be implemented in accordance with hardware (embodied in one or more chips including an integrated circuit such as an application specific integrated circuit), or may be implemented as software or firmware for execution by a processor. In particular, in the case of firmware or software, the embodiment can be provided as a computer program product including a computer readable medium or storage structure embodying computer program code (*i.e.*, software or firmware) thereon for execution by the processor.

[0061] FIG. 14 is a flow-chart diagram of at least a portion of a method (1400) according to one or more aspects of the present disclosure. The method (1400) may be at least partially executed by at least a portion of apparatus shown in one or more of FIGS. 1-13. The method (1400) may include conveying (1405) a downhole apparatus in a wellbore towards a subterranean formation.

[0062] The method (1400) includes operating a downhole apparatus disposed in a wellbore that extends into a subterranean formation. Such operation may comprise generating (1410) a pressure wave in a drilling fluid disposed in the wellbore, receiving (1420) data from a data source, and encoding (1430) the data in the pressure wave. At least one of generating (1410) and encoding (1430) the pressure wave may comprise modulating the pressure wave utilizing at least two, three, or more different pressure levels, such as shown in FIG. 3 and/or described above. For example, the downhole apparatus may comprise a stator and a rotor, as described above, and modulating the pressure wave utilizing at least three different pressure levels may utilize at least two different axial offsets (gaps) between the stator and the rotor.

[0063] Operating the downhole apparatus may also comprise obtaining (1440) the data to be encoded (1430) in the pressure wave. For example, the downhole apparatus may also comprise and/or be operated in conjunction with various MWD, LWD, and/or other downhole instruments and/or sensors operable to measure information relevant to drilling operations and/or the subterranean formation, for example.

[0064] In view of the entirety of the present disclosure, including the figures, a person having ordinary skill in the art will readily recognize that the present disclosure introduces an apparatus comprising: a mud-pulse telemetry tool carried by a drill collar and comprising: a stator; a rotor axially offset from the stator by a gap; a first actuator operable to cause selective rotation of the rotor relative to the stator; and a second actuator operable to cause selective adjustment of a dimension of the gap during operation of the mud-pulse telemetry tool within a wellbore that extends into a subterranean formation.

[0065] The dimension adjustment may be in a direction substantially parallel with an axis of rotation of the rotor.

[0066] The dimension may have a maximum of about 0.10 inches (0.25 cm).

[0067] The second actuator may be an electrical actuator.

[0068] The second actuator may be selected from the group consisting of: an electromechanical actuator; and an electromagnetic actuator.

[0069] The second actuator may be a hydraulic actuator.

[0070] The stator may be positionally fixed relative to the drill collar.

[0071] The mud-pulse telemetry tool may further comprise: an internal chassis positionally fixed relative to the drill collar, wherein the first and second actuators are each positionally fixed relative to the internal chassis; a shaft coupled with the rotor and extending at least partially through the internal chassis; and a bearing positionally fixed relative to the shaft and slidable within a recess of the internal chassis in response to operation of the second actuator. The second actuator may comprise: a motive source positionally fixed relative to the internal chassis; and a linkage assembly extending between the motive source and the bearing. The motive source may be a linear motive source comprising an output shaft that is reciprocally driven in directions that are substantially parallel with an axis of rotation of the rotor. The linkage assembly may comprise: a bearing seat abutting the bearing; and a linkage arm comprising: a first end rotatably coupled to the bearing seat; and a second lend rotatably coupled to the output shaft of the linear motive source. The apparatus may further comprise a biaser axially urging the bearing into contact with the bearing seat. The linkage assembly may comprise a ball joint rotatably coupling the second end of the linkage arm to the output shaft of the linear motive source.

[0072] The second actuator may comprise: a rotary motive source positionally fixed relative to the internal chassis and comprising an output shaft that is rotationally driven about a first axis of rotation that is substantially parallel to a second axis of rotation about which the rotor rotates; a rotating cam rotationally driven around the first axis of rotation by the rotary motive source and comprising a first undulating surface; and a stationary cam rotationally fixed between the rotating cam and the bearing and comprising a second undulating surface abutting the first undulating surface, such that rotation of the rotating cam relative to the stationary cam varies a stack height of the rotating and stationary cams between a minimum stack height and a maximum stack height. The minimum stack height may be about 0.10 inches (0.25 cm) less than the maximum stack height.

[0073] The present disclosure also introduces an apparatus comprising: a pressure pulse generator disposed in a wellbore and operable to generate a pressure wave in a drilling fluid disposed in the wellbore; and a data encoder disposed in the wellbore and operable to receive data from a data source and vary the pressure wave based on the data such that the pressure wave encodes the data; wherein the pressure pulse generator and the data encoder are collectively operable to modulate the data-encoded pressure wave utilizing at least three different pressure levels. The pressure pulse generator may comprise a stator and a rotor, and two of the at least three different pressure levels may correspond to two different axial offsets between the stator and the rotor. The apparatus may further comprise the data source. The data source may comprise at least one sensor operable in obtaining the data from within at least one of: the wellbore; and a subterranean formation into which the wellbore extends.

[0074] The present disclosure also introduces a method comprising: operating downhole apparatus disposed in a wellbore that extends into a subterranean formation, wherein operating the downhole apparatus comprises: generating a pressure wave in a drilling fluid disposed in the wellbore; receiving data from a data source; and encoding the data in the pressure wave; wherein at least one of generating and encoding the pressure wave comprises modulating the pressure wave utilizing at least three different pressure levels.

