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(54) **Steerable bit assembly and methods**

Steuerbare Bohrmeisselanordnung und entsprechende Verfahren

Ensemble trépan orientable et procédés

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Description

[0001] In one aspect, this invention relates generally to systems and methods utilizing materials responsive to an excitation signal. In another aspect, the present invention relates to drilling systems that utilize directional drilling assemblies actuated by smart materials. In another aspect, the present invention related to systems and methods for producing fast response steerable systems for wellbore drilling assemblies.

[0002] To obtain hydrocarbons such as oil and gas, boreholes are drilled by rotating a drill bit attached at a drill string end. A large proportion of the current drilling activity involves directional drilling, *i.e.*, drilling deviated and horizontal boreholes to place a wellbore as required, to increase the hydrocarbon production and/or to withdraw additional hydrocarbons from the earth's formations. Modem directional drilling systems generally employ a drill string having a bottomhole assembly (BHA) and a drill bit at end thereof that is rotated by a drill motor (mud motor) and/or the drill string. A number of downhole devices placed in close proximity to the drill bit measure and control certain downhole operating parameters associated with the drill string. Such devices typically include sensors for measuring downhole temperature and pressure, azimuth and inclination measuring devices and a resistivity measuring device to determine the presence of hydrocarbons and water. Additional downhole instruments, known as logging-while-drilling ("LWD") tools, are frequently attached to the drill string to determine the formation geology and formation fluid conditions during the drilling operations.

[0003] Most hydrocarbon wellbores are currently drilled using a combination of rotary and hydraulic energy sources. Rotation of the drill string is often used as at least one source of the rotary energy. Drilling fluid, or "mud," is used to clean the bore hole and drill bit and to cool and lubricate the drill bit. Because the drilling fluid is pump downhole under pressure, the drilling fluid is often used as an additional source of energy for driving drilling motors that provide some or all of the rotary power required to drill the borehole. Different BHAs are selected depending on the nature of the wellbore 'directional path' and the method by which the wellbore is being drilled (*e.g.*, pure rotary, rotary with downhole motor, or only a downhole motor). Certain BHAs are configured to allow the wellbore to be steered along a pre-determined path. In steered wellbore path drilling, drilling motors or other devices are configured in one or more ways to facilitate controlled steering of the wellbore. In these BHAs, the drill bit is usually connected to a 'drive-shaft' that is supported and stabilized by a series of axial and radial bearings. A drilling motor is used to turn the drive shaft that then turns the bit. The configuration of the motor housing containing the drive-shaft (typically referred to as the bearing housing) and its relationship the remainder of the BHA and drill string allows the well bore to be steered. These motor-based directional BHAs are typically referred to as steerable motor systems.

[0004] In recent times, a modification to the motor bearing housing configuration has been introduced to the drilling marketplace. These systems are commonly known as rotary steerable systems. These systems were originally driven or powered by rotation of only the drill pipe, but certain systems presently available combine downhole motors and rotation of the drill string.

[0005] Boreholes are usually drilled along predetermined paths and the drilling of a typical borehole proceeds through various formations. To design the path of a subterranean borehole to be other than linear in one or more segments, it is conventional to use "directional" drilling. Variations of directional drilling include drilling of a horizontal, or highly deviated, borehole from a primary, substantially vertical borehole, and drilling of a borehole so as to extend along the plane of a hydrocarbon-producing formation for an extended interval, rather than merely transversely penetrating its relatively small width or depth. Directional drilling, that is to say varying the path of a borehole from a first direction to a second, may be carried out along a relatively small radius of curvature as short as five to six meters, or over a radius of curvature of many hundreds of meters. In many directional boreholes, the well path is a complex 3D curve with multiple radii of curvature. The variation of the curvature (radius) depends upon the pointing (aiming) and bending of the BHA.

[0006] Some arrangements for effecting directional drilling include positive displacement (Moineau) type motors as well as turbines that are employed in combination with deflection devices such as bent housing, bent subs, eccentric stabilizers, and combinations thereof. Such arrangements are used in what is commonly called oriented slide drilling. Other steerable bottomhole assemblies, commonly known as rotary steerable systems, alter the deflection or orientation of the drill string by selective lateral extension and retraction of one or more contact pads or members against the borehole wall.

[0007] US 4,291,773 which is considered the closest prior art document describes a deflectable collar having strictive material deflectable element that can be energized so as to bend or articulate the drill string or drill bit in order to change the advancement angle of the borehole.

[0008] Referring initially to **Fig. 1,** there is shown a flowchart for an exemplary conventional rotary steering control system **10** for a rotary steerable directional drilling assembly. An intelligent control unit **12** evaluates directional data **14** using programmed instructions **16** and transmits signals **18** as necessary to align the rotary steerable bottomhole assembly with the required well path. With conventional rotary steerable steering systems, there is a time lag between the transmission of the command signals **16** and corresponding physical change of the BHA elements that influence the drilling direction. This time lag is largely attributable to the mechanical and electrical architecture of conventional rotary steering

units representatively shown as **20.** These conventional rotary steering units **20** employ a number of subsystems **22a-i** for effecting a change in drilling direction **24.** For instance, in one arrangement, subsystem A may be a valve assembly that opens to control hydraulic fluid flow; subsystem B may be a hydraulic chamber that is filled by hydraulic fluid flowing through the valve assembly; subsystem C may be a piston and associated linkages that converts hydraulic pressure in the hydraulic chamber to translational movement; and subsystem D can be an arm or pad that applies a force on a wellbore wall in response to the movement of the piston and associated linkages. In another arrangement, subsystem A can be an electrical circuit that closes to energize an electrical motor within a subsystem B. Subsystem C can be a gear drive that converts motor rotation into translational movement and subsystem D can be mechanism that adjusts the position of a bit in response to the actuation of the gear drive.

[0009] The steering control system **10** shown in the **Fig. 1** flow chart is merely a generic representation of conventional rotary steerable BHA assemblies wherein all the elements of the system **10** are packaged within the BHA. Limited commands such as a redirection adjustment of target can be sent from the surface. However, the typical rotary steerable BHA is self sufficient from a decision and tool configuration change / adjustment implementation stand point on a moment by moment basis.

[0010] The use of multiple subsystems **22a-i**, whether mechanical, electromechanical or hydraulic, can cause hydraulic and mechanical time lags for at least two reasons. First, these conventional subsystems must first overcome system inertia and friction upon receiving the command signal. For instance, motors whether electrical or hydraulic require time to wind up to operating speed and/or produce the requisite motive force. Likewise, hydraulic fluids take time to build pressure sufficient to move a reaction device such as a piston. Second, each interrelated subsystem introduces a separate time lag into the response of the conventional rotary steering drilling system. The separate time lags accumulate into a significant time delay between the issuance and execution of a command signal. In conventional rotary steerable systems, up to several tenths of a second can separate the issuance of a command signal and a corresponding change in drilling direction forces or system geometry that influences drilling direction. If these time lags are great enough relative to drill string RPM and rate of penetration, a reduction in directional control and expected borehole curvature can occur. This can result in a reduction in directional control.

[0011] Other configurations of rotary steerable drilling systems minimize the dependency on response time by using a non-rotating stabilizer or pad sleeve. Introduction of the non-rotating (or slow rotating) sleeve decreases the actuation speed requirement but increases the complexity of the steering unit (*e.g.*, the need for rotating seals, rotary electrical connections, etc.). Thus, conventional rotary steerable systems have a limited mechanical response rate, are mechanically complex, or both.

[0012] The present invention, at least in some embodiments, addresses these and other needs in the prior art.

[0013] The present invention relates to systems, devices and methods for efficient and cost effective drilling of directional wellbores. The system includes a well tool such as a drilling assembly or a bottom hole assembly ("BHA") at the bottom of a suitable umbilical such as drill string. The BHA includes a steering unit and a control unit. The steering unit and control unit provide dynamic control of bit orientation by utilizing fast response "smart" materials. In one embodiment, the control unit utilizes one or more selected measured parameters of interest in conjunction with instructions to determine a drilling direction for the BHA. The instructions can be either preprogrammed or updated during the course of drilling in response to measured parameters and optimization techniques. The control unit issues appropriate command signals to the steering unit. The steering unit includes one or more excitation field/signal generators and a "smart" material. In response to the command signal, the excitation signal/field generator produces an appropriate excitation signal/field (*e.g.*, electrical or magnetic). The excitation signal/field causes a controlled material change (*e.g.*, rheological, dimensional, etc.) in the "smart" material. The utilization of smart materials allows direct control rates that are faster and less mechanically complex than conventional rotary steerable directional systems.

[0014] In embodiments of the present invention, the steering unit, employing smart materials, controls drilling direction by changing the geometry of a BHA ("system geometry change tools").

[0015] According to an aspect of the present invention, there is provided a system for drilling a wellbore in an earthen formation as claimed in claim 1.

[0016] According to another aspect of the present invention, there is provided a method for drilling a well bore in an earthen formation as claimed in claim 7.

[0017] Steering units that utilize system geometry change steering units to effect a change in drilling direction can employ a "composite geometry change" or "local geometry change." Exemplary composite geometry change steering units can include a deformable sleeve between two attachment points on a rigid tube. These attachment points can be stiffeners, a flange, a diametrically enlarged portion or other suitable feature formed integral with or separate from the drill string or BHA. The sleeve is formed at least partially of one or more smart materials that expand or contract when subjected to an excitation field/signal. By actively controlling the excitation field (*e.g.*, electrical field) associated with the sleeve, the sleeve expands to push the attachment points apart or contracts to pull the attachment points together. This expansion or contraction is transferred to the rigid tube, which then flexes or curls in a selected manner. Exemplary "local geometry change" steering units can include

a dynamically adjustable articulated hinge or joint that, when actuated, can adjust the orientation of the bit. The articulated joint can be positioned immediately adjacent to the bit or disposed in the BHA or washer. In one embodiment, the articulated joint includes a washer or ring having a plurality of elements that are at least partially made of one or more solid smart materials. In response to an excitation signal, the elements individually or collectively deform (expand or contract) along a longitudinal axis of the BHA. This controlled longitudinal deformation alters the physical orientation of a face of the ring. This local discontinuity effects a change in the tilt or point of the drill bit. In certain embodiments, a washer face can include a circumferential array of hydraulic chambers filled with a smart fluid (*e.g.*, a fluid having variable-viscosity) and associated pistons. In one application, the smart fluid provides increased or decreased resistance to compression when subjected to an excitation signal, such as an electrical impulse. In this embodiment, the piston individually or collectively contract or relax when subjected to the forces inherent during drilling (*e.g.*, weight on bit). Varying the viscosity alters the distance a given piston shifts, which causes a tilt in the washer face. This tilt causes a local geometry change that controls the physical orientation of the drill bit.

[0018] In certain embodiments, the steering unit is incorporated into the bit body. For example, a washer utilizing smart materials can be inserted into a body of the drill bit and placed in close proximity to the bit face. A controller communicates with the washer via a telemetry system to control the excitation signals provided to the smart material used by washer by a suitable generator. The telemetry system can be a short hop telemetry system, hard wiring, inductive coupling or other suitable transmission devices.

[0019] It is also contemplated in other arrangements, which do not fall within the scope of the claims, that the steering unit, employing smart materials, could control the drilling direction by generating a selected bit force vector ("force vector systems") or by controlling the cutting action of the bit ("differential cutting systems").

[0020] Exemplary steering units that utilize force vectors to produce a bit force include one or more stabilizers utilizing smart materials configured to produce/adjust bit side force or alter BHA centerline relative to the borehole centerline. In one arrangement, the stabilizer is fixed to a rotating section of the BHA and includes a plurality of force pads for applying a force against a borehole wall. In this arrangement, steering is effected by a force vector, which creates a reaction force that urges the bit in the direction generally opposite to the force vector. The force pads are actuated by a shape change material that deform in response to an excitation signal produced by a signal/filed generation device or other suitable generator as discussed earlier. The expansion/contraction of the shape change material extends or urges the force pads radially inward and/or outward. In another arrangement, the stabilizer includes a plurality of nozzles that form hydraulic jets of pressurized drilling fluid. The nozzles use a smart material along the fluid exit path to selectively regulate the flow of exiting fluid. The strength of the hydraulic jets can be controlled via a signal/field generator to produce a selected or pre-determined reactive forces. Controlling the hydraulic jet velocity/flowrate can alter the symmetry of the lateral hydraulic force vectors and thus control the direction of the lateral deflection of the drill bit.

[0021] In certain arrangements, a deflection device is fixed to a bit to manipulate the radial positioning of the bit relative to the wellbore. In one embodiment, the deflection device includes a plurality of force pads for applying a force against a borehole wall and gage cutters for cutting the borehole wall. The force pads and gage cutters are actuated by a shape change material that expands/contracts in response to an excitation signal. In one mode, either the force pads or gage cutters are extended to contact the borehole wall at a selected frequency. In another mode, the action of the gage cutters and force pads are coordinated such that when a force pad extends out, the corresponding cutter on the opposite side also extends out to cut the borehole wall. A controller communicates with the deflection device via a telemetry system to control the operation of the force pads and gage cutters. The telemetry system can be a short hop telemetry system, hard wiring, inductive coupling or other suitable transmission devices. In other arrangements, the deflection device includes only force pads or only gage cutters. In another arrangement, a hydraulic jet force deflection device fixed in the drill bit uses smart material controlled nozzles along the outer diameter of the bit to produce controllable hydraulic jets to produce reactive forces for controlling the position of the drill bit.

[0022] Exemplary differential cutting steering units change well bore path and direction by controlling the forward (face) rate of penetration of the bit. In one arrangement, a drill bit incorporating differential cutting includes a plurality of nozzles that utilize smart materials to modulate the flow through one or more selected nozzles. By selectively and actively changing the flow through one or more of the nozzles, the degree of bottom hole cleaning on one side of the hole can be made more or less effective versus another side. To manage the face segment influenced, the rate or frequency of modulation can be synchronous with the bit rotation or a multiple of a consistent fraction of bit speed. This differential bottom hole cleaning results in a differential rate of penetration across the bottom of the hole. For instance, drilling cuttings accumulate to a greater degree under a selected segment. The relatively greater accumulation of drilling cuttings reduces local ROP and causes the desired change in well path direction. In another arrangement, the drill bit includes a plurality of cutters, which are disposed on a face of the drill bit, that can be individually or collectively (*e.g.*, selected groups) axially lengthened by selectively energizing a smart material. By adjusting the rate of penetration of certain cutters, a differential rate of penetration is created which cause a change in drilling

direction. In another arrangement, a differential rate of penetration is provided by actively controlling segmental depth of cut using smart materials to alter the height of one or more depth of cut limiting protrusions provided on a bit face. These arrangements can also provide a controlled distribution of the gross total weight or force on the bit amongst the multiple cutting surfaces. For drill bits utilizing such steering units; data, command signals, and power can be transmitted to the steering unit via a short hop telemetry system, hard wiring, inductive coupling or other suitable transmission devices and systems.

[0023] For "oriented slide drilling," which are substantially stationary relative to the wellbore during operation, an associated control unit transmits excitation signals that effectively bend a portion of the BHA (*e.g.*, through local geometry change or composite geometry change) to create a tilt angle that points the bit in a specified direction. Because the steering unit is not rotating relative to the wellbore, this bend can remain substantially fixed (other than to correct for changes in BHA and/or steering unit orientation) until the next desired change in bit direction/orientation.

[0024] For steering units that rotate during operation, the control unit energizes or activates the actively controlled elements (*e.g.*, washer segments, nozzles, force pad segments, etc.) of that steering unit as a function of the rotational speed of the steering unit (which may be the rotational speed of a drill string or drill bit). For example, a specified bend or tilt may require one or more elements to be activated while in a specified azimuthal location in the wellbore (*e.g.*, top-dead-center of the wellbore). The azimuthal location can be a point or zone. The elements rotate into the specified location once per shaft revolution. Thus, the control unit energizes the elements every time the elements are in that location. The control unit can also activate the element at one or fewer than one times per reference rotation/cycle provided that the elements are in the selected location. This provides a means for tuning or adjusting the directional deflection aggressiveness via frequency of activation in addition to the amount of shape change.

[0025] The control unit can be programmed to adjust one or more operational parameters or variables in connection with the activation of the elements. For instance, the control unit can control the timing or sequence of activation. For example, the region for activation may be a single point or a specified region (*e.g.*, a selected azimuthal sector) or multiple locations. Also, the control unit can simultaneously or sequentially activate any number of elements is selected groups or sets. Additionally, the control unit can control the magnitude or strength of the excitation signal to control the amount of material change (*e.g.*, length change) of the smart material. For instance, by controlling the signal/field intensity, the control unit can change the length of the element and/or the magnitude of the force produced by the element. By controlling these illustrative variables, and other variables, the control unit can control the degree or aggressiveness of path deflection.

