

[21] Appl. No.: 139,526

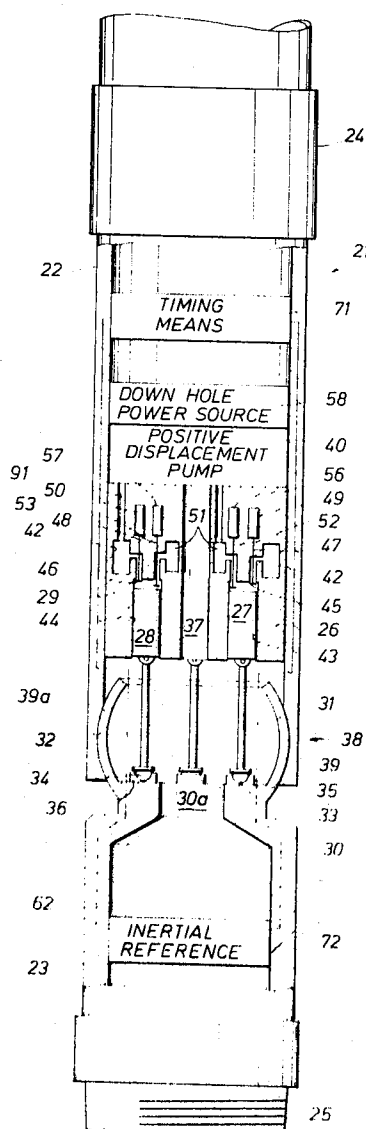
[58] **Field of Search**..... 175/61, 73, 256,
175/45, 74

2,345,766	4/1944	Miller	175/256
3,526,285	9/1970	Adkins	175/73
3,465,834	9/1969	Southworth	175/73
3,593,810	10/1969	Fields	175/61
3,627,356	11/1969	Anderson	175/61

Primary Examiner—James A. Leppink
Assistant Examiner—Richard E. Favreau
Attorney—Rand N. Shulman and Harold L. Denkler

Method and apparatus for maintaining the orientation of a laterally unsupported driven shaft constant with respect to a non-rotating coordinate system as the driven shaft is rotated by a non-coaxial rotating driving shaft. In a directional drilling method, the apparatus is disposed in a well drill string along with means for adjusting the orientation of the portion of the drill string below the apparatus to provide a steerable drill string. The apparatus for maintaining the orientation of the shafts comprises an axial-piston machine mounted on one of the shafts and operatively connected to a control flange affixed to the other of the shafts. A universal coupling connects the shaft in driving-driven relationship. The deflection of the shaft at the universal joint is maintained constant with respect to a non-rotating coordinate system by driving the pistons of the axial piston machine in timed relationship with the rotation of the shafts so that each piston completes one reciprocating cycle each time the shafts complete one rotation.