[0075] The downhole apparatus may comprise a stator and a rotor, and modulating the pressure wave utilizing the at least three different pressure levels may utilize at least two different axial offsets between the stator and the rotor.

[0076] Operating the downhole apparatus may further comprise obtaining the data.

[0077] The present disclosure also introduces a method comprising operating downhole apparatus disposed in a wellbore that extends into a subterranean formation, the downhole apparatus comprising a stator and a rotor axially offset from the stator by a gap, wherein operating the downhole apparatus comprises: rotating the rotor relative to the stator to generate a pressure wave in a drilling fluid disposed in the wellbore; and encoding data in the pressure wave; wherein at least one of generating and encoding the pressure wave comprises selectively adjusting the gap between the rotor and the stator to modulate the pressure wave utilizing at least three pressure levels. The method may also comprise obtaining the data.

[0078] The foregoing outlines features of several embodiments so that a person having ordinary skill in the art may better understand the aspects of the present disclosure. A person having ordinary skill in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. A person having ordinary skill in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

[0079] For instance, the gap dimension adjustment could be handled by various appropriate ways, such as moving the rotor axially relative to the drill collar while the stator axial position is fixed relative to the drill collar.

[0080] The Abstract at the end of this disclosure is provided to comply with 37 C.F.R. §1.72(b) to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

Claims

1. An apparatus, comprising:

a mud-pulse telemetry tool carried by a drill collar and comprising:

a stator;
a rotor axially offset from the stator by a gap;
a first actuator operable to cause selective rotation of the rotor relative to the stator; and
a second actuator operable to cause selective adjustment of a dimension of the gap during operation of the mud-pulse telemetry tool within a wellbore that extends into a subterranean formation.

2. The apparatus of claim 1 wherein the dimension adjustment is in a direction substantially parallel with an axis of rotation of the rotor.

3. The apparatus of claim 1 wherein the second actuator is an electrical actuator.

4. The apparatus of claim 1 wherein the stator is positionally fixed relative to the drill collar.

5. The apparatus of claim 1 wherein the mud-pulse telemetry tool further comprises:

an internal chassis positionally fixed relative to the drill collar, wherein the first and second actuators are each positionally fixed relative to the internal chassis;
a shaft coupled with the rotor and extending at least partially through the internal chassis; and
a bearing positionally fixed relative to the shaft and slidable within a recess of the internal chassis in response to operation of the second actuator.

6. The apparatus of claim 5 wherein the second actuator comprises:

a motive source positionally fixed relative to the internal chassis; and
a linkage assembly extending between the motive source and the bearing.

7. The apparatus of claim 6 wherein:

the motive source is a linear motive source comprising an output shaft that is reciprocally driven in directions that are substantially parallel with an axis of rotation of the rotor; and
the linkage assembly comprises:

a bearing seat abutting the bearing; and
a linkage arm comprising:

a first end rotatably coupled to the bearing seat; and
a second end rotatably coupled to the output shaft of the linear motive source.

8. The apparatus of claim 7 wherein the linkage assembly comprises a ball joint rotatably coupling the second end of the linkage arm to the output shaft of the linear motive source.

9. The apparatus of claim 1 wherein the second actuator comprises:

a rotary motive source positionally fixed relative to the internal chassis and comprising an output shaft that is rotationally driven about a first axis of rotation that is substantially parallel to a second axis of rotation about which the rotor rotates;
a rotating cam rotationally driven around the first

axis of rotation by the rotary motive source and comprising a first undulating surface; and
a stationary cam rotationally fixed between the rotating cam and the bearing and comprising a second undulating surface abutting the first undulating surface, such that rotation of the rotating cam relative to the stationary cam varies a stack height of the rotating and stationary cams between a minimum stack height and a maximum stack height.

10. The apparatus of claim 1 wherein ones of the stator, the rotor, the first actuator, and the second actuator collectively form:

a pressure pulse generator disposed in the wellbore and operable to generate a pressure wave in a drilling fluid disposed in the wellbore; and
a data encoder disposed in the wellbore and operable to receive data from a data source and vary the pressure wave based on the data such that the pressure wave encodes the data;
wherein the pressure pulse generator and the data encoder are collectively operable to modulate the data-encoded pressure wave utilizing at least three pressure levels.

11. The apparatus of claim 10 wherein the pressure pulse generator comprises the stator and the rotor, and wherein two of the at least three pressure levels correspond to two different axial offsets between the stator and the rotor.

12. The apparatus of claim 10 further comprising the data source.

13. The apparatus claim 12 wherein the data source includes at least one sensor operable in obtaining the data from within at least one of:

the wellbore; and
a subterranean formation into which the wellbore extends.

14. A method, comprising:

operating downhole apparatus disposed in a wellbore that extends into a subterranean formation, the downhole apparatus comprising a stator and a rotor axially offset from the stator by a gap, wherein operating the downhole apparatus comprises:

rotating the rotor relative to the stator to generate a pressure wave in a drilling fluid disposed in the wellbore; and
encoding data in the pressure wave;
wherein at least one of generating and encoding the pressure wave comprises selectively adjusting the gap between the rotor and the stator to modulate the pressure wave utilizing at least three pressure levels.