[0026] In further arrangements, which again do not fall within the scope of the claims, it is contemplated that the steering unit may comprise a mechanical steering devices that may or may not utilize smart materials. In one such arrangement, a mechanical adjustable joint is disposed in a section of a BHA. The joint includes two or more members that have sloped/inclined faces (*e.g.*, tubulars, plates, disks, washers, rings) and can rotate relative to one another. A positional sensor package associated with a rotating member (*e.g.*, drilling tubular) provides drilling torque and WOB for a drilling operation. By referencing an external reference plane and actively correlating an internal reference plane to the external reference plane, the sensor package defines a known orientation to the reference vector during random rotation of the rotating member. The sensor package transmits the orientation data to a control / driver device that controls a secondary rotary drive device coupled to one or more of the members having sloped/inclined faces of the adjustable joint. In one arrangement, the drive device counter rotates the ring positioned on the rotating member to maintain a fixed or desired orientation to the external reference plane. While the devices are shown as part of a drill string or BHA, these devices can also be incorporated into a drill bit body in a manner previously described.

[0027] Examples of the more important features of the invention have been summarized (albeit rather broadly) in order that the detailed description thereof that follows may be better understood and in order that the contributions they represent to the art may be appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

[0028] For detailed understanding of the present invention, reference should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawing:

Figure 1 illustrates a flow chart for a control method and system for directional drilling using a conventional rotary steerable drilling system;

Figure 2 is a schematic illustration of one embodiment of a drilling system for directional drilling of a wellbore;

Figure 3 illustrates an exemplary flow chart for a directional drilling control method and system that is made in accordance with the present invention;

Figure 4 schematically illustrates one embodiment of a system geometry change steering unit made in accordance with the present invention;

Figure 5A schematically illustrates one embodiment of deformable sleeve for a steering unit made in accordance with the present invention;

Figure 5B schematically illustrates an end view of the **Fig.** 5A embodiment;

Figure 5C schematically illustrates another embodiment of deformable sleeve for a steering unit made

in accordance with the present invention;

Figure 5D schematically illustrates an end view of the Fig. 5C embodiment;

Figure 5E schematically illustrates an embodiment of deformable sleeve having one or more washers for a steering unit made in accordance with the present invention;

Figure 5F schematically illustrates an end view of the Fig. 5E embodiment;

Figure 6A schematically illustrates one embodiment of a local geometry change steering unit made in accordance with the present invention;

Figure 6B schematically illustrates the Fig. 6A embodiment effecting a local geometry change;

Figure 6C schematically illustrates an embodiment of a steering unit made in accordance with the present invention that utilizes a smart fluid;

Figure 7 schematically illustrates one embodiment of a local geometry change steering unit provided on a drill bit;

Figure 8 schematically illustrates an exemplary force vector change steering unit;

Figure 9A illustrates an exemplary force vector change steering unit that utilizes a stabilizer having pads actuated by a smart material;

Figure 9B illustrates an exemplary force vector change steering unit that utilizes a stabilizer producing hydraulic jets modulated by a smart material;

Figure 10 illustrates an exemplary drill bit provided with a steering unit;

Figure 11A illustrates an exemplary differential cutting steering unit that modulates drilling fluid flow;

Figure 11B illustrates an exemplary differential cutting steering unit that controls cutter extension into a wellbore bottom;

Figure 11C illustrates an exemplary differential cutting steering unit that controls bit face protrusion height;

Figure 12 illustrates a flow chart for controlling exemplary elements of a steering unit during directional drilling;

Figure 13A illustrates an exemplary dynamically adjustable mechanical joint;

Figure 13B illustrates a sectional view of the Fig. 13A arrangement;

Figure 14A illustrates the **Fig. 13A** arrangement having a selected tool centerline deflection;

Figure 14B illustrates a sectional view of the Fig. 14A arrangement; and

Figure 15 illustrates an exemplary dynamically adjustable mechanical joint that is disposed in a conventional BHA.

[0029] The present invention relates to devices and methods utilizing smart materials for steerable systems, and devices and methods for drilling complex curvature directional wellbores. There are shown in the drawings, and herein will be described in detail, specific embodiments of the present invention and other arrangements with the understanding that the present disclosure is to be considered an exemplification of the principles of the invention, and is not intended to limit the invention to that illustrated and described herein.

[0030] Referring initially to **Fig. 2,** there is schematically illustrated a system **100** for performing one or more operations related to the construction, logging, completion or work-over of a hydrocarbon producing well. In particular, **Fig. 2** shows a schematic elevation view of one embodiment of a wellbore drilling system **100** for directionally drilling a wellbore **102.** The drilling system **100** is a rig for land wells and includes a drilling platform **104,** which may be a drill ship or another suitable surface workstation such as a floating platform or a semi-submersible for offshore wells. For offshore operations, additional known equipment such as a riser and subsea wellhead will typically be used. Further, the wellbore drilling system **100,** while described below as a conventional flow system, can be readily adapted to reverse circulation (*i.e.*, wherein drilling fluid is conveyed into an annulus and returned via the drill string). To drill a wellbore **102,** well control equipment **106** (also referred to as the wellhead equipment) is placed above the wellbore **102.**

[0031] This system **100** further includes a well tool such as a drilling assembly or a bottom hole assembly ("BHA") **108** at the bottom of a suitable umbilical such as drill string or tubing **110** (such terms will be used interchangeably). In one embodiment, the BHA **108** includes a drill bit **112** adapted to disintegrate rock and earth. The bit **112** can be rotated by a surface rotary drive, a downhole motor using pressurized fluid (e.g., mud motor), and/or an electrically driven motor or combinations thereof. The tubing **110** can be formed partially or fully of drill pipe, metal or composite coiled tubing, liner, casing or other known member. Additionally, the tubing **110** can include data and power transmission carriers such as fluid conduits, fiber optics, and metal conductors. Sensors S are disposed throughout the BHA to measure drilling parameters, formation parameters, and BHA parameters.

[0032] During drilling, a drilling fluid from a surface mud system **114** is pumped under pressure down the tubing **110.** The mud system **114** includes a mud pit or supply source **116** and one or more pumps **118.** In one embodiment, the supply fluid operates a mud motor in the BHA **108,** which in turn rotates the drill bit **112.** The drill string **110** rotation can also be used to rotate the drill bit **112,** either in conjunction with or separately from the mud motor. The drill bit **112** disintegrates the formation (rock) into cuttings that flow uphole with the fluid exiting the drill bit **112.**

[0033] The BHA **108** includes a steering unit **120** and a control unit **122.** The BHA **108** can also include a processor **124** in communication with the sensors **S,** the control unit **120** and/or a surface controller **126** and peripherals **128.** The sensors **S** can be configured to measure formation parameters (e.g., resistivity, porosity, nuclear

measurements), BHA parameters (e.g., vibration), and drilling parameters (e.g., weight on bit **112**). The steering unit **120** and control unit **122** (with or without control signals from the surface) provide dynamic control of bit **112** orientation to influence borehole curvature and direction. The steering unit **120** utilizes a fast response "smart" material, described more fully below, coupled with directional drilling assemblies. It is believed that using smart material controller in an active manner will allow control and change / response of the steering head system configuration at speeds not feasible with conventional electro-hydraulic-mechanical systems. It is further believed that this step change in system control and response speed will allow the steering head to become an integral part of the rotating assembly and allow shaft or drill string rotations speeds greater than conventional rotary steering systems integrated into a rotating assembly will allow.

[0034] Referring now to **Figs. 2** and **3,** a control system **130** for controlling a steering unit **120** made in accordance with one embodiment of the present invention is shown. The control system **130** receives measured data **132** (which can be one or more parameters of interest), which in conjunction with instructions **134** (pre-programmed or dynamically updated), is used to determine appropriate command signals **136** that are transmitted to the steering unit **120.** In one embodiment, the measured data **132** can include data used in relation to a fixed reference point, such as the surface. Such data can include the three-dimensional orientation of the BHA **108** in the wellbore **102.** This data can include azimuth, inclination and depth data. The measured data **132** can also include data that characterizes the formation in the vicinity of the BHA **108** such as porosity, resistivity, etc. Still other measured data **132** can include data that can be used to evaluate the health and efficiency of the BHA **108** as well as data indicative of the wellbore environment such as wellbore pressure and temperature. The control unit **130** uses the measured data **132** to determine the appropriate adjustments to the BHA **108** for more accurate wellbore placement and positioning and enhanced drilling efficiency and BHA health. This determination is based at least in part on the instructions **134.** The instructions, in one embodiment, can be static and provide a specific wellbore trajectory that is to be followed by the BHA **108.** In another embodiment, the instructions can be revised based on learned experience; *i.e.*, updated periodically based on optimization techniques, prescribed operating parameters, dynamic drilling models, and in response to measured data. Thus, for example, the instructions **134** can periodically adjust the drilling direction to be followed based on measurements lathered regarding a particular geological formation and/or reservoir.

[0035] The appropriate drilling direction can be determined in reference to a pre-defined well path, a well path adjusted to reflect revised down hole reservoir information, a well path revised from the surface, and/or a well path revised relative to marker limit spacing. After this determination, the control unit **130** computes the necessary adjustments to be made to the BHA **108** to effect the new drilling direction and transmits via a suitable telemetry system (not shown) the corresponding command or control signals **136** to the steering unit **120.**

[0036] In response to the command signal **136,** an excitation signal/field generator produces an appropriate excitation signal/field. The generator can be a conductor, a circuit, a coil or other device adapted produce and/or transmit a controlled energy field. The excitation signal/field causes a controlled material change (*e.g.*, rheological, dimensional, etc.) in an appropriately formulated material, hereafter "smart" material. Smart materials include, but are not limited to, electrorheological fluids that are responsive to electrical current, magnetorheological fluids that are responsive to a magnetic field, and piezoelectric materials that responsive to an electrical current. This change is a change in dimension, size, shape or viscosity. The smart material is deployed such that a change in shape or viscosity can alter system geometry, or in other arrangements apply side forces and/or vary the cutting action by the bit face, to thereby control drilling direction of the drill bit **112.** Additionally, the "smart" material is formulated to exhibit the change within milliseconds of being subjected to the excitation signal/field. Thus, in response to a given command signal, the requisite field/signal production and corresponding material property can occur within a few milliseconds. Thus, hundreds of command signals can be issued in, for instance, one minute. Accordingly, command signals can be issued at a frequency in the range of rotational speeds of conventional drill strings (*i.e.*, several hundred RPM).

[0037] Illustrative embodiments and arrangements of steering units employing smart materials are discussed below in the context of steering units configured to controlling direction by changing the geometry of a BHA ("system geometry change tools"), by generating a selected bit force vector ("force vector systems"), and by controlling the cutting action of the bit 112 ("differential cutting systems").

[0038] It should be appreciated, however, that the teachings of the present invention are not limited to the described embodiments nor their representative systems.

System Geometry Change Steering

[0039] System geometry change steering units effect a change in drilling direction by influencing the way the bit **112** and bottom hole assembly **108** lays in the previously drilled hole so as to influence the tilt of the bit **112.** The end effect is that the bit face points or tilts in a selected orientation for the selected new direction of the hole. For steering units utilizing system geometry change, the act of pointing (through flexure) or tilting (via a hinged joint) the bit **112** generally causes the lower end of the drilling assembly **108** to have a tool assembly centerline that is different from that of the previously drilled

hole. This variable tool centerline will occur above and below the point of tilt or area of flexure (can be non-linear) and will be continuous although slope discontinuities within the mechanical assembly may occur. Methods and arrangements for pointing or tilting of the bit face can utilize "composite geometry change" and "local geometry change," both of which are described below.

[0040] Referring now to **Fig. 4,** there is shown a steering unit **120** adapted to steer a BHA **108** using composite geometry change. The steering unit **120** changes the pointing of the bit face 150 of the bit **112** by introducing bending stresses in the BHA **108** above the bit **112** to change a bit face tilt angle α. The BHA **108** is shown in the wellbore **102** as having three points of contact: a contact point **C1** at the bit **112,** a contact point **C2** at a stiffener **152** behind the bit **112**, and either a top hole stiffener **154** or the point where the BHA **108** flexes to lay along a side of the wellbore **102** as contact point **C3.** The steering unit **120** induces a bending moment between contact points **C2** and **C3** that causes a pointing of the bit face **150** (contact point **C1**) in a selected direction. Stiffeners **152, 154,** which act merely as a relatively rigid attachment point, can be a separate element or formed integral with a drill string or the BHA **108** (*e.g.*, a flange).

[0041] Referring now to **Fig. 5A-D**, there are shown embodiments of a geometry change steering unit that includes a deformable sleeve. Merely for ease of explanation, the embodiment of **Figs. 5A-B** depict a sleeve that expands when subjected to an excitation signal and **Fig. 5C-D** depict a sleeve that contracts when subjected to an excitation signal. As will be discussed below, other embodiments can include a sleeve configured to expand or contract depending on the excitation signal. Still other embodiments can include a sleeve having some elements that expand when subjected to an excitation signal or other elements that contract when subjected to an excitation signal. It should be understood, however, that these described embodiments are merely illustrative and that the teachings of the present invention are not limited to the described embodiments.

[0042] Referring now to **Fig. 5A-B,** in one embodiment, a geometry change steering unit **200** includes a deformable sleeve **202** between stiffeners **152** and **154.** The sleeve **202** is formed at least partially of one or more smart materials that expand longitudinally (shown with arrow E) when subjected to an excitation field/signal. In one embodiment, a tube **204** is configured to carry the compressive and tensional loads for drilling (e.g., a "rigid" tube) and acts as a housing for the sleeve **202.** The sleeve **202** is disposed inside the tube **204** and includes a plurality of longitudinal ribs or tendons **206 a-i** running the length of the rigid tube **204.** The tendons **206a-i** are fixedly attached to the stiffeners **152** and **154** to form classic 'bone and tendon network'. The tendons **206 a-i** can also attach to the tube **204** at other locations and by other suitable methods (*e.g.*, chemical bond, fasteners, weld, etc.) A signal/field generating device **208i** produces an excitation signal that causes the tendons **206a-i** to react in a predictable manner. In certain embodiments, the signal/field generating device **208i** is an EMF flow circuit where EMF potential difference is controlled and modulated. As shown, each tendon 206a-i has an associated signal/filed generation device **208,** but other

[0043] (*e.g.*, shared) arrangements can also be used In certain applications. In this embodiment, the smart material performs in an expansion mode. That is, by actively controlling the applied excitation field (*e.g.*, electrical field), one or more selected ribs or tendons (*e.g.*, ribs **206c-e**) are caused to expand against the stiffeners **152** and **154** that are fixed to the rigid tube **204.** Under this applied force, the rigid tube **204** flexes or curls in the opposite direction of the expanded ribs or tendons **206 c-e.** This has the net effect of bending or changing the composite geometry of the BHA **108** proximate the bit **112 (Fig. 4).** An exemplary composite geometry tool center line produced by the steering unit 200 is shown as tool center line **TL1.**

[0044] Referring now to **Fig. 5C-D**, there is shown another embodiment of a geometry change steering unit **220** that also includes a deformable sleeve **222** between stiffeners **152** and **154.** The sleeve **222** is formed at least partially of one or more smart material that contracts longitudinally (shown with arrow **C**) when subjected to an excitation field/signal. In one embodiment, a tube **224** is configured to carry the compressive and tensional loads for drilling (e.g., a "rigid" tube) and acts as a housing for the sleeve **222.** The sleeve **222** is disposed outside of the tube **224** and includes a plurality of longitudinal ribs or tendons **226 a-i** running the length of the rigid tube **224.** The tendons **226a-i** are fixedly attached to stiffeners **152** and **154** to form classic 'bone and tendon network'. The tendons **226 a-i** can also attach to the tube **224** at other locations and by other suitable methods (*e.g.*, chemical bond, fasteners, weld, etc.). A signal/filed generation device **228i** or other device produces an excitation signal that cause the tendons **226a-i** to react in a predictable manner. As shown, each tendon **226a-i** has an associated signal/filed generation device **228,** but other (*e.g.*, shared) arrangements can also be used in certain applications. In this embodiment, the smart material performs in a contraction mode. That is, by actively controlling the excitation field (*e.g.*, EMF, electrical field) produced by the slgnal/filed generation devices **228,** one or more selected ribs or tendons (*e.g.*, ribs **226 c-e**) are caused to contract and effective pull together the stiffeners **152** and **154** that are fixed to the rigid tube **224.** Under this applied force, the rigid tube **224** flexes or curls in the direction opposite of the shortened ribs or tendons **226 c-e.** This has the net effect of bending or changing the composite geometry of the BHA **108** proximate the bit **112 (Fig. 4).** An exemplary composite geometry tool center line produced by the steering unit **220** is shown as tool center line TL2.