19 Claims, 5 Drawing Figures



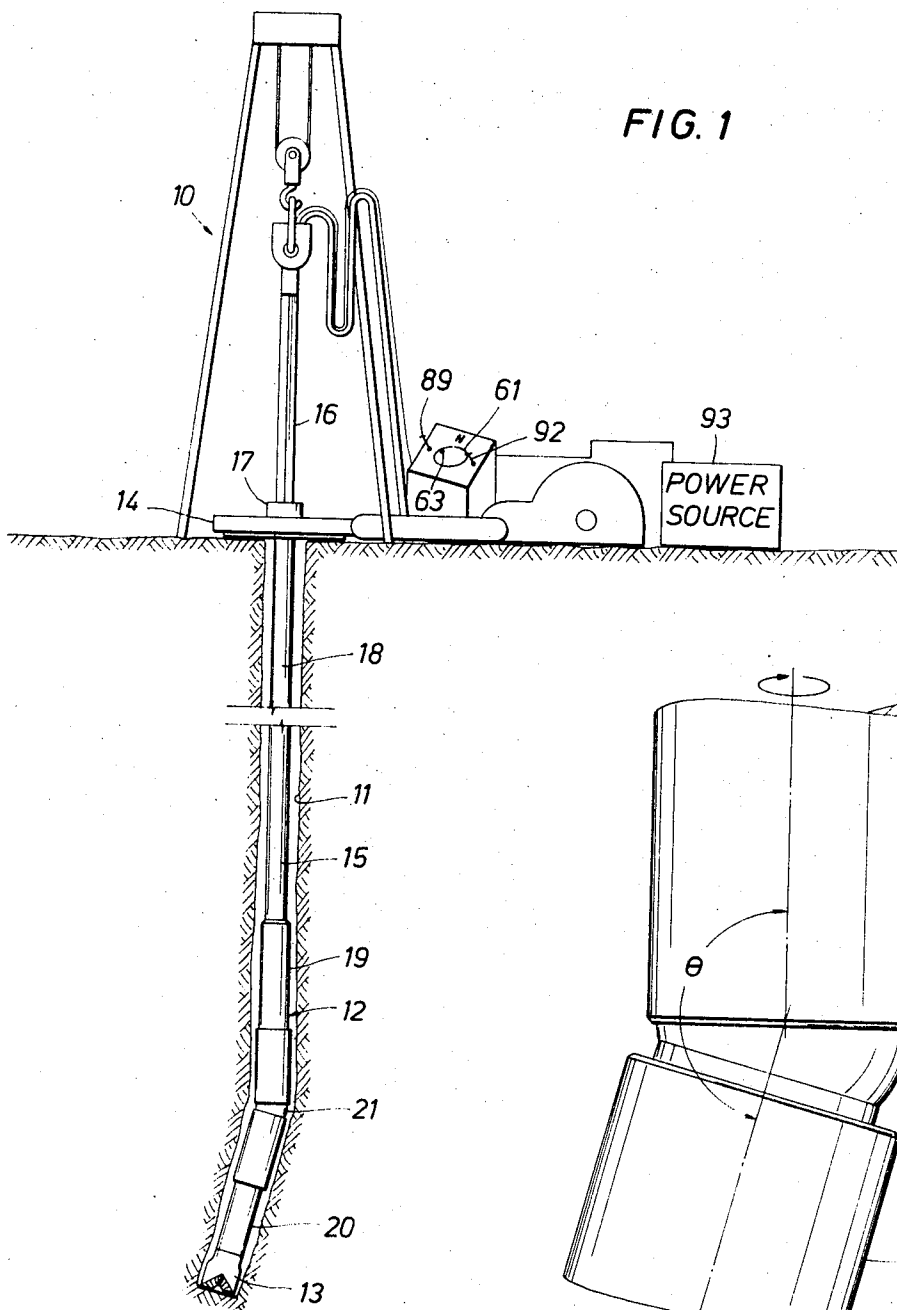