15. The method of claim 14 wherein operating the downhole apparatus further comprises obtaining the data.

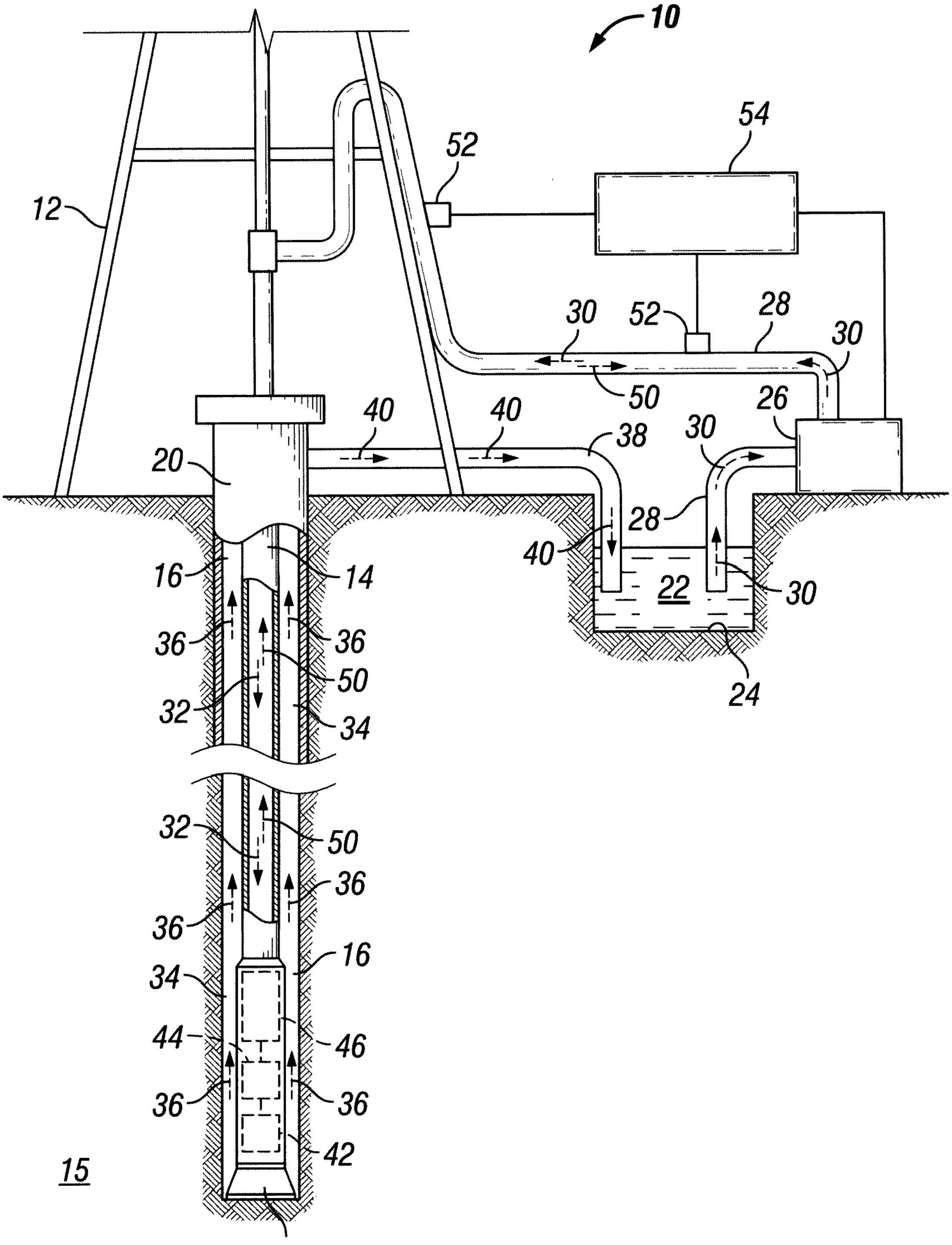
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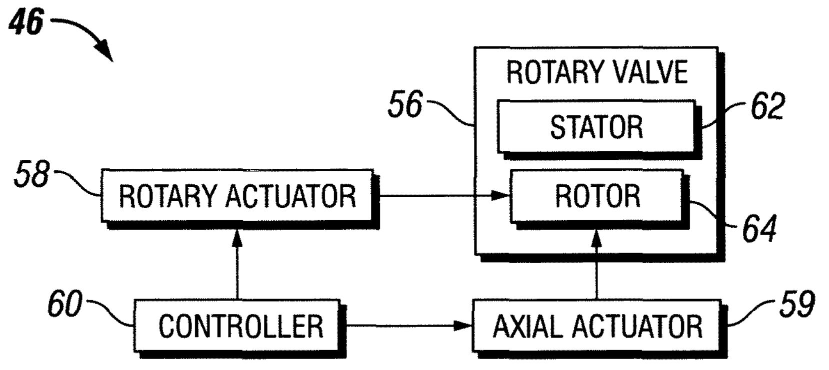
FIG. 1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ROTARY VALVE
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STATOR
62
58
ROTARY ACTUATOR
ROTOR
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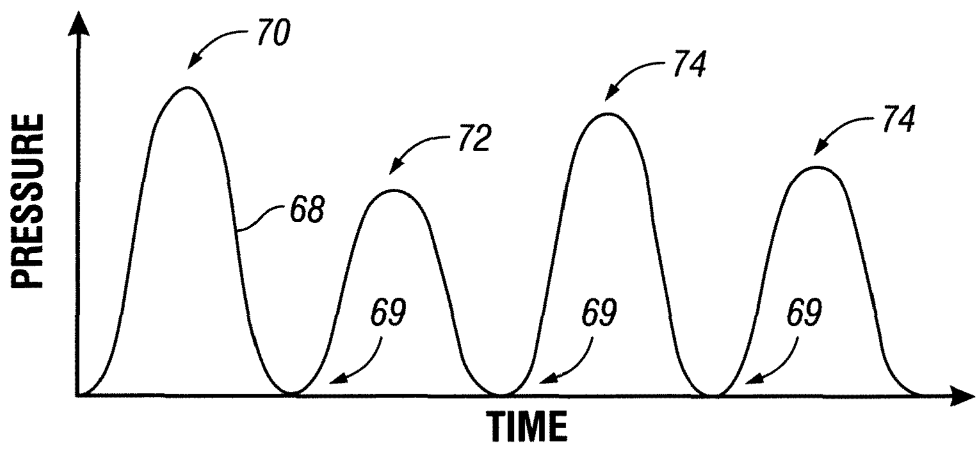
60
CONTROLLER
AXIAL ACTUATOR
59