[0045] It should be understood that the embodiments described in **Figs. 5A-D** (as well as those described below) can include elements for expanding and contracting

portions of the rigid tube **204.** Thus, for instance, one element **206a** can expand and another element **206i** that is oppositely aligned can contract to bend rigid tube **204.** In certain applications, a first excitation signal can cause an element **206i** to contract and a second excitation signal can cause the element **206i** to expand. In other applications, the elements **206a-i** are formulated to either contract or expand when subjected to an excitation signal. Thus, the sleeve 202 can include one set of elements configured to expand and another set of elements configured to contract.

[0046] Referring now to **Fig**. **5E-F**, there is shown another embodiment of a geometry change steering unit **240** that also includes a deformable sleeve **242** between stiffeners **152** and **154.** The sleeve **242** includes a plurality of axially arranged rings or washers **244** disposed inside or outside of a rigid tube **246.** Each washer **244** includes a plurality of circumferentially arrayed deformable elements **248a-h.** The elements **248a-h** are formed of smart material that deform (*e.g.*, expand or contract) along the longitudinal axis A when subjected to an excitation signal, such as an electrical impulse, transmitted via suitable conductors or coils (not shown) from the control unit (not shown). The elements **248a-h** can be formed to deform from a steady-state shape or geometry (*e.g.*, width or length). The selective excitation of the elements **248a-h** in the same sector of each washer can produce a combined tension or compression along the rigid tube such that the tube bends in a controlled manner. In certain embodiments, a tension can be produced in one sector and a compression in a different sector.

[0047] In certain embodiments, the smart materials are configured to provide a material change that is proportional to a selected parameter of the excitation signal (*i.e.*, the strength, intensity, magnitude, polarity, etc.). Referring now to **Fig. 5A-B**, merely by way of illustration, the elements **206a-i** can be configured to expand or lengthen an amount proportional to the intensity of the excitation signal. For instance, in response to a low intensity excitation signal, the elements **206a-e** expand to a first length to cause a tool center line deflection **TL1** for the rigid tube **204.** In response to a medium intensity excitation signal, the elements **206a-e** expand to a second length to cause a tool center line deflection **TL1a** for the rigid tube **204.** In response to a high intensity excitation signal, the elements **206a-e** expand to a third length to cause a tool center line deflection **TL1b** for the rigid tube **204.** There need not be a step-wise correlation between the controlled parameter of the excitation signal and the response of the smart material. Rather, the response of the smart material to the selected parameter of the excitation signal can be of a sliding scale fashion. Also, the response of the smart material can vary directly or inversely with a selected parameter of the excitation signal.

[0048] The above described composite steering units can be in a lower section of a rotary drill string BHA **108,** in a component of a bearing housing in a modular or conventional drilling motor assembly (not shown), or other suitable location sufficiently proximate to the bit **112.**

[0049] Referring now to **Figs. 6A-B**, there is shown a steering unit **250** that utilizes a local geometry change (*i.e.*, a discontinuity in slope of tool centerline) to change the direction the bit **112** is pointing. In one embodiment, the steering unit **250** includes a dynamically adjustable articulated hinge or joint **252** that, when actuated, can adjust the orientation of the bit **112.** The articulated joint **252** can be positioned immediately adjacent to the bit **112** or disposed in the BHA **108.** In one embodiment, the articulated joint **252** includes a washer or ring **254** having a plurality of elements **256a-n** that can individually or collectively deform (expand or contract) along a longitudinal axis A of the BHA **108.** An exemplary washer arrangement has been previously described in reference to **Figs. 5E-F**. This controlled longitudinal deformation alters the physical orientation of a face **258** of the ring **254.** For instance, one or more of the elements **256a-n** can expand to produce thrust that acts against a bearing surface of an adjacent structure (*e.g.*, a sub, thrust bearing, stabilizer, load flange, etc.). This action causes a discontinuity between a tool center line uphole **A2** of the joint **252** and a tool center line downhole **A3** of the joint **252.**

[0050] It should be appreciated that the elements operate effectively as an adjustable joint that allows the steering unit to flex or bend (*e.g.*, assume a bend radius). Merely for illustrative purposes, there is shown element **256n** expanded (and/or element **256a** contracted) to produce a tilt of angle α' from a reference plane **B** for a ring face **258.** This angle α' provides a corresponding tilt for the bit **112** such that a bit face 260 tilts a corresponding angle β from a reference plane **C.** The term "tilt" refers merely to a displacement or shift of position from a previous position or a nominal / reference position. The displacement can be longitudinal, radial, and in certain instances rotational, or combinations thereof. Moreover, the displacement need not be parallel or orthogonal to any particular reference plane or axis. It should be understood that a tilt can also be produced by expanding elements **256a** and **256n** in different amounts, contracting elements **256a** and **256n** in different amounts, or expanding/contracting element **256a** while having element **256n** remain static. That is, the slope of the face **258** may be controlled by variation of the energizing field strength for the smart material. Thus the degree of the tilt change for the bit face **260** may be not just turned on or off, it may be tuned and adjusted for aggressiveness and rate of hole angle direction change. By selectively energizing segments **256 a-n,** a counter rotation is simulated for the ring face **258** at a speed similar to the bit **112.** The simulated counter-rotation effectively cancels the actual rotation of the bit **112** (or other rotating member) such that the deflection always points (tilts) the bit **112** in a selected direction and thus actively control directional behavior of the well path. Referring also to **Fig. 4** and **6A,** the smart material washer or ring **254** may be placed between con-

tact points **C2** and **C3** to cause a rocking tilt change out on the bit **112** at contact point **C1.**

[0051] Referring now to **Fig. 6C,** there is shown another embodiment of an arrangement for producing dynamic tilting of a bit **112 (Fig. 6A)** that wherein a joint **261** includes a plurality of hydraulic chamber **262** filled with a smart fluid (*e.g.*, a fluid having variable-viscosity) and associated pistons **264.** In one application, the smart fluid provides increased or decreased resistance to compression when subjected to an excitation signal, such as an electrical impulse. Thus, application of an excitation signal causes, for example, the fluid within the chamber to allow the piston **264** to slide into the chamber **262.** A conduit **266** can provide communication between the fluid in the chamber **262** and a separate reservoir (not shown) and/or convey the excitation signal from a controller (not shown) to the chamber fluid. In other embodiments, one or more excitation signal/field generators **268** can be positioned proximate the chamber **262.** Thus, in this embodiment, the pistons **264** individually or collectively contract or relax when subjected to the forces inherent during drilling (*e.g.*, weight on bit **112**). Because selective activation of the smart fluid causes the pistons **264** to compress in different axial amounts, the face **269** of the joint **261** tilts. This tilt thereby alters the physical orientation of the drill bit **112.** It should be appreciated that a plurality of serially arranged piston-cylinders can be utilized to provide a composite geometry change.

[0052] Referring now to **Fig. 7,** in still another embodiment, a washer **270** utilizing smart materials can be incorporated directly into a body **272** of the drill bit **112** and placed in close proximity to the bit face **274.** A controller **276** communicates with the washer **270** via a short hop telemetry system **278** to control the excitation signals provided to the smart material used by washer **270** by a suitable generator (not shown). The telemetry system can also include hard wiring, inductive coupling or other suitable transmission devices.

Force Vector Change Steering Unit

[0053] The exemplary force vector change steering units discussed below do not fall within the scope of the claims.

[0054] Referring now to **Fig. 8,** there is shown an exemplary steering unit **280** that utilizes force vectors to produce a bit force **BF** at the bit **112** to result in side cutting and a change in well bore path and direction. This bit force **BF** at the bit **112** can be caused by moving the centerline of rotation for contact point **C2** off the centerline **A4** of the well bore **102.** As shown in **Fig. 8,** the eccentricity of the tool centerline of rotation towards a high side **282** of the well bore **102** causes a bending stress that results in a high side bit force BF for the drill bit **112** (contact point **C1**). The bit **112** is 'forced' into the high side by the bending stress within the deflected steering head assembly **280** caused by the offset of the centerline **A5** of tool rotation at contact point **C2.** The bit **112** tends to preferentially cut where it is forced (the side of the hole) and a change in direction of the well path results. The manipulation of vector forces can be applied to rotary or motor drilling BHAs.

[0055] Referring now to **Figs. 8** and **9A,** there is shown an arrangement wherein a stabilizer **300** utilizing smart materials is configured to produce/adjust bit side force **BF.** The stabilizer **300** is fixed to a rotating section of the BHA **108.** The stabilizer **300** includes a plurality of force pads **302** for applying a force **F** against a borehole wall **304.** In this embodiment, steering is effected by force vector **F,** which creates a reaction force that urges the bit **112** in the direction generally opposite to the force vector **F.** In one arrangement, the stabilizer **300** can be used at contact point **C2** to produce a force **F1** that causes bit force **BF.** The force pads **302** are actuated by a shape change material **306** that deform in response to an excitation signal produced by a signal/filed generation device or other suitable generator (not shown) as discussed earlier. The expansion/contraction of the shape change material extends or urges the force pads **302** radially inward and/or outward. A controller (not shown) communicates with the stabilizer **300** to control the operation of the force pads **302.** The stabilizer 300 can be positioned as close as possible to the bit **112** to maximize the leverage provided by the extended pads **302.**

[0056] Referring now to **Figs. 8** and **9B**, there is shown another arrangement wherein a stabilizer **310** is fixed to a rotating section of the BHA **108.** The stabilizer **310** includes a plurality of nozzles **312** that form hydraulic jets **314** of pressurized drilling fluid. As noted earlier, pressurized drilling fluid is pumped downhole via the drill string **110** during drilling. The nozzles **312** use a smart material along the fluid exit path to selectively regulate the flow of exiting fluid. For example, the smart material **316** that is disposed in a valve can expand to reduce the cross-sectional flow path to restrict or stop the flow of drilling fluid. Thus, the strength of the hydraulic jets **314** can be controlled via a signal/field generator (not shown) to produce reactive forces. The hydraulic jets **314** produce reactive forces that shift the centerline of rotation away from the center of the well bore analogous to all actions discussed with reference to **Fig. 9A.** Controlling the hydraulic jet **314** velocity/flowrate can alter the symmetry of the lateral hydraulic force vectors and thus control the direction of the lateral deflection in a manner quite similar to mechanical pushing against the well bore wall **304.**

[0057] In certain arrangements, the stabilizers **300** and **310** can be placed at either contact points **C2** or **C3.** In other arrangements, the stabilizers **300** and **310** can be deployed at **C2** and **C3.** In such arrangements, the stabilizers **300** and **310** can be operated to produce opposite but axially spaced apart reaction forces (*e.g.*, **F1** and **F2**).

[0058] Referring now to **Fig. 10,** there is an arrangement wherein a deflection device **320** is fixed to a bit **112** to manipulate the radial positioning of the bit **112** relative to the wellbore **102.** The drill bit **112** has a bit body **322** adapted to receive the deflection device **320.** The deflec-

tion device **320** includes a plurality of force pads **324** for applying a force **F3** against a borehole wall **103** and gage cutters **326** for cutting the borehole wall **103.** The force pads **324** and gage cutters **326** are actuated by a shape change material that expands/contracts in response to an excitation signal as discussed earlier. The expansion/contraction of the shape change material moves or urges the force pads **324** and gage cutters **326** radially. In this arrangement, steering is effected by force vector **F3,** which creates a reaction force urges the bit **112** in the direction generally opposite to the force vector **F3.** The action of the gage cutters **326** and force pads **324** are coordinated such that when a force pad **324** extends out, the corresponding cutter **326** on the opposite side also extends out to cut the borehole wall. A controller **328** communicates with the deflection device **320** via a short hop telemetry system **330** to control the operation of the force pads **324** and gage cutters **326.** In other arrangements, the deflection device **320** includes only force pads **324.** Thus, the deflection device **320** can dynamically adjust the center of rotation for the bit **112,** the direction in which the bit **112** is 'pushed' and the aggressiveness of gage cutting structure in a synchronous action. Furthermore, a hydraulic deflection device **340,** shown in phantom, can be used in lieu of or in addition to the deflection device **320.** The hydraulic deflection device **340** uses smart material controlled nozzles **312** along the outer diameter of the bit **112** to produce controllable hydraulic jets **344** to facilitate the same actions denoted above with respect to **Fig. 9B.** Data, command signals, and power can also be transmitted to the deflection device **320** via a hard wiring, inductive coupling or other suitable transmission devices and systems.

[0059] While **Fig. 10** illustrates a fixed cutter style bit, the above described method and arrangement can also be adapted to other styles of bits, including, but not limited to, roller cone bits, winged reamers and other varieties of hole openers (*e.g.*, bi-center bits).

Bit face Differential Rate of Penetration

[0060] The exemplary differential cutting steering systems discussed below do not fall within the scope of the claims.

[0061] Referring now to **Fig. 11A,** differential cutting steering systems change well bore path and direction by controlling the forward (face) rate of penetration of the bit **112.** An aerially variable (*i.e.*, in one orientation relative to the bore hole axis) cutting rate under a face **400** of the bit **112** can cause the well bore **102** to curve away from the higher ROP segment orientation. Thus, by controlling the cutting effectiveness or efficiency of one or more selected segments (*e.g.*, a pie shaped wedge approaching **180** degrees in coverage) making up a forward bit face **400,** the depth of cut can be increased in a consistent face segment (or range of segments) and this portion of the bore hole will be slighter deeper. After multiple rotations where the same face segment is deepened relative to other segments, the bore hole will bend away from the deep side of the bore hole. Exemplary preferential or differential cutting arrangements are described below.

[0062] Referring still to **Fig. 11A**, there is shown a drill bit **112** provided with a plurality of nozzles **402** that utilize smart materials to modulate the flow through the nozzle **402.** By selectively and dynamically changing the flow through one or more of the nozzles **402** (synchronous with the bit **112** rotation to manage the face segment influenced), the degree of bottom hole cleaning in one segment of the hole can be made more or less effective versus another segment. In the arrangement shown in **Fig. 11A**, nozzles **402** formed of smart materials or controlled by smart material restrictions restrict the flow of drilling fluid **404** when subjected to a suitable excitation signal. Thus, for instance, a first set of nozzles **402** denoted by numeral **406** and a second set of nozzles **402** denoted by numeral **408** restrict flow upon entering a first selected sector **410** below the bit face **400** and allows full drilling fluid flow upon entering a second selected sector **412** below the bit face **400.** The nozzle sets **406** and **408** cycle the flow of fluid at a frequency that corresponds to the RPM of the bit **112.** This differential bottom hole cleaning results in a differential rate of penetration across the bottom of the hole. For instance, drilling cuttings **416** accumulate to a greater degree under segment **410,** which reduces ROP and causes the desired change in well path direction.

[0063] Referring now to **Fig. 11B,** there is shown an exemplary steering unit **420** that aerially modifies bottom hole cutter contact loading on the wellbore bottom **422.** The steering unit **420** includes a plurality of cutters **424a-n,** which are disposed on a face **426** of a drill bit **112,** that can be individually or collectively (*e.g.*, selected groups) axially lengthened. For instance, cutters **424i+1** to **424n,** when activated by an appropriate excitation signal, extend deeper into the wellbore bottom **422** than cutters **424a** to **424i.** Moreover, cutters **424i+1** to **424n** can extend the same depth into the well bore bottom **422** or have a graduated depth or extension. By changing local WOB or force applied to individual or groups of cutter **424a-n,** the cutter embedment can be preferentially controlled to increase / decrease rate of penetration (ROP) in one wellbore bottom sector or segment **428** versus another wellbore bottom sector or segment **430.** Thus, the bit face **426** effectively deforms so that the plane of the face of the bit **112** is extended or retracted from an average or reference face plane **R1**. This cutter extension / retraction creates a force imbalance (greater or less than average cutter force) between one or more cutters **424a-n** and will cause the wellbore bottom **422** to become non-perpendicular to the axis **A5** of the bit **112** through controlled differential ROP. At the same time summation of the force vector lines from the cutters **424a-n** in contact with the wellbore bottom **422** no longer pass through the center of bit **112** rotation. As shown in representative cutter **424n**, the axial extension/retraction of the cutters

424a-n is provided by the selective excitation of a smart material **432n** incorporated into the cutter post, mount structure or other component to move the cutter relative to the bit face. A signal/field generation device, conductor or other suitable excitation signal generator **434n** disposed in the drill bit **112,** can be used to produce the excitation signal or field. Data, command signals, and power can be transmitted to the steering unit **420** via a short hop telemetry system, hard wiring, inductive coupling or other suitable transmission devices and systems.