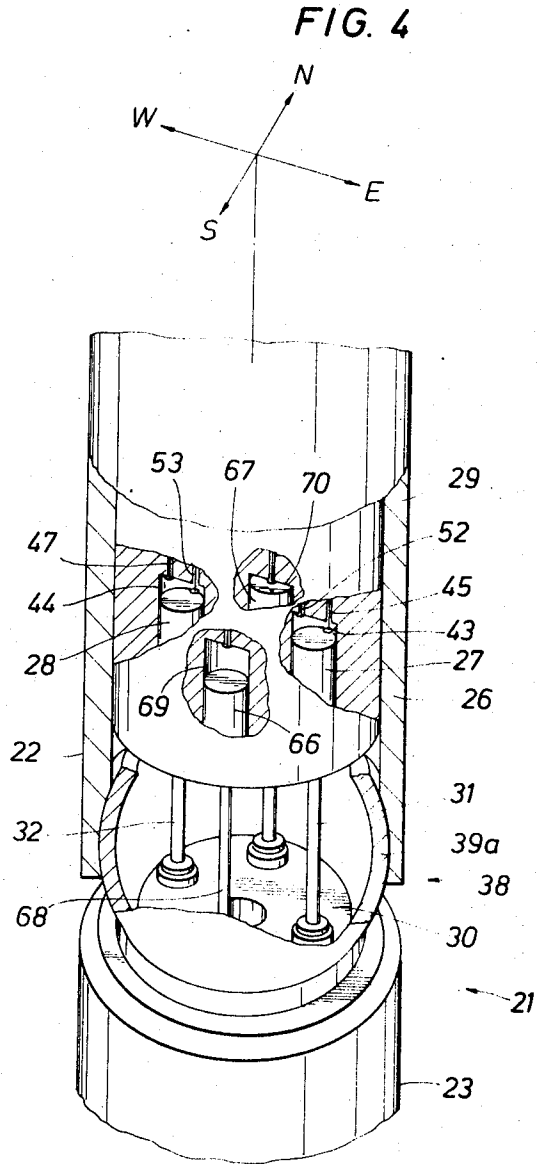
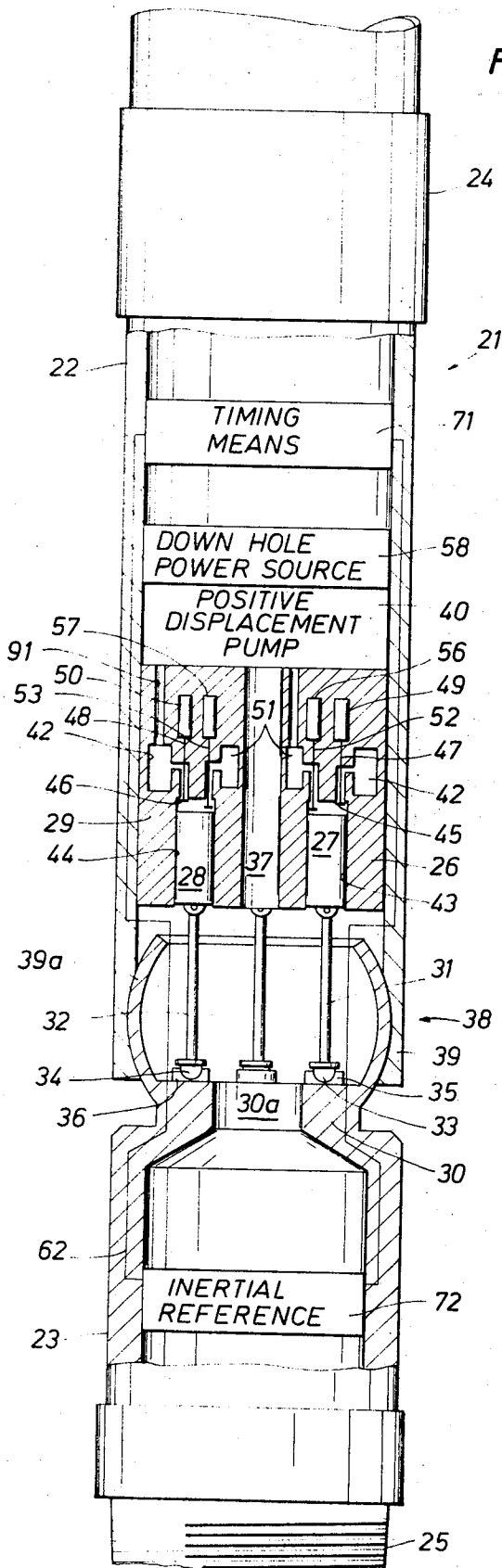