FIG. 2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PRESSURE
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69
TIME

FIG. 3

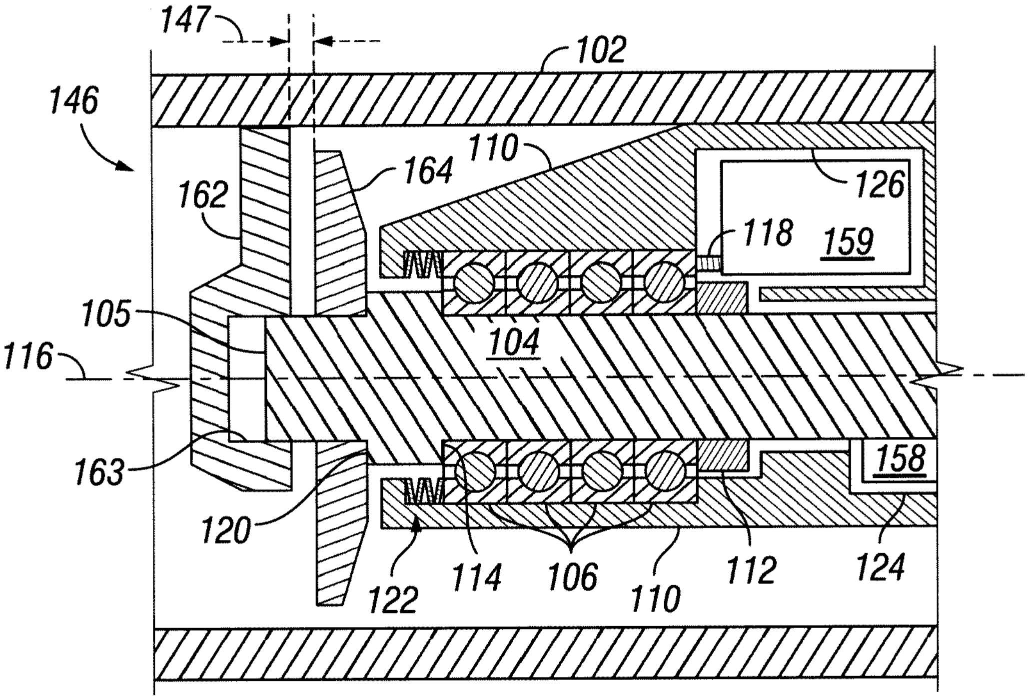
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FIG. 4

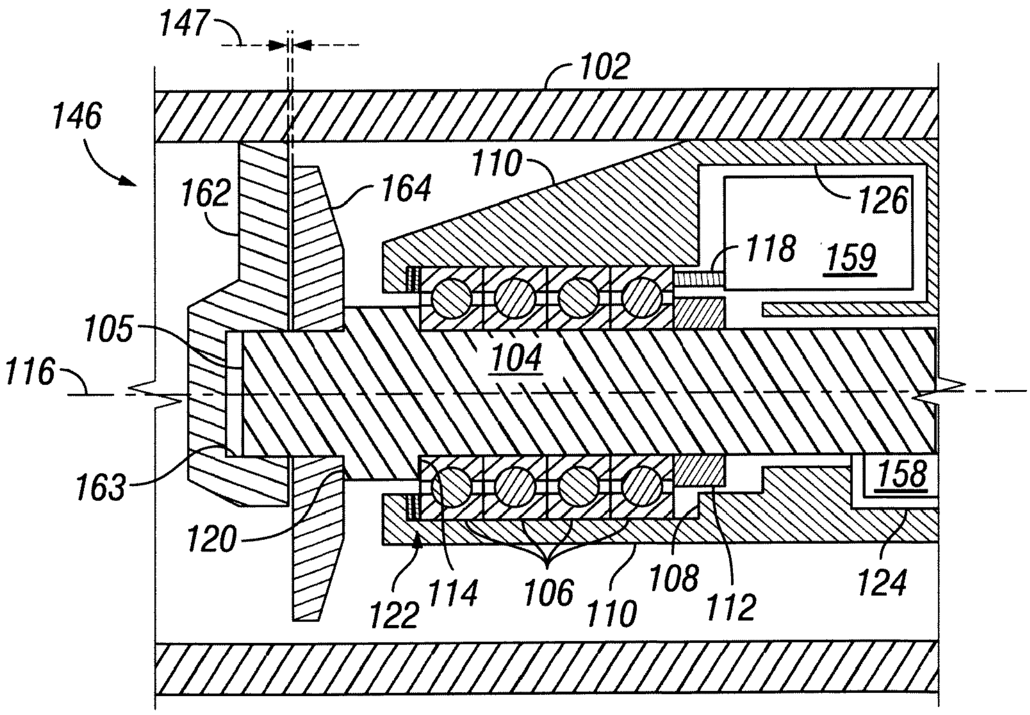
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FIG. 5