[0064] Referring now to **Fig. 11C,** in another arrangement, a steering unit **448** actively controls segmental depth of cut using smart materials to alter the height of one or more depth of cut (DOC) limiting protrusions **450** provided on a bit face **451.** Some fixed cutter matrix bits (PDC and some impregnate) include DOC limiting protrusions set at a fixed depth from a reference or control cutter face. The rate of penetration can be controlled by differentially moving the DOC protrusion **450** in or out of the bit face **451** in one orientation relative to the bit **112** centerline **A5**. As discussed with reference to **Fig. 11B,** the differential rate of cut can alter bit drilling direction. The axial extension/retraction of the protrusions **450** is provided by the selective excitation of a smart material **452** incorporated into the protrusions **450.** A signal/field generation device, conductor or other suitable excitation signal generator **454** disposed in the drill bit **112,** can be used to produce the excitation signal or field. Data, command signals, and power can be transmitted to the steering unit **448** via a short hop telemetry system, hard wiring, inductive coupling or other suitable transmission devices and systems (not shown). While two protrusions **450** are shown, greater or fewer may be used.

[0065] While **Figs. 11A-C** illustrate a fixed cutter style bit, the above described method and arrangement can also be adapted to other styles of bits, including, but not limited to, roller cone bits, winged reamers and other varieties of hole openers (*e.g.*, bi-center bits).

[0066] Referring generally to the Figures discussed above, the manner in which a steering unit is incorporated into the BHA **108** can influence the type of control the control unit exerts over the steering unit. For instance, in certain embodiments, such as during sliding drilling, a drilling motor, which can be substantially stationary relative to the wellbore **102,** rotates the drill bit **112.** In such applications, an arrangement can be devised such that the steering unit (*e.g.*, the steering units of **Figs. 4** or **8**) is fixed to the drilling motor or other non-rotating portion of the BHA **108.** Thus, the steering unit would be substantially stationary relative to the well bore **102.** To alter bit **112** direction, such a control unit transmits excitation signals that effectively bend a portion of the BHA **108** (*e.g.*, through local geometry change or composite geometry change) to create a tilt angle that points the bit **112** in a specified direction. Because the steering unit is not rotating relative to the wellbore **102,** this bend can remain substantially fixed (other than to correct for changes in BHA and/or steering unit orientation) until the next desired change in bit **112** direction/orientation.

[0067] In other embodiments, however, the steering unit can rotate. For example, the steering unit may be fixed directly or indirectly to the drill bit **112** and rotate at the rotational speed of the drill bit **112** (*e.g.*, as shown in **Fig. 10**). Also, during rotary drilling, the steering unit may be positioned in a rotating drill string **110** and rotate at the rotational speed of the drill string **110** (*e.g.*, as shown in **Figs. 9A-B**). It should be apparent that a steering unit having a bend, causing a tilt, or causing differential cutting action, will "wobble" about the axis of rotation of the drill string or drill bit **112.** Therefore, in these arrangements, a control unit continually transmits excitation signals to the steering unit to compensate for the rate of rotation of the drill string or drill bit **112** (hereafter "reference rotation"). That is, the excitation signals are generated in a reverse synchronous fashion relative to the reference rotation speed.

[0068] Referring now to **Figs. 12,** there is schematically illustrated an exemplary rotating steering unit **500** having a plurality of elements **502** that can be actively controlled to adjust/maintain/change drilling direction. The steering unit 500 is merely representative of the steering units previously discussed. Likewise the elements **502a-n,** each of which have a smart material **504a-n** and an associated excitation field/signal generator **506a-n,** are representative of the embodiments and arrangements previously discussed for effecting drilling direction; *e.g.*, elements for changing system geometry, applying reaction forces, controlling fluid flow for differential cutting, etc.

[0069] In an exemplary use, a control unit **508** for controlling the steering unit **500** determines that the wellbore direction should be changed in accordance with a controlling condition, surface input, reservoir property, etc. Execution of the direction change can, for example, require that a bend, point, or differential cutting, etc. occur with reference to an arbitrary point or region such as top-dead-center (TDC) **510** of the wellbore. Because the elements **502a-n** are rotating at the reference rotation speed RPM (which can be considered a frequency, *i.e.*, cycles per second), an element **502i** is at TDC **510** only once per rotation of the drill string or drill bit. Accordingly, the control unit **508** activates element **502i** when entering TDC **510** and deactivates upon leaving TDC **510.** Thus, the element **502i** is activated at a frequency corresponding to the reference rotation RPM or frequency.

[0070] The control unit **508** can be programmed to adjust a number of variables in connection with the activation of the elements **502a-n.** With respect to frequency of activation, the control unit **508** can activate the unit **502i** at ratios of one activation per rotation/cycle, one activation per two rotations/cycles, one activation per three rotations/cycles, etc. Thus, the activation frequency can be less than one per rotation as long as the activation occurs while the unit **502i** is within the selected region (*e.g.*, TDC **510**). Further, TDC **510** is merely one illustrative reference point. The region for activation may be an

azimuthal sector having a specified arc (*e.g.*, ninety degrees, one-hundred degrees, etc.). Thus, the zone or region wherein activation of the unit **502i** can be adjusted. Another variable is the number of elements activated; *i.e.*, groups of elements as well as individual elements such as elements **502a-b** can be collectively energized. Moreover, the control unit **508** can select multiple zones or reference segments for activation. For example, an element **502n** entering another reference point such as bottom-dead-center (BDC) **512** can be energized simultaneous (or otherwise) in conjunction with the activation of the elements entering TDC **510.** For instance, an element entering TDC **510** can expand or lengthen while the element entering BDC **512** can retract or shorten.

[0071] Referring now to **Figs. 13A,B** and **14A,B,** there are shown mechanical steering devices that may or may not utilize smart materials, and which again do not fall within the scope of the claims. While the devices are shown as part of a drill string or BHA, these devices can also be incorporated into a drill bit body in a manner previously described.

[0072] Referring now to **Figs. 13A,B,** there is shown an adjustable joint **1000** having a first ring **1100** and a second ring **1200** that can rotate relative to one another about a reference tool center line **X**. Each ring **1100** and **1200** includes an inclined face **1102** and **1202,** respectively, that bear on one another. In other arrangements, members such as tubulars, disks, plates, etc. that have inclined surfaces can be used instead of rings. As shown in **Fig. 13A,** the angles of inclination for the faces **1102** and **1202** are selected such that when rings **1100** and **1200** are at a selected baseline or nominal rotational position relative to one another, the angles of inclination of the faces **1102** and **1202** offset or cancel and the tool center line **X** is not deflected. As shown in **Fig. 13B,** a reference position **R1** for ring **1100** and a reference position **R2** for ring **1200,** which can be arbitrarily defined, are set to cause no deflection of the tool centerline **X**.

[0073] In a particular arrangement, the rings **1100** and **1200** have at least two operational modes. First, the rings **1100** and **1200** rotate relative to one another to set the desired deflection angle, which then produces a corresponding tilt to the BHA/drill bit. Once the deflection angle is set, the relative rotation between the rings **1100** and **1200** is fixed until the deflection angle needs to be changed. Thus, the rings **1100** and **1200** are substantially locked together and the deflection angle does not change during a section of the drilling operation. If the joint **1000** is not being rotated (*e.g.*, oriented slide drill mode), then the locked rings **1100** and **1200** are rotated as a unit only to maintain the proper orientation. During slide drilling, tools can tend to drift out of proper orientation. In such circumstances, the joint **1000** can be rotated as needed to counter any rotational drift caused by torsional or other dynamic string wind-up between down hole and the torsional anchor point (which can be at the surface or at a downhole anchor). During rotary drilling, the locked rings **1100** and **1200** are counter rotated as a unit at the speed of the string rotation so as to maintain the selected tilt angle heading.

[0074] Referring now to **Figs. 14A,B,** there is shown the adjustable joint **1000** wherein the reference positions **R1** and **R2** have been shifted relative to one another to cause a tilt in the BHA as shown by deflected tool center line Y. In one arrangement, a downhole motor (*e.g.*, electric, hydraulic, etc.)(not shown) is used to rotate one ring relative to the other. For example, the motor (not shown) is coupled to the first ring **1100** via a shaft (not shown) and the second ring 1200 is fixed or attached to a drill string (not shown), BHA (not shown) or drill bit (not shown). The motor is energized to make the appropriate alignment changes for **R1** and **R2** to cause the desired tool centerline deflection. In another mode of operation, the rings **1100** and **1200** (or other suitable members) are formed at least partially of a smart material. Thus, a control unit can provide an excitation signal to such rings in a manner that simulates an appropriate counter rotation.

[0075] Referring now to **Fig. 15,** there is shown the adjustable joint **1000** disposed in a section of a BHA **2000.** The joint **1000** includes a first ring **1100** and a second ring **1200.** A positional sensor package **2100** is located within and rotating with a rotating drilling tubular **2200** that provides drilling torque and WOB for a drilling operation. The positional sensor package **2100** is configured to reference an external reference plane (*e.g.* gravity vector, magnetic field vectors, etc.) and actively correlate an internal reference plane to the external reference plane. This allows the sensor package **2100** to create a known orientation (it knows its global and local rotary orientation) to the reference vector during random rotation of the drilling tubular **2200.** The sensor package **2100** provides input to a control / driver device **2300** that controls a secondary rotary drive device **2400** connected to the first ring **1100** and the second ring **1200** of the adjustable joint **1000.** In one arrangement, the drive device **2400** counter rotates the joint **1000** to maintain a fixed or desired orientation to the external reference plane. In another arrangement, the control device **2300** provides an excitation signal that for energizing a smart material in the rings **1100** and **1200** to simulate an appropriate counter rotation. As noted earlier, nearly any member providing an inclined surfaces that produce a deflection of the BHA when aligned in a selected manner may be used in lieu of rings (*e.g.*, tubulars, disks, plates, etc.).

[0076] It should be understood that the above teachings can be advantageously utilized in systems, devices and methods that are variations of, or different from, the above-described embodiments and arrangements. These teachings include, but are not limited to, steering units utilizing smart materials (hereafter "smart material steering units"), control units for canceling the effect the rotation of a drilling tubular or other member, and steering units utilizing actively adjustable rotating members (*e.g.*, tubulars, disks, rings, plates, etc.) (hereafter "rotating member steering units"). Merely for convenience, a few

of the above-described teachings are repeated, in albeit cursory fashion, below:

- Systems, devices and methods have been described for use in a rotary drilling system (*i.e.*, bit driven by drill string rotation) wherein (i) excitation of a smart material in a smart material steering unit causes a change in BHA geometry or operation (*e.g.*, tool center line deflection, force vector change, differential cutting, etc.); and (ii) a control unit excites the smart material at a frequency that simulates a counter rotation at a speed that effectively cancels the drill string rotation.

- Systems, devices and methods have been described for use in a rotary drilling system (*i.e.*, bit driven by drill string rotation) wherein (i) a excitation of a smart material in a smart material steering unit causes a change in BHA geometry or operation (*e.g.*, tool center line deflection, force vector change, differential cutting, etc.); and (ii) a control unit operates a rotary drive (*e.g.*, a motor) coupled to the smart material steering unit to provide a counter rotation at a speed that effectively cancels the drill string rotation.

- Systems, devices and methods have been described for use in a sliding drilling system (*i.e.*, bit driven by downhole motor) wherein excitation of a smart material in a smart material steering unit causes a change in BHA geometry or operation (*e.g.*, tool center line deflection, force vector change, differential cutting, etc.). No counter rotation is needed since the steering unit using the smart material is not rotating.

- Systems, devices and methods have been described for use in a rotary drilling system (*i.e.*, bit driven by drill string rotation) wherein (i) a rotating member steering unit is adjusted to cause a change in BHA geometry or operation (*e.g.*, tool center line deflection, force vector change, differential cutting, etc.); and (ii) a control unit excites a smart material associated with the rotating member steering unit at a frequency that simulates a counter rotation at a speed that effectively cancels the drill string rotation.

- Systems, devices and methods have been described for use in a rotary drilling system (*i.e.*, bit driven by drill string rotation) wherein (i) a rotating member steering unit is adjusted to cause a change in BHA geometry or operation (*e.g.*, tool center line deflection, force vector change, differential cutting, etc.); and (ii) a control unit operates a rotary drive (*e.g.*, a motor) coupled to the rotating member steering unit to provide a counter rotation at a speed that effectively cancels the drill string rotation.

- Also described are systems, devices and methods integral with or provided in a drill bit or other cutting structure to control drilling direction.

[0077] Although the teachings of the present invention have been discussed with reference to devices and systems for directional drilling, it should be apparent that the advantageous of the present invention can be equally applicable to other wellbore tools, although such arrangements do not fall within the scope of the claims. For example, the system geometry change devices may be utilized with formation testing tools, wellbore completion tools, etc., including branch wellbore, lateral re-entry guide tools, tools conveyed on drill pipe or coiled tubing, and casing exit oriented milling/cutting tools. Accordingly, while the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope of the appended claims be embraced by the foregoing disclosure.

Claims

1. A system for drilling a wellbore in an earthen formation, comprising:

a drill string (110) conveyed into the wellbore;
a bottom hole assembly (108) coupled to an end of the drill string (110), the bottom hole assembly including a drill bit (112); and
a steering unit (120; 200; 240; 250) associated with the bottom hole assembly (108) for controlling the drilling direction of the bottom hole assembly, the steering unit including a plurality of deflection elements (206; 226; 248; 256; 270) each formed at least partially of a smart material that changes in shape, size, dimension and/or viscosity in response to an excitation signal to control a deflection of an axial tool line (A) of the bottom hole assembly;
characterised in that:

each of the plurality of deflection elements (206; 226; 248; 256; 270) is independently excitable; and
the steering unit further includes a control unit for providing the excitation signal or signals to the plurality of deflection elements (206; 226; 248; 256; 270).

2. The system according to claim 1, wherein the plurality of deflection elements (206; 226; 248; 256; 270) are disposed in one of: (i) a sleeve (202; 222; 242); (ii) a washer (270); (iii) a joint (252); and (iv) the drill bit (112).

3. The system according to claim 1 or 2, wherein the

control unit is arranged to provide the excitation signal or signals at a frequency determined at least partially from a rotational speed of one of: (i) the drill bit (112); and (ii) drill string (110), the frequency causing the deflection in the BHA axial tool line (A) to remain substantially rotationally stationary relative to the wellbore.

4. The system according to any preceding claim, wherein the smart material is selected from one of: (i) an electrorheological material; (ii) a magnetorheological material; and (iii) a piezoelectric material.

5. The system according to any preceding claim, further comprising a rotation sensor for measuring a reference rotation, the rotation sensor being arranged to provide the measurements to the control unit and the control unit being arranged to provide the excitation signal or signals at a frequency determined at least partially using the rotational speed measurements.

6. The system according to any preceding claim wherein the deflection is one of: (i) a local geometry change in the BHA axial tool line (A); (ii) a composite geometry change in the BHA axial tool line (A); and (iii) a tilt at a face of the drill bit (112).

7. A method for drilling a wellbore in an earthen formation, comprising:

conveying a drill string (110) into the wellbore, the drill string having a bottomhole assembly (108) coupled to an end thereof, the bottom hole assembly including a drill bit (112); and
steering the bottom hole assembly (108) with a steering unit having a plurality of deflection elements (206; 226; 248; 256; 270) each formed at least partially of a smart material that changes in shape, size, dimension and/or viscosity in response to an excitation signal to control a deflection of an axial tool line (A) of the bottom hole assembly;
characterised in that:

each of the plurality of deflection elements (206; 226; 248; 256; 270) is independently excitable; and
the steering unit further includes a control unit for providing the excitation signal or signals to the plurality of deflection elements (206; 226; 248; 256; 270).

8. The method according to claim 7, further comprising disposing the plurality of deflection elements (206; 226; 258; 256; 270) in one of: (i) a sleeve (202; 222; 242); (ii) a washer (270); (iii) a joint (252); and (iv) the drill bit (112).

9. The method according to claim 8 or 9, wherein the control unit provides the excitation signal or signals at a frequency determined at least partially from a rotational speed of one of: (i) the drill bit (112); and (ii) drill string (110), the frequency causing the deflection in the BHA axial tool line (A) to remain substantially rotationally stationary relative to the wellbore.