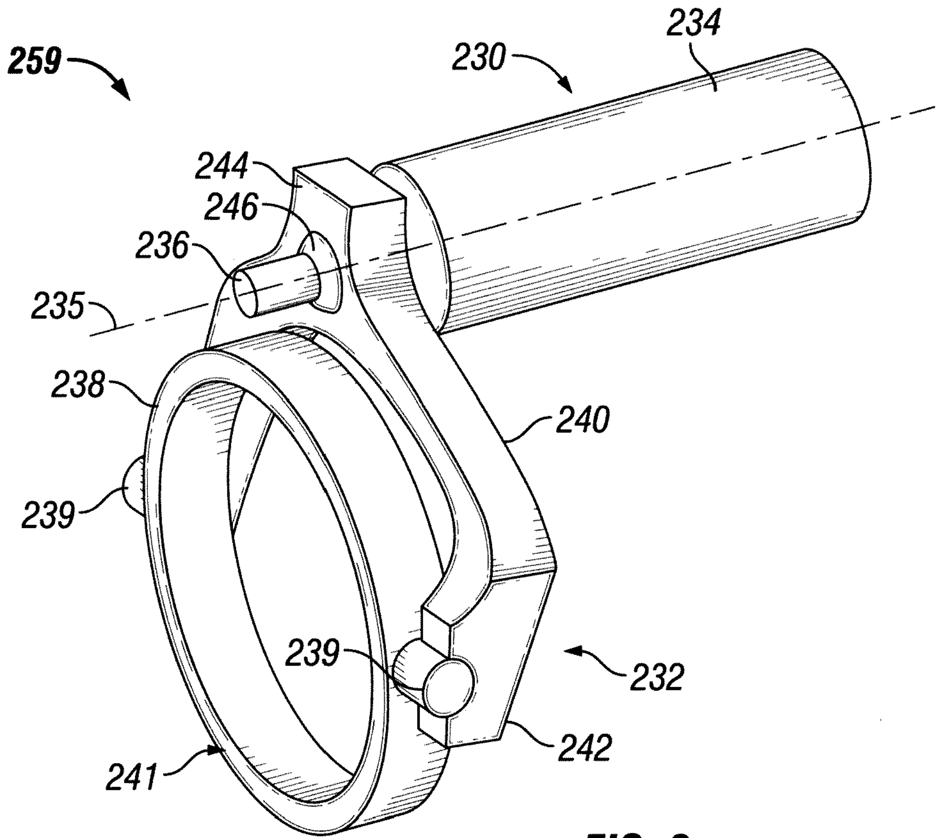
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FIG. 6

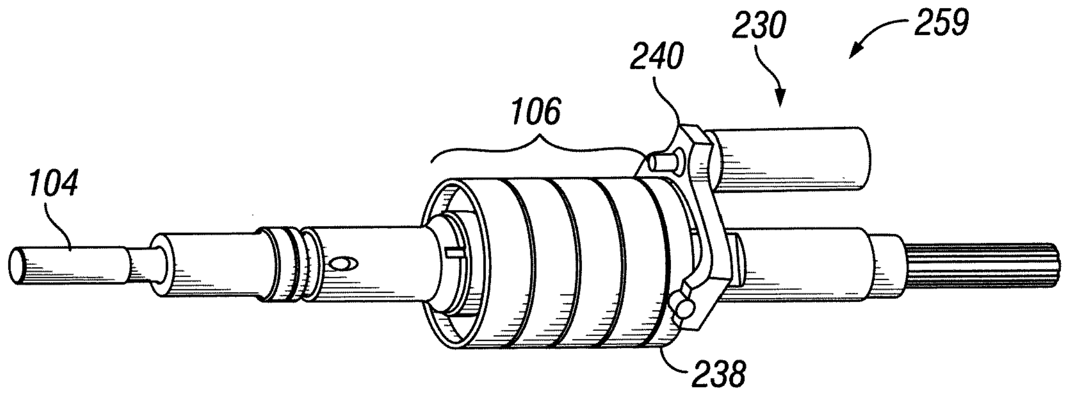
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FIG. 7

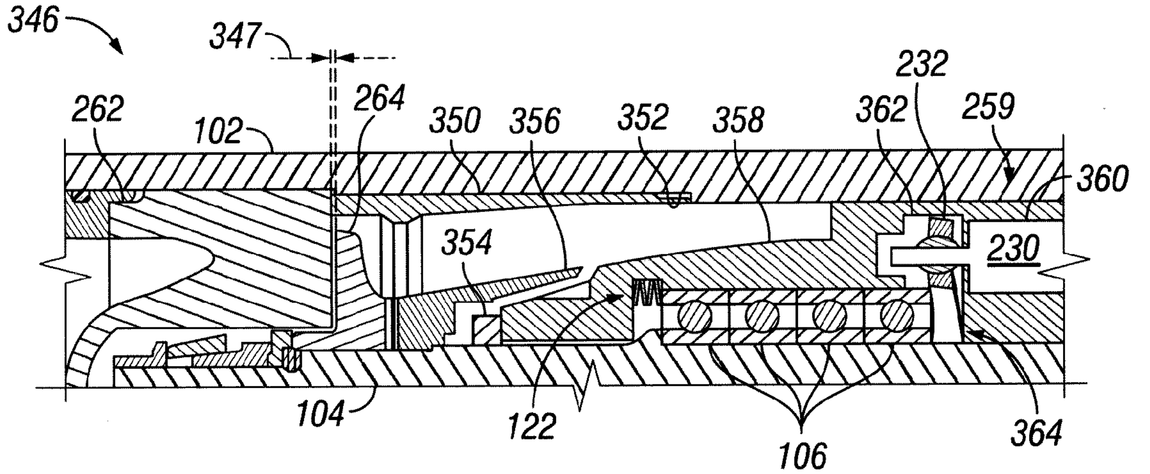
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FIG. 8