10. The method according to any of claims 7 to 9, wherein the smart material is selected from one of: (i) an electrorheological material; (ii) a magnetorheological material; and (iii) a piezoelectric material.

11. The method according to any of claims 7 to 10, further comprising measuring a reference rotation using a rotation sensor, and wherein the control unit provides the excitation signal or signals at a frequency determined at least partially using the rotational speed measurements.

12. The method according to any of claims 7 to 11, wherein the deflection is one of: (i) a local geometry change in the BHA axial tool line (A); (ii) a composite geometry change in the BHA axial tool line (A); and (iii) a tilt at a face of the drill bit (112).

Patentansprüche

1. System zum Bohren eines Bohrlochs in einer Erdformation, aufweisend:

einen Bohrstrang (110), der in das Bohrloch befördert wird;
eine Bohrlochsohlenanordnung (108), die an ein Ende des Bohrstrangs (110) gekoppelt ist, wobei die Bohrlochsohlenanordnung einen Bohrmeißel (112) aufweist; und
eine Lenkeinheit (120; 200; 240; 250), die mit der Bohrlochsohlenanordnung (108) verbunden ist, zum Steuern der Bohrrichtung der Bohrlochsohlenanordnung, wobei die Lenkeinheit mehrere Ablenkungselemente (206; 226; 248; 256; 270) aufweist, die jeweils wenigstens teilweise aus einem intelligenten Material gebildet sind, das sich in Form, Größe, Abmessung und/oder Viskosität in Reaktion auf ein Erregungssignal zum Steuern einer Ablenkung einer axialen Werkzeuglinie (A) der Bohrlochsohlenanordnung ändert;
dadurch gekennzeichnet, dass
jedes der mehreren Ablenkungselemente (206; 226; 248; 256; 270) unabhängig erregbar ist; und
die Lenkeinheit ferner eine Steuereinheit zum Bereitstellen des Erregungssignals oder der Erregungssignale für die mehreren Ablenkungs-

elemente (206; 226; 248; 256; 270) aufweist.

2. System nach Anspruch 1, wobei die mehreren Ablenkungselemente (206; 226; 248; 256; 270) in einem von (i) einer Hülse (202; 222; 242), (ii) einer Scheibe (270), (iii) einer Verbindung (252) und (iv) dem Bohrmeißel (112) angeordnet sind.

3. System nach Anspruch 1 oder 2, wobei die Steuereinheit so ausgelegt ist, dass sie das Erregungssignal oder die Erregungssignale mit einer Frequenz bereitstellt, die wenigstens teilweise aus einer Drehgeschwindigkeit von einem von (i) dem Bohrmeißel (112) und (ii) dem Bohrstrang (110) bestimmt wird, wobei die Frequenz bewirkt, dass die Ablenkung in der axialen BHA-Werkzeuglinie (A) in Bezug auf das Bohrloch hinsichtlich der Drehung im Wesentlichen unbeweglich bleibt.

4. System nach einem der vorhergehenden Ansprüche, wobei das intelligente Material aus einem von (i) einem elektrorheologischen Material, (ii) einem magnetorheologischen Material und (iii) einem piezoelektrischen Material ausgewählt ist.

5. System nach einem der vorhergehenden Ansprüche, ferner aufweisend einen Rotationssensor zum Messen einer Bezugsdrehung, wobei der Rotationssensor so ausgelegt ist, dass er die Messungen an die Steuereinheit liefert, und die Steuereinheit so ausgelegt ist, dass sie das Erregungssignal oder die Erregungssignale mit einer Frequenz bereitstellt, die wenigstens teilweise unter Verwendung der Drehgeschwindigkeitsmessungen bestimmt wird.

6. System nach einem der vorhergehenden Ansprüche, wobei die Ablenkung eine von (i) einer örtlichen Geometrieänderung der axialen BHA-Werkzeuglinie (A), (ii) einer zusammengesetzten Geometrieänderung der axialen BHA-Werkzeuglinie (A) und (iii) einer Neigung an einer Vorderseite des Bohrmeißels (112) ist.

7. Verfahren zum Bohren eines Bohrlochs in einer Erdformation, aufweisend:

Befördern eines Bohrstrangs (110) in das Bohrloch, wobei der Bohrstrang eine Bohrlochsohlenanordnung (108) aufweist, die an ein Ende davon gekoppelt ist, und die Bohrlochsohlenanordnung einen Bohrmeißel (112) aufweist; und
Lenken der Bohrlochsohlenanordnung (108) mit einer Lenkeinheit mit mehreren Ablenkungselementen (206; 226; 248; 256; 270), die jeweils wenigstens teilweise aus einem intelligenten Material gebildet sind, das sich in Form, Größe, Abmessung und/oder Viskosität in Reaktion auf ein Erregungssignal zum Steuern einer Ablenkung einer axialen Werkzeuglinie (A) der Bohrlochsohlenanordnung ändert;
dadurch gekennzeichnet, dass
jedes der mehreren Ablenkungselemente (206; 226; 248; 256; 270) unabhängig erregbar ist; und
die Lenkeinheit ferner eine Steuereinheit zum Bereitstellen des Erregungssignals oder der Erregungssignale für die mehreren Ablenkungselemente (206; 226; 248; 256; 270) aufweist.

8. Verfahren nach Anspruch 7, ferner umfassend ein Anordnen der mehreren Ablenkungselemente (206; 226; 248; 256; 270) in einem von (i) einer Hülse (202; 222; 242), (ii) einer Scheibe (270), (iii) einer Verbindung (252) und (iv) dem Bohrmeißel (112).

9. Verfahren nach Anspruch 8 oder 9, wobei die Steuereinheit das Erregungssignal oder die Erregungssignale mit einer Frequenz bereitstellt, die wenigstens teilweise aus einer Drehgeschwindigkeit von einem von (i) dem Bohrmeißel (112) und (ii) dem Bohrstrang (110) bestimmt wird, wobei die Frequenz bewirkt, dass die Ablenkung in der axialen BHA-Werkzeuglinie (A) in Bezug auf das Bohrloch hinsichtlich der Drehung im Wesentlichen unbeweglich bleibt.

10. Verfahren nach einem der Ansprüche 7 bis 9, wobei das intelligente Material aus einem von (i) einem elektrorheologischen Material, (ii) einem magnetorheologischen Material und (iii) einem piezoelektrischen Material ausgewählt ist.

11. Verfahren nach einem der Ansprüche 7 bis 10, ferner aufweisend ein Messen einer Bezugsdrehung unter Verwendung eines Rotationssensors, und wobei die Steuereinheit das Erregungssignal oder die Erregungssignale mit einer Frequenz bereitstellt, die wenigstens teilweise unter Verwendung der Drehgeschwindigkeitsmessungen bestimmt wird.

12. Verfahren nach einem der Ansprüche 7 bis 10, wobei die Ablenkung eine von (i) einer örtlichen Geometrieänderung der axialen BHA-Werkzeuglinie (A), (ii) einer zusammengesetzten Geometrieänderung der axialen BHA-Werkzeuglinie (A) und (iii) einer Neigung an der Vorderseite des Bohrmeißels (112) ist.

Revendications

1. Système pour le forage d'un puits dans une formation de terre, comprenant :

un train de forage (110) introduit dans le puits ;
un ensemble de fond de puits (108) couplé à une extrémité du train de forage (110), l'ensem-

ble de fond de puits comprenant un trépan (112) ; et
une unité d'orientation (120 ; 200 ; 240 ; 250) associée à l'ensemble de fond de puits (108) pour contrôler la direction de forage de l'ensemble de fond de puits, l'unité d'orientation comprenant une pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270), chacun formés au moins en partie d'un matériau intelligent qui change de forme, de taille, de dimension et/ou de viscosité en réponse à un signal d'excitation pour contrôler une déviation d'un ensemble d'outils axial (A) de l'ensemble de fond de puits ; **caractérisé en ce que** :

chacun de la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270) est excitable indépendamment ; et
l'unité d'orientation comprend en outre une unité de commande pour présenter le signal d'excitation ou les signaux d'excitation à la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270).

2. Système selon la revendication 1, dans lequel la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270) est disposée dans l'un de : (i) un manchon (202 ; 222 ; 242) ; (ii) une rondelle (270) ; (iii) un joint (252) ; et (iv) le trépan (112).

3. Système selon la revendication 1 ou 2, dans lequel l'unité de commande est disposée pour présenter le signal d'excitation ou les signaux d'excitation à une fréquence déterminée au moins en partie à partir d'une vitesse de rotation de l'un de : (i) le trépan (112) ; et (ii) le train de forage (110), la fréquence agissant de sorte que la déviation dans l'ensemble d'outils axial de l'ensemble de fond de puits (EFP) (A) reste fondamentalement stationnaire en rotation par rapport au puits.

4. Système selon l'une quelconque des revendications précédentes, dans lequel le matériau intelligent est sélectionné parmi l'un de : (i) un matériau électrorhéologique ; (ii) un matériau magnétorhéologique ; et (iii) un matériau piézoélectrique.

5. Système selon l'une quelconque des revendications précédentes, comprenant en outre un capteur de rotation pour mesurer une rotation de référence, le capteur de rotation étant disposé pour présenter les mesures à l'unité de commande et l'unité de commande étant disposée pour présenter le signal d'excitation ou les signaux d'excitation à une fréquence déterminée au moins en partie en utilisant les mesures de vitesse de rotation.

6. Système selon l'une quelconque des revendications précédentes, dans lequel la déviation est l'une de : (i) un changement géométrique local dans l'ensemble d'outils axial de l'EFP (A) ; (ii) un changement géométrique composite dans l'ensemble d'outils axial de l'EFP (A) ; et (iii) une inclinaison au niveau d'une face du trépan (112).

7. Procédé pour le forage d'un puits dans une formation de terre, comprenant :

l'introduction d'un train de forage (110) dans le puits, le train de forage comportant un ensemble de fond de puits (108) couplé à une extrémité de celui-ci, l'ensemble de fond de puits comprenant un trépan (112) ; et
l'orientation de l'ensemble de fond de puits (108) avec une unité d'orientation comprenant une pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270), chacun formés au moins en partie d'un matériau intelligent qui change de forme, de taille, de dimension et/ou de viscosité en réponse à un signal d'excitation pour contrôler une déviation d'un ensemble d'outils axial (A) de l'ensemble de fond de puits ;
caractérisé en ce que :

chacun de la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270) est excitable indépendamment ; et
l'unité d'orientation comprend en outre une unité de commande pour présenter le signal d'excitation ou les signaux d'excitation à la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270).

8. Procédé selon la revendication 7, comprenant en outre la disposition de la pluralité d'éléments de déviation (206 ; 226 ; 248 ; 256 ; 270) dans l'un de : (i) un manchon (202 ; 222 ; 242) ; (ii) une rondelle (270) ; (iii) un joint (252) ; et (iv) le trépan (112).

9. Procédé selon la revendication 8 ou 9, dans lequel l'unité de commande présente le signal d'excitation ou les signaux d'excitation à une fréquence déterminée au moins en partie à partir d'une vitesse de rotation de l'un de : (i) le trépan (112) ; et (ii) le train de forage (110), la fréquence agissant de sorte que la déviation dans l'ensemble d'outils axial de l'EFP (A) reste fondamentalement stationnaire en rotation par rapport au puits.

10. Procédé selon l'une quelconque des revendications 7 à 9, dans lequel le matériau intelligent est sélectionné parmi l'un de : (i) un matériau électrorhéologique ; (ii) un matériau magnétorhéologique ; et (iii) un matériau piézoélectrique.

11. Procédé selon l'une quelconque des revendications 7 à 10, comprenant en outre la mesure d'une rotation de référence en utilisant un capteur de rotation, et dans lequel l'unité de commande présente le signal d'excitation ou les signaux d'excitation à une fréquence déterminée au moins en partie en utilisant les mesures de vitesse de rotation.

12. Procédé selon l'une quelconque des revendications 7 à 11, dans lequel la déviation est l'une de : (i) un changement géométrique local dans l'ensemble d'outils axial de l'EFP (A) ; (ii) un changement géométrique composite dans l'ensemble d'outils axial de l'EFP (A) ; et (iii) une inclinaison au niveau d'une face du trépan (112).

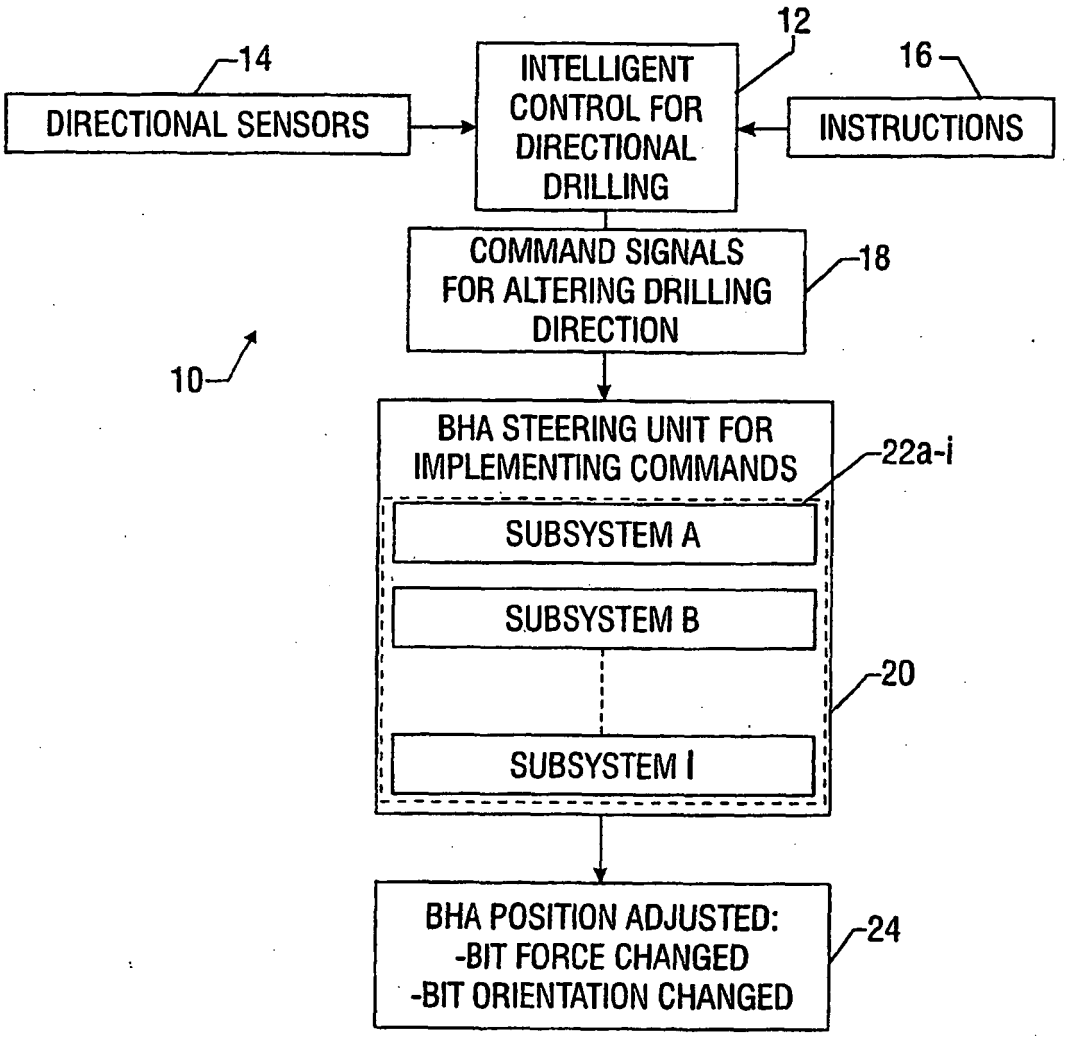


FIG. 1
(Prior Art)