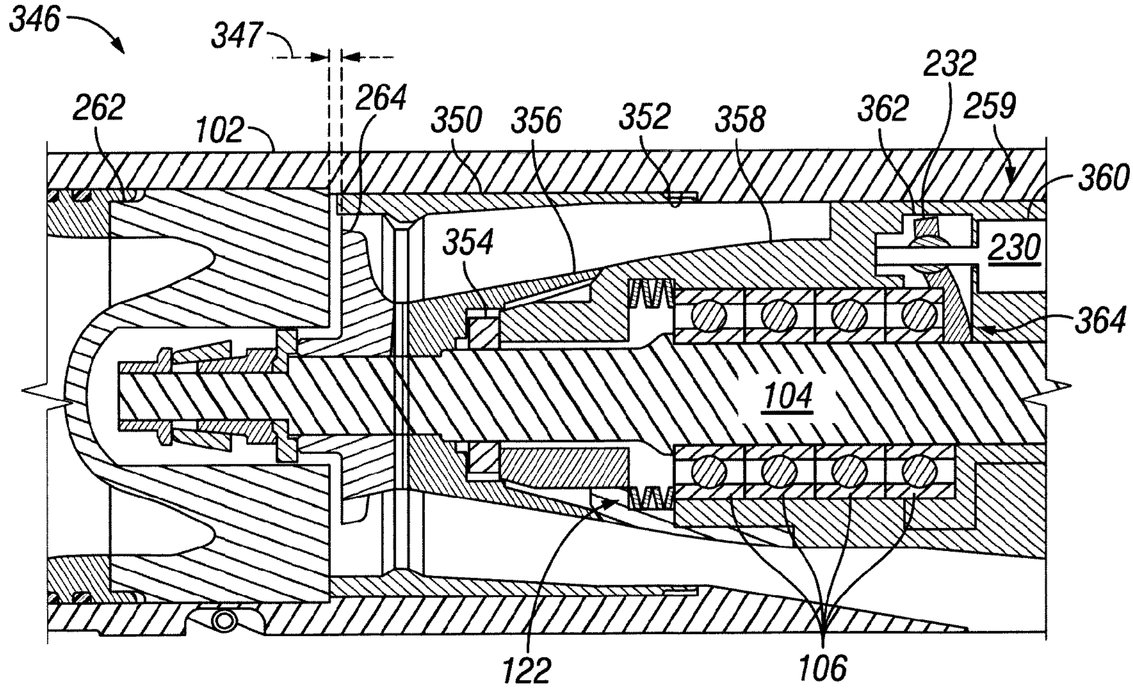
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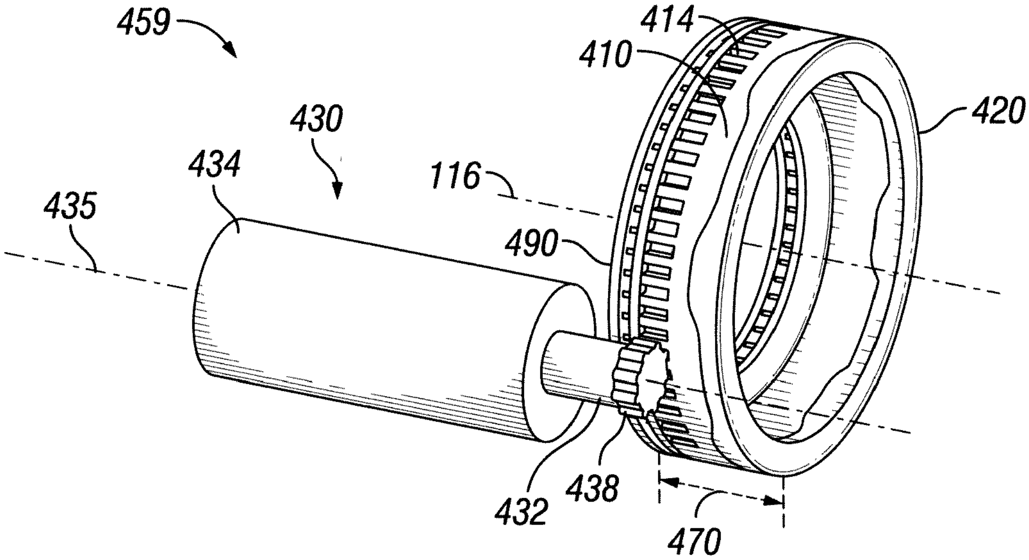
FIG. 9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430
420
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438
470