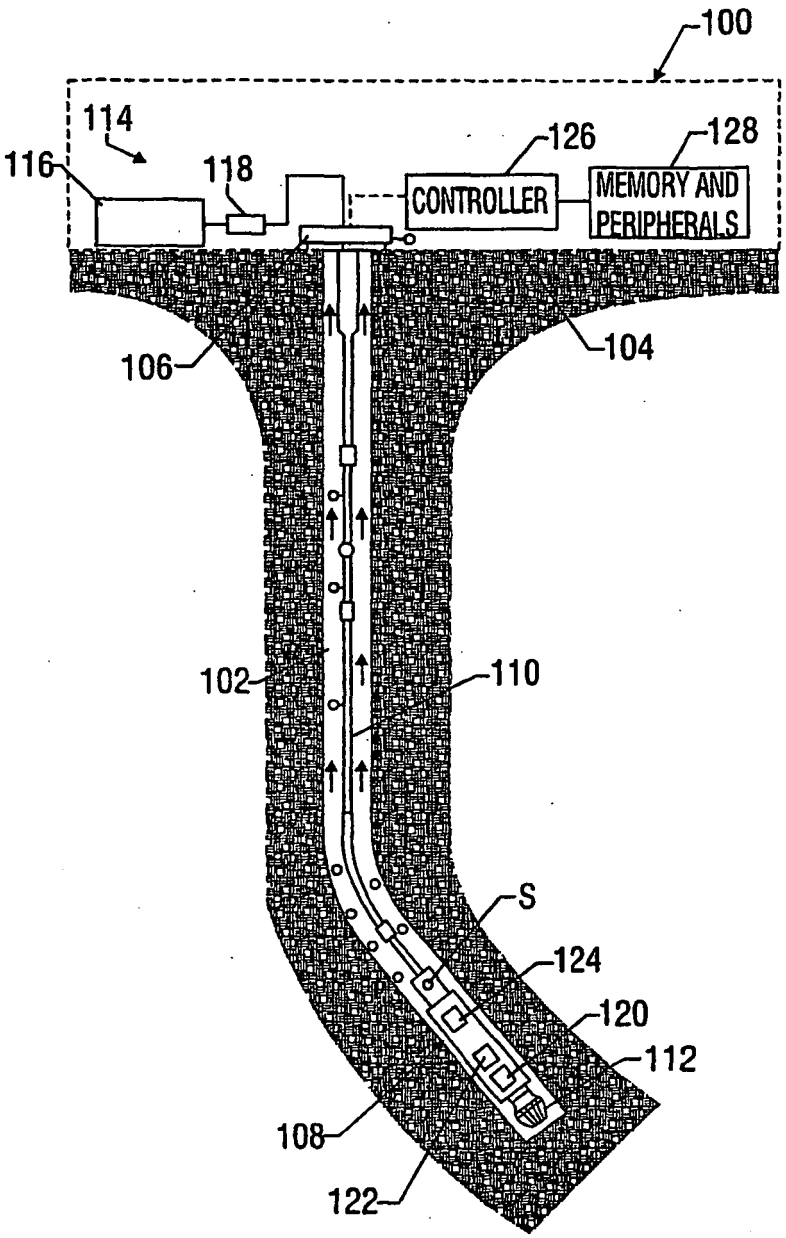

100
114
116
118
126
128
CONTROLLER
MEMORY AND PERIPHERALS
106
104
102
110
S
124
120
112
108
122

FIG. 2

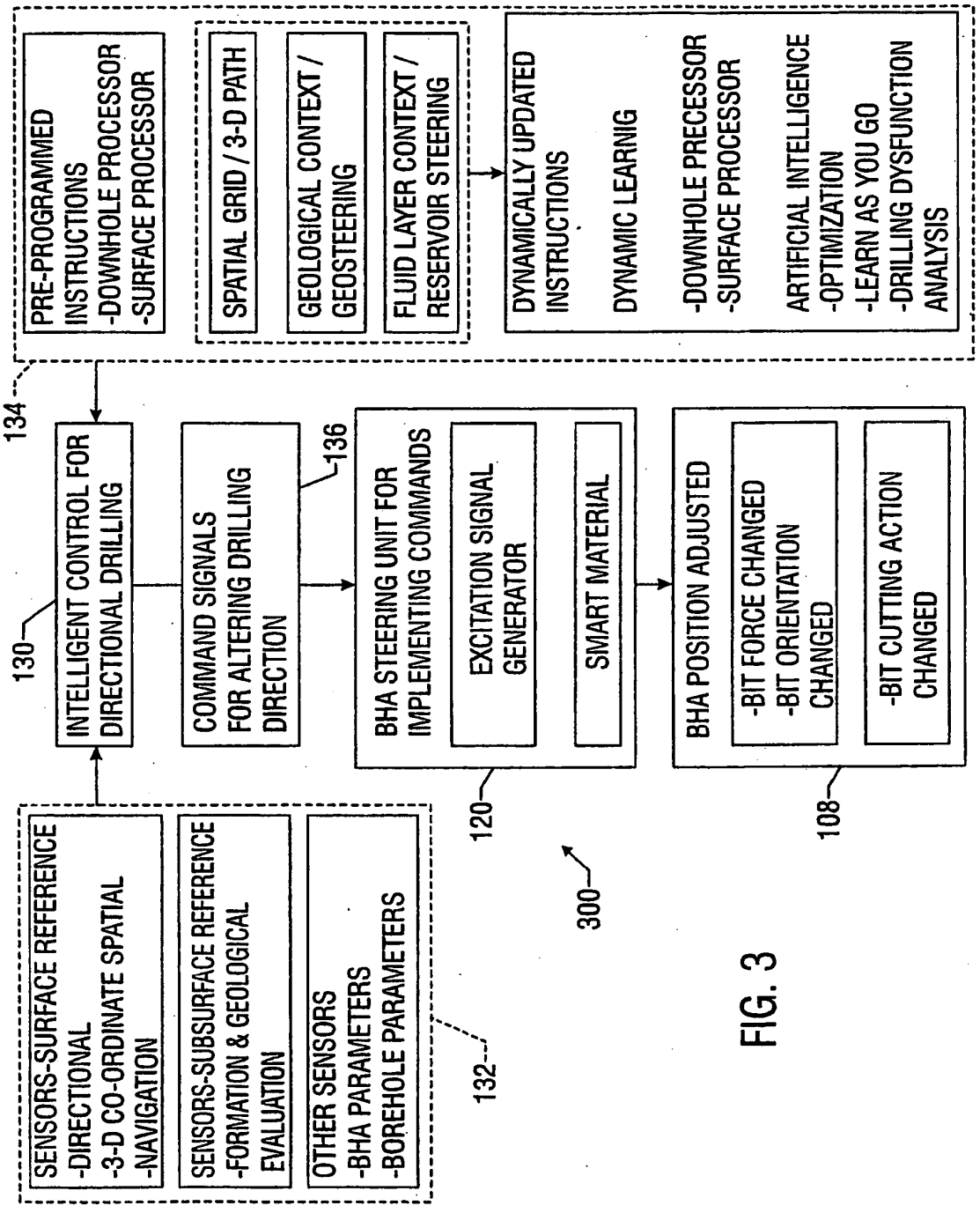

PRE-PROGRAMMED INSTRUCTIONS -DOWNHOLE PROCESSOR -SURFACE PROCESSOR
SPATIAL GRID / 3-D PATH
GEOLOGICAL CONTEXT / GEOSTEERING
FLUID LAYER CONTEXT / RESERVOIR STEERING
DYNAMICALLY UPDATED INSTRUCTIONS
DYNAMIC LEARNING
-DOWNHOLE PRECESSOR -SURFACE PROCESSOR
ARTIFICIAL INTELLIGENCE -OPTIMIZATION -LEARN AS YOU GO -DRILLING DYSFUNCTION ANALYSIS
134
130
INTELLIGENT CONTROL FOR DIRECTIONAL DRILLING
COMMAND SIGNALS FOR ALTERING DRILLING DIRECTION
136
BHA STEERING UNIT FOR IMPLEMENTING COMMANDS
EXCITATION SIGNAL GENERATOR
SMART MATERIAL
BHA POSITION ADJUSTED
-BIT FORCE CHANGED -BIT ORIENTATION CHANGED
-BIT CUTTING ACTION CHANGED
SENSORS-SURFACE REFERENCE -DIRECTIONAL -3-D CO-ORDINATE SPATIAL -NAVIGATION
SENSORS-SUBSURFACE REFERENCE -FORMATION & GEOLOGICAL EVALUATION
OTHER SENSORS -BHA PARAMETERS -BOREHOLE PARAMETERS
132
120
300
108