FIG. 10

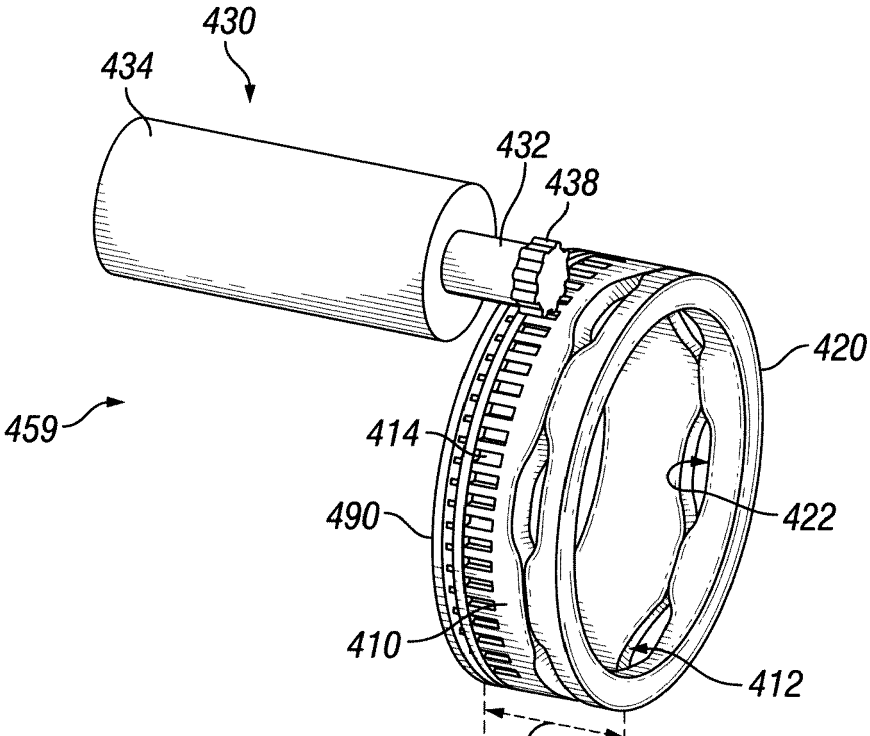
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FIG. 11

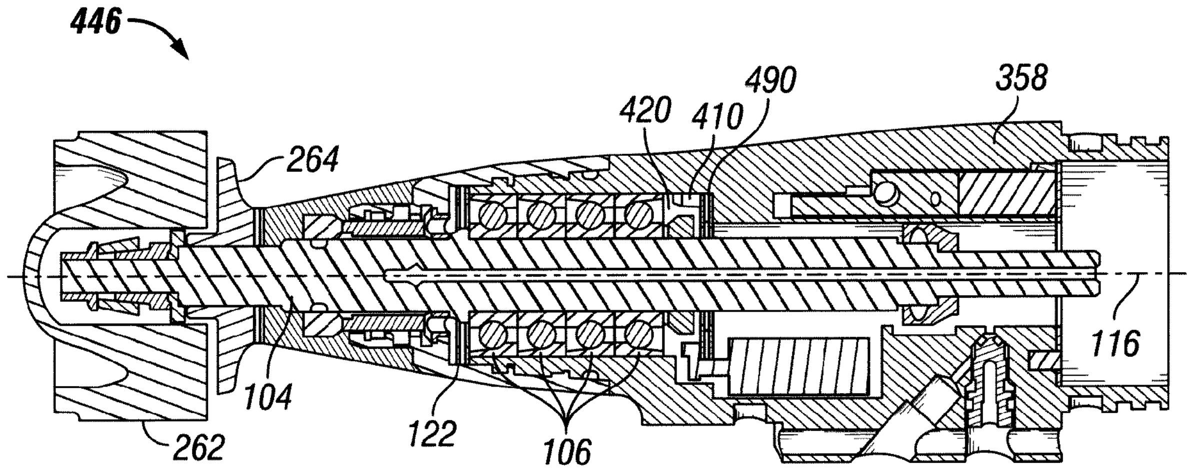
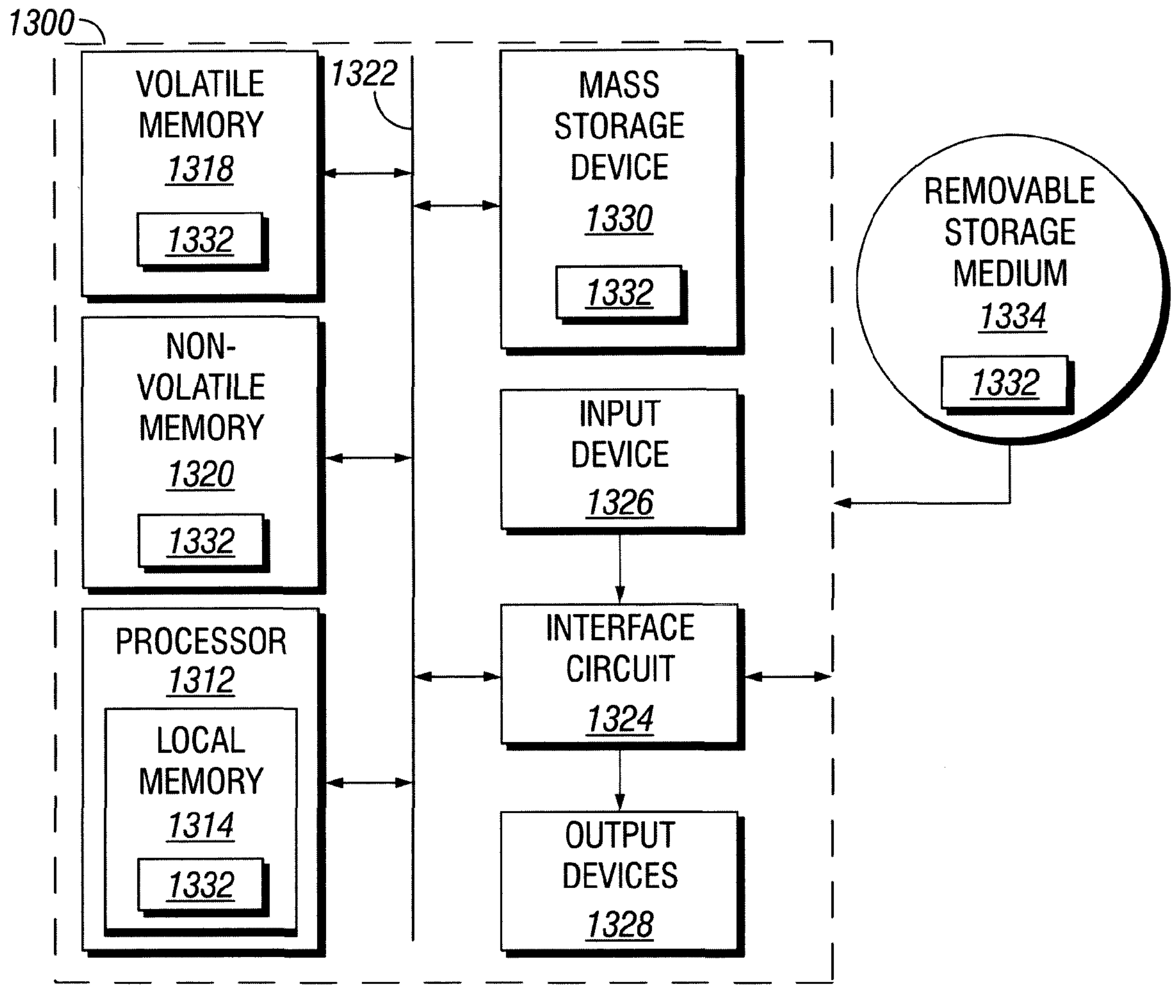