FIG. 3

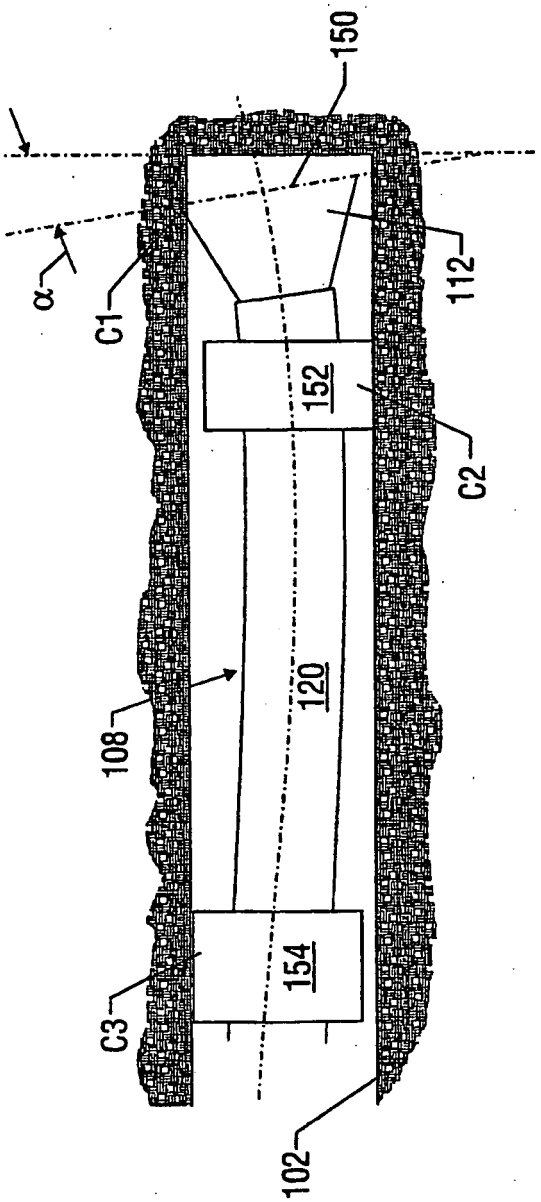


FIG. 4

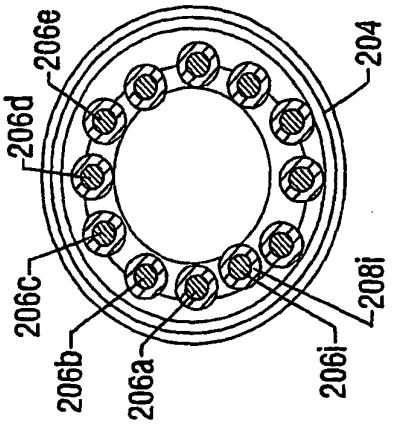


FIG. 5B

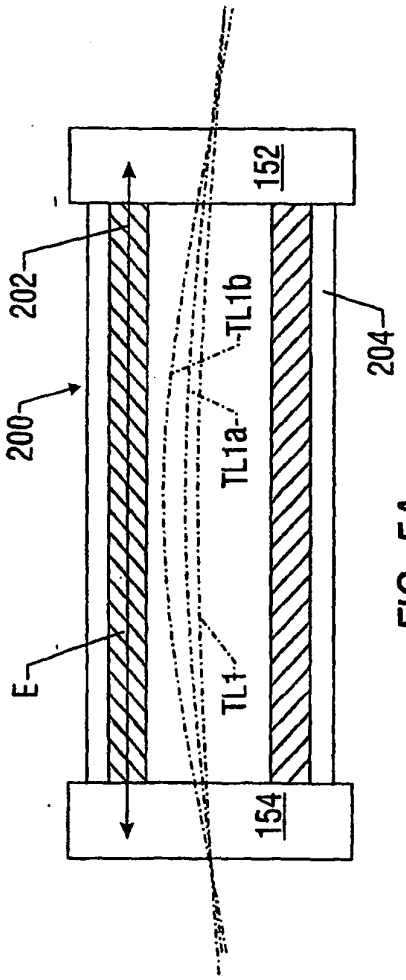


FIG. 5A

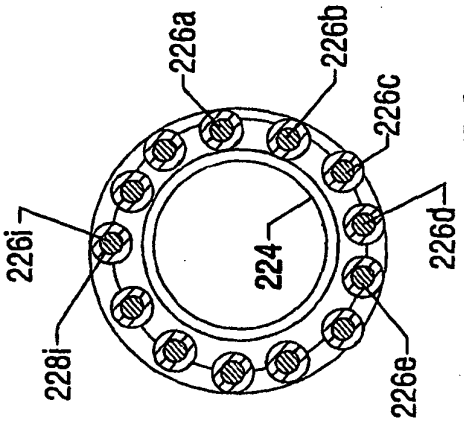


FIG. 5D

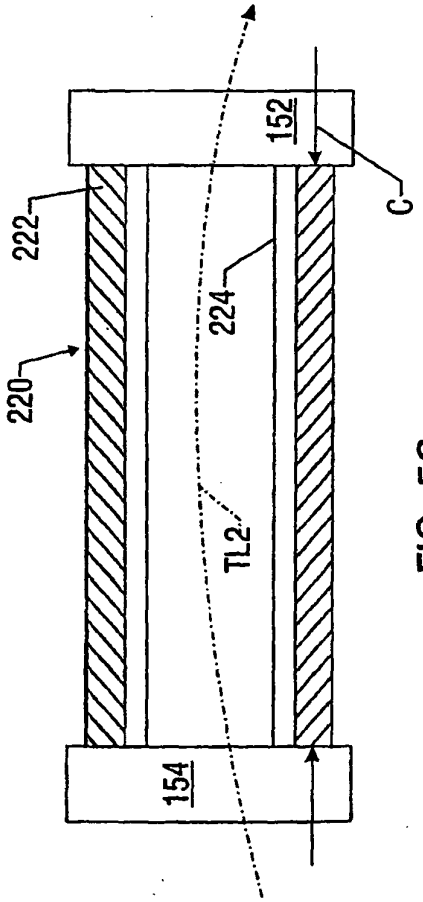


FIG. 5C

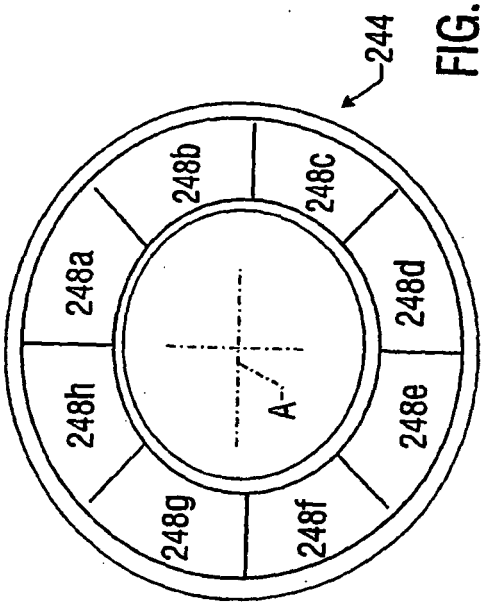

244
248a
248b
248c
248d
248e
248f
248g
248h
A

FIG. 5F

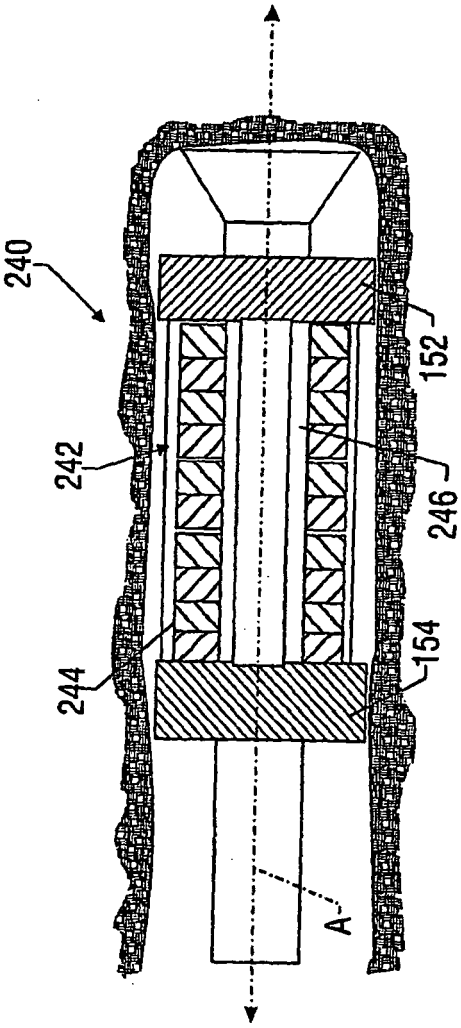

240
242
244
246
152
154
A

FIG. 5E

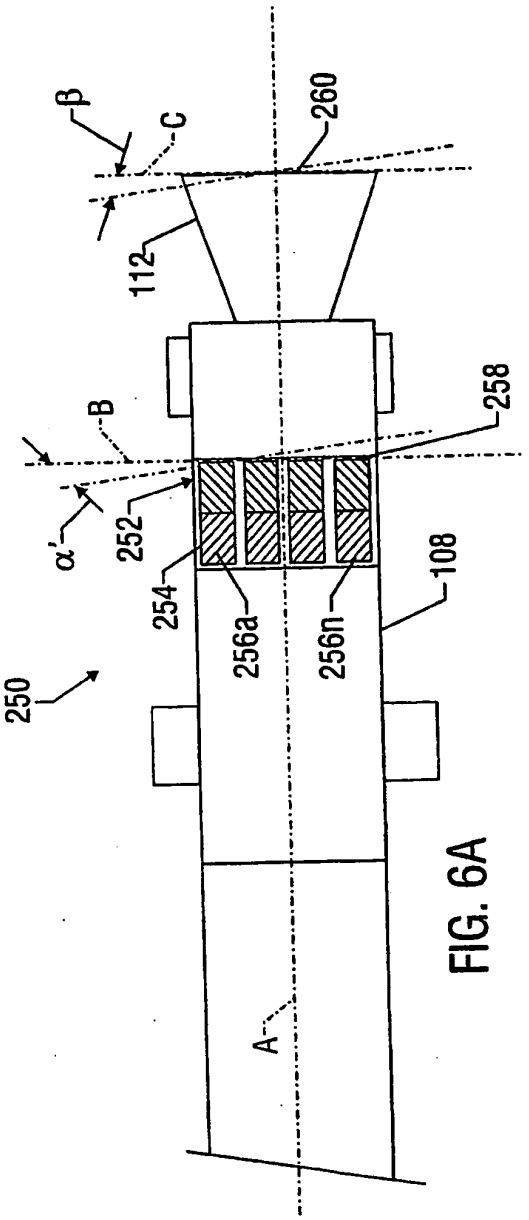

β
C
260
112
B
258
α'
252
254
256a
256n
108
250
A

FIG. 6A

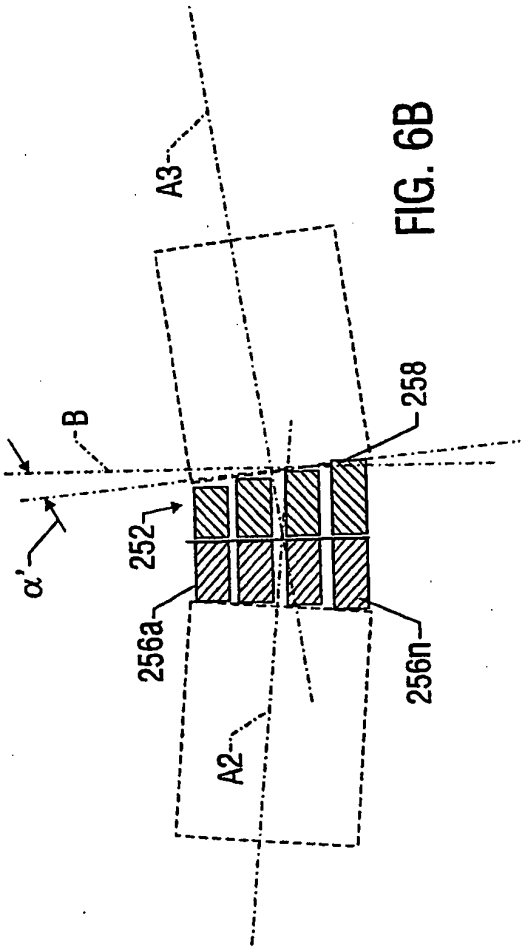

A3
B
258
α'
252
256a
256n
A2

FIG. 6B

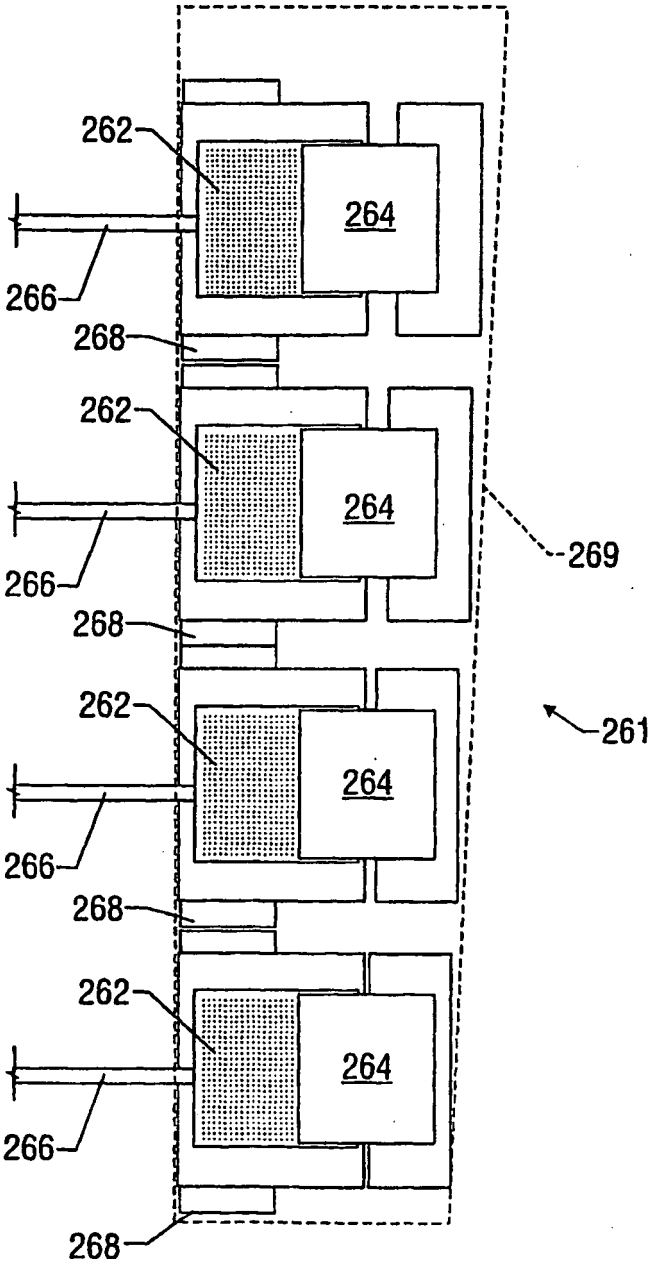

262
264
266
268
262
264
266
268
269
261
262
264
266
268
262
264
266
268

FIG. 6C

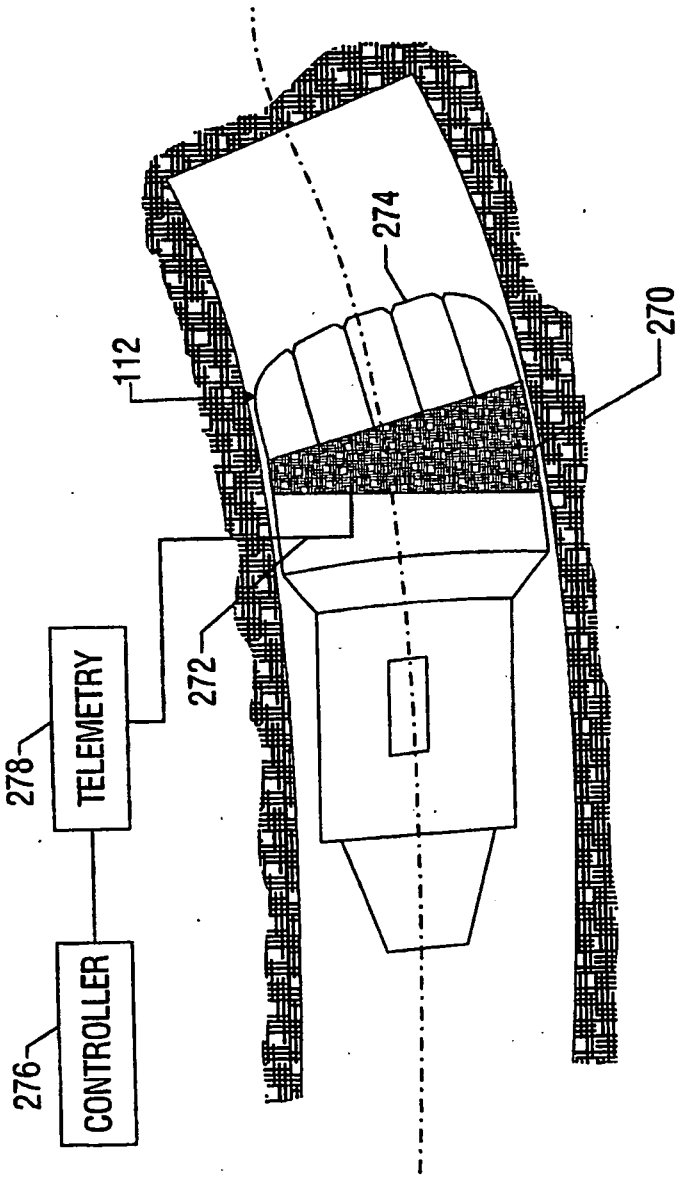


FIG. 7

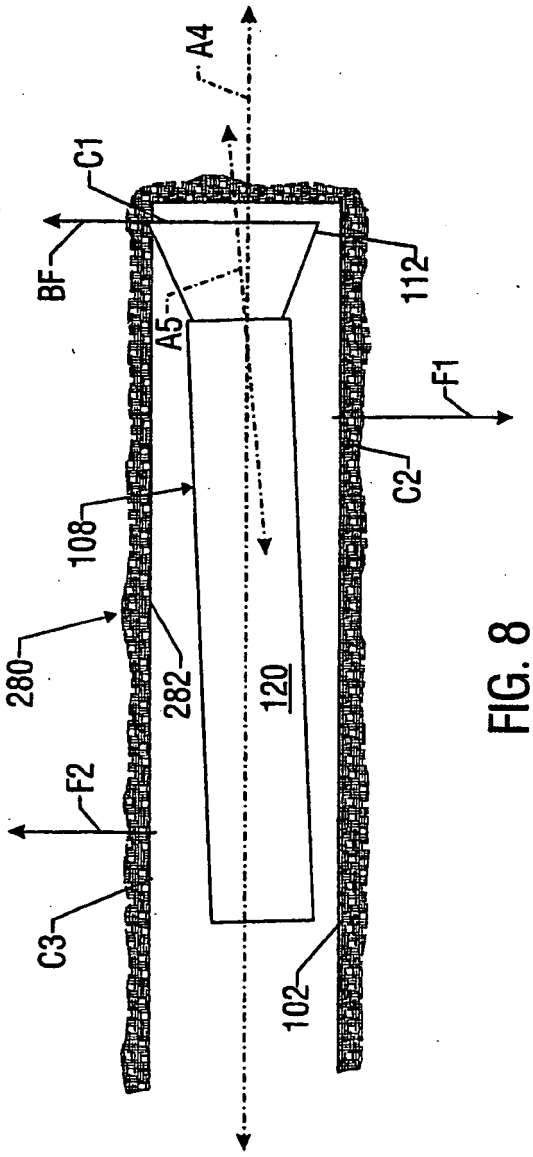


FIG. 8

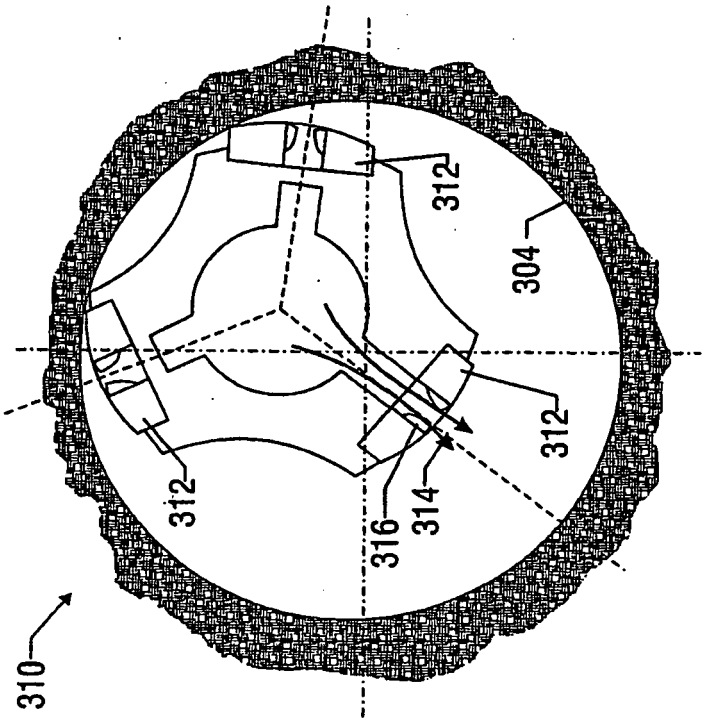


FIG. 9B

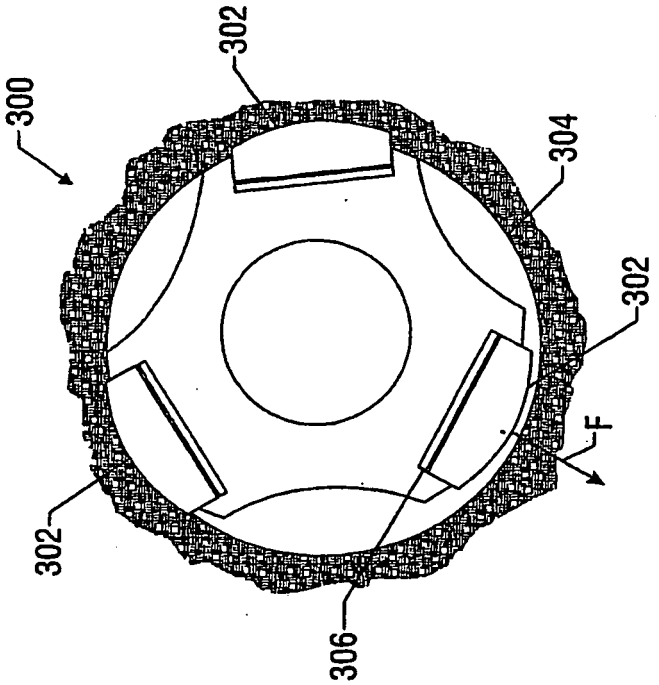


FIG. 9A

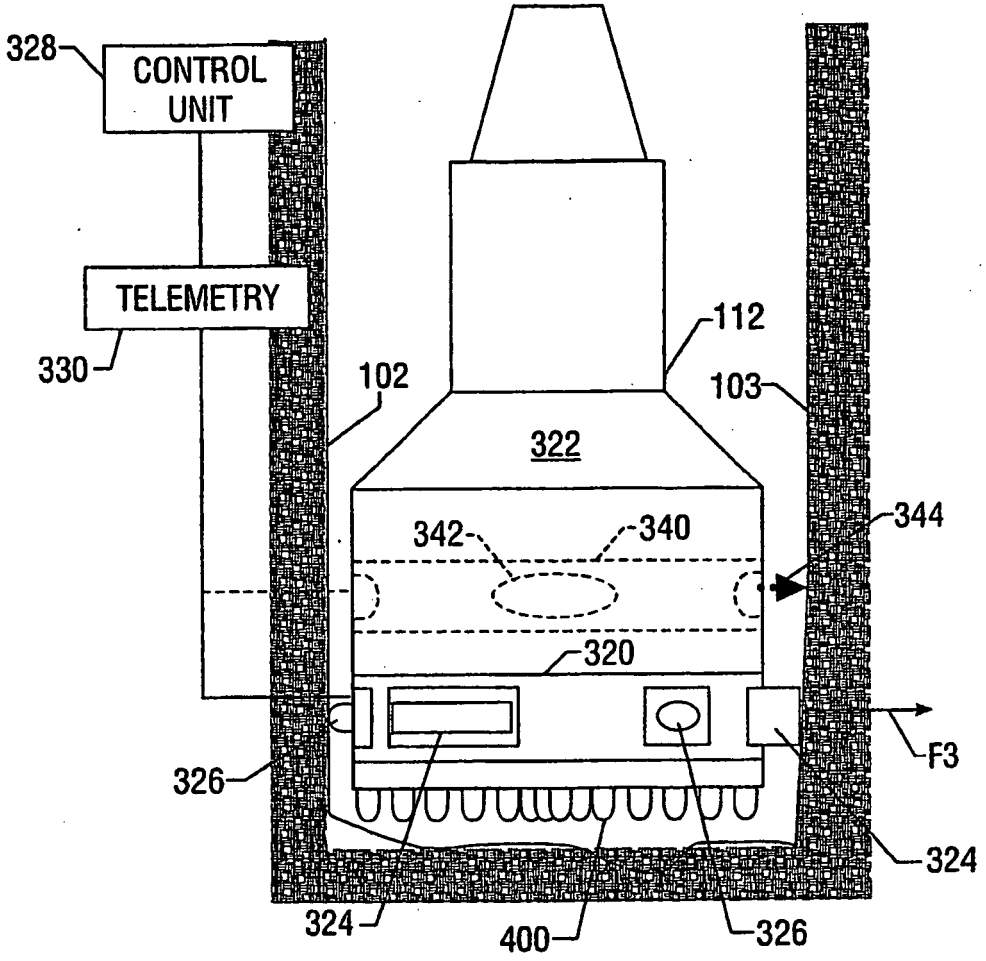

328
CONTROL UNIT
TELEMETRY
330
102
112
103
322
342
340
344
320
326
F3
324
324
400
326

FIG. 10

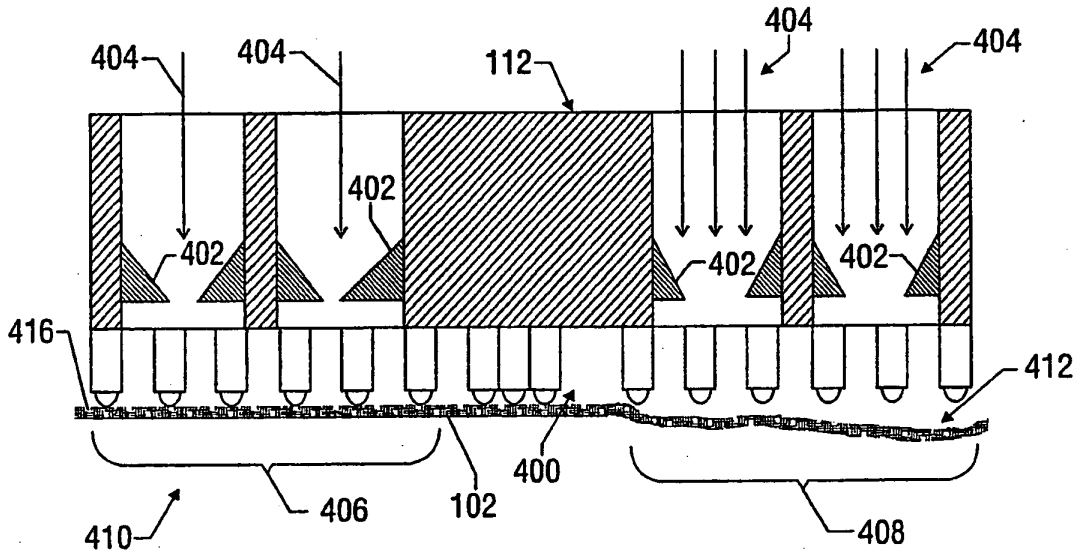


FIG. 11A

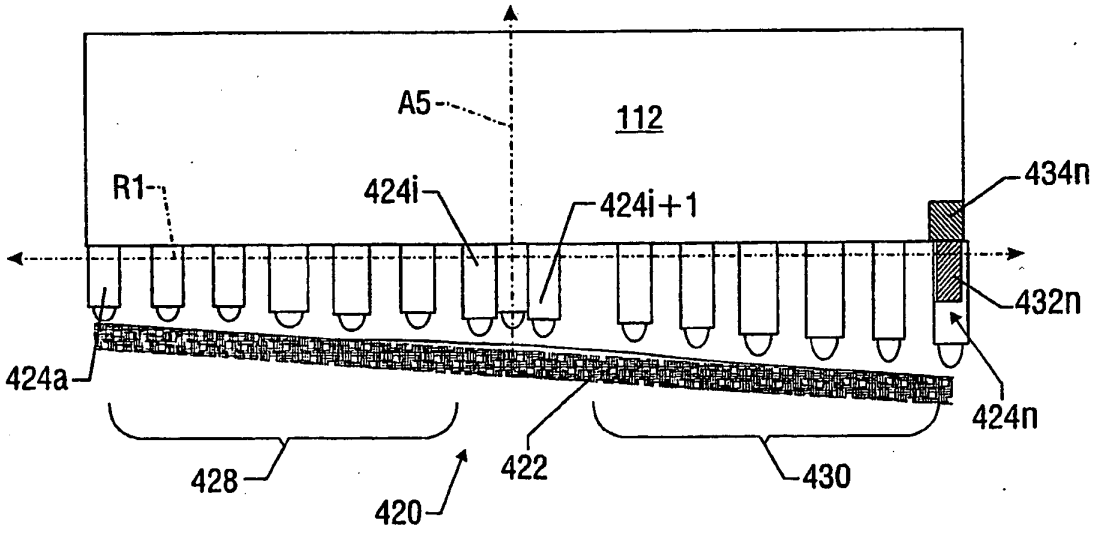


FIG. 11B

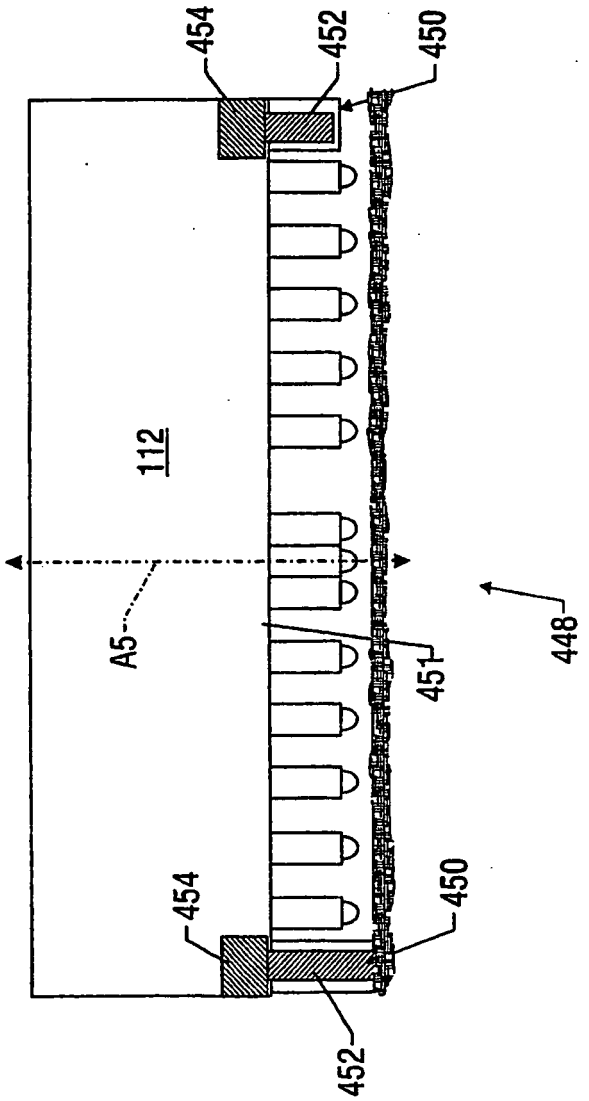


FIG. 11C

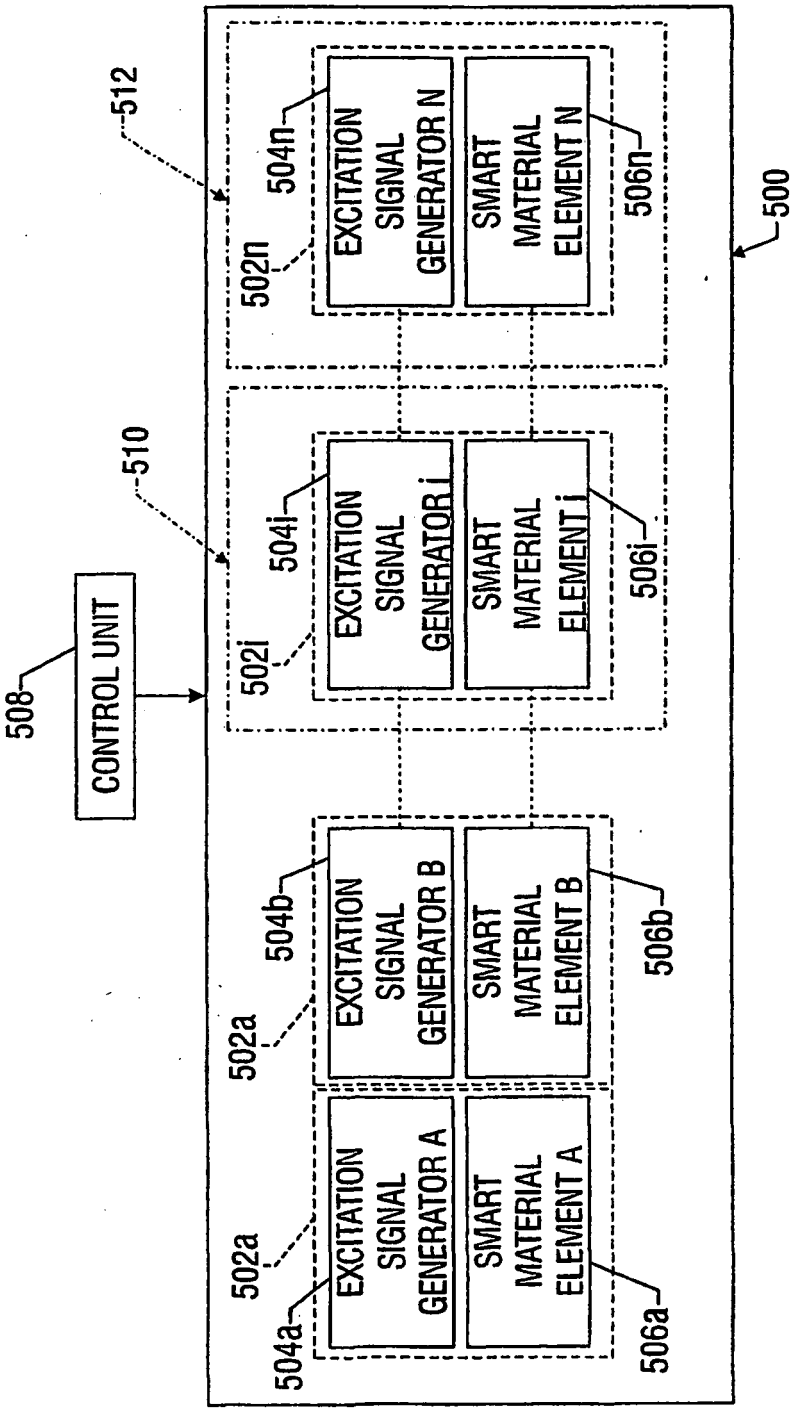

512
510
508
CONTROL UNIT
500
502n
504n
EXCITATION SIGNAL GENERATOR N
SMART MATERIAL ELEMENT N
506n
502i
504i
EXCITATION SIGNAL GENERATOR i
SMART MATERIAL ELEMENT i
506i
502a
504b
EXCITATION SIGNAL GENERATOR B
SMART MATERIAL ELEMENT B
506b
502a
504a
EXCITATION SIGNAL GENERATOR A
SMART MATERIAL ELEMENT A
506a

FIG. 12

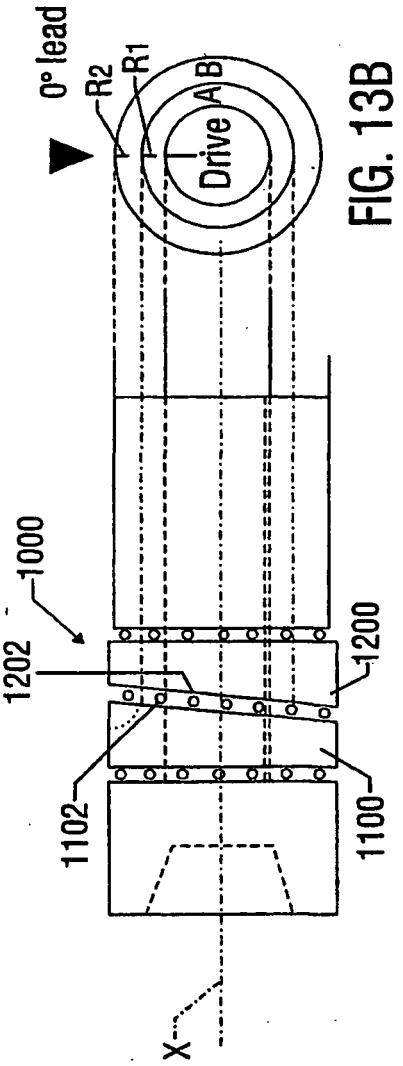


FIG. 13B

FIG. 13A

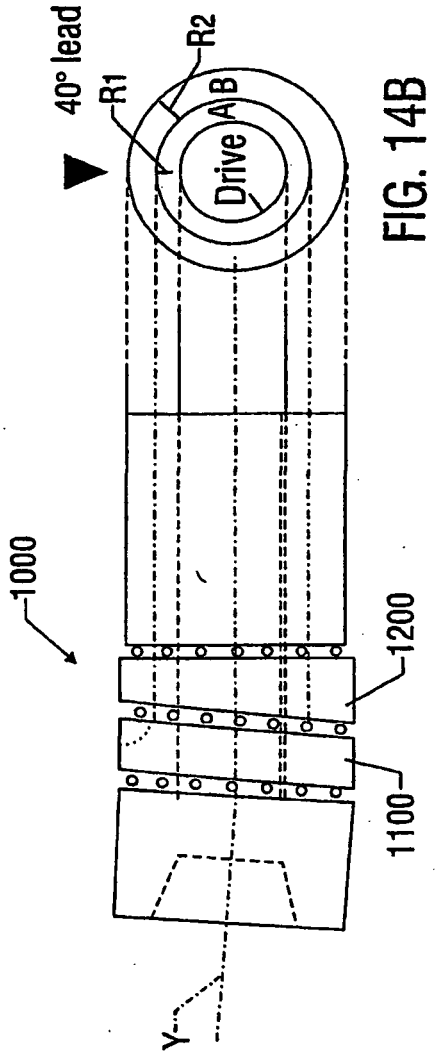


FIG. 14B

FIG. 14A

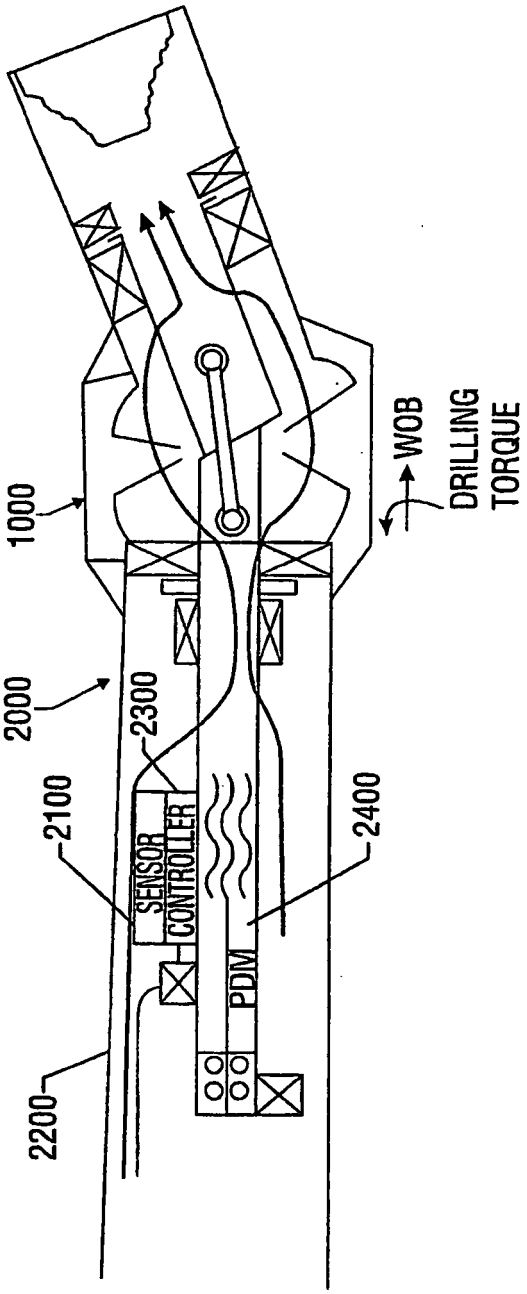

1000
2000
2300
2100
2400
2200
SENSOR
CONTROLLER
PDM
WOB
DRILLING
TORQUE

FIG. 15

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 4291773 A **[0007]**