FIG. 12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1332
1322
MASS STORAGE DEVICE 1330
1332
REMOVABLE STORAGE MEDIUM 1334
1332
NON-VOLATILE MEMORY 1320
1332
INPUT DEVICE 1326
PROCESSOR 1312
LOCAL MEMORY 1314
1332
INTERFACE CIRCUIT 1324
OUTPUT DEVICES 1328

FIG. 13

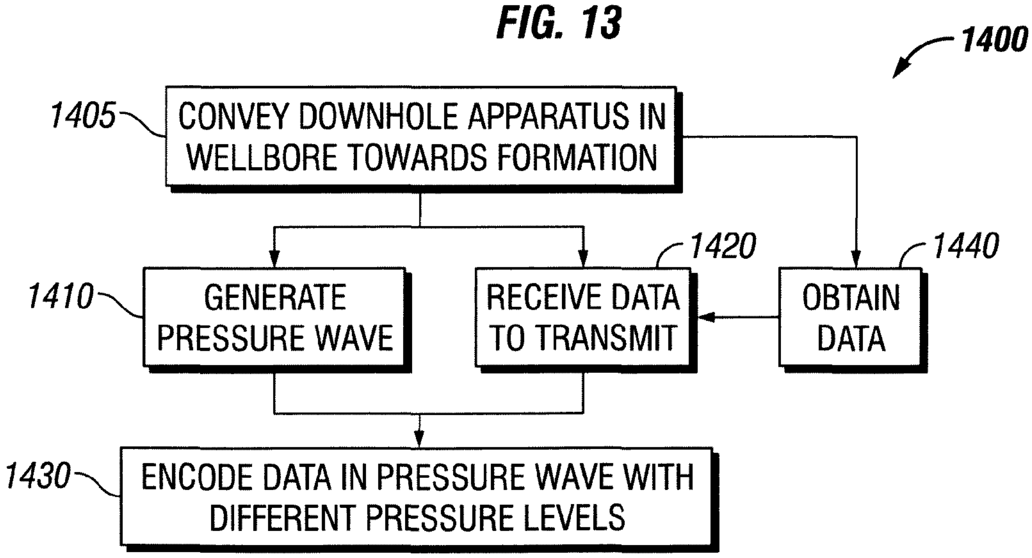
1400
1405
CONVEY DOWNHOLE APPARATUS IN WELLBORE TOWARDS FORMATION
1410
GENERATE PRESSURE WAVE
1420
RECEIVE DATA TO TRANSMIT
1440
OBTAIN DATA
1430
ENCODE DATA IN PRESSURE WAVE WITH DIFFERENT PRESSURE LEVELS

FIG. 14

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 14 29 0191

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	US 5 583 827 A (CHIN WILSON C [US]) 10 December 1996 (1996-12-10) * column 6, line 15 - line 62 * * column 9, line 24 - line 40 * -----	1-15	INV. E21B47/18
A	US 2013/076527 A1 (SITKA MARK A [US] ET AL) 28 March 2013 (2013-03-28) * paragraphs [0031], [0055] * -----	1-15	
A	US 3 770 006 A (SEXTON J ET AL) 6 November 1973 (1973-11-06) * column 2, line 33 - column 3, line 2 * * column 5, line 13 - column 5, line 64 * -----	1-15	
A	US 3 739 331 A (SLOVER V ET AL) 12 June 1973 (1973-06-12) * column 2, line 21 - column 3, line 2 * * column 4, line 61 - column 5, line 57 * -----	1-15	
			TECHNICAL FIELDS SEARCHED (IPC)
			E21B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	5 December 2014	Ott, Stêphane

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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T : theory or principle underlying the invention
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 14 29 0191

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05-12-2014

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