FIG. 3

W. B. BRADLEY
INVENTOR



W. B. BRADLEY
INVENTOR

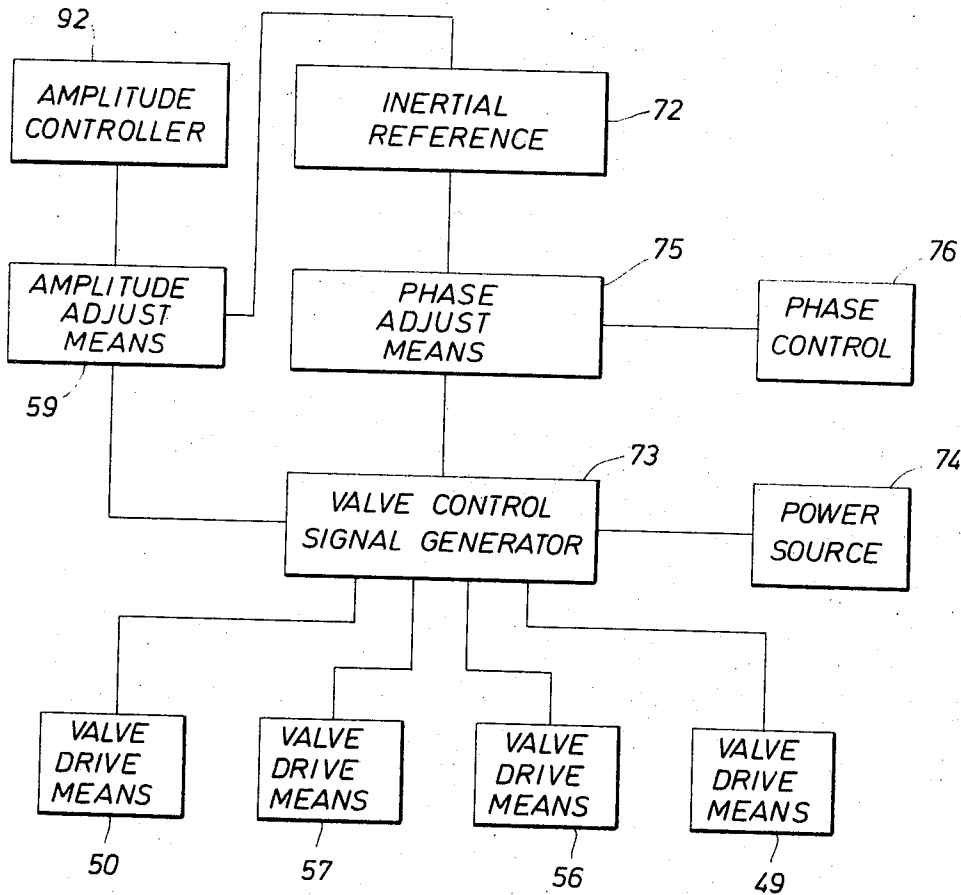


FIG. 5

W. B. BRADLEY
INVENTOR

STEERABLE DRILL STRING

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the field of drilling wells. More particularly, the invention relates to a method and apparatus for directionally drilling a well into the surface of the earth and to a method and apparatus for maintaining the orientation constant with respect to a non-rotating coordinate system of a laterally unsupported driven shaft connected in end to end relationship with a non-coaxial driving shaft as the driving shaft rotates to drive the driven shaft.

2. Description of the Prior Art

In the drilling of wells, such as oil and gas wells, it is often necessary to adjust the direction in which the well drilling equipment is progressing into the earth's surface. In some cases, it may be desired to redirect the drill string toward the vertical. In other cases, it may be desired to direct the string away from vertical in order to reach a point which is displaced horizontally as well as vertically from the surface drilling location. Such a practice is quite common, for example, when drilling operations are conducted from an off-shore platform or from a drilling island in a city.

A number of techniques are currently in use for directing wells. One of these is to whipstock the drilling stem. According to this technique, a wedge-like device or shoe is located in the hole so that upon drilling past the wedge the bit is deflected by the wedge to change the angle at which the hole progresses. Each time a change in direction is desired, the drill pipe must be withdrawn from the hole and a new setting of the shoe must be made.

A second technique is to use a bent sub or a variably bendable sub in conjunction with a down hole powered bit driven by an electrical or hydraulic motor carried at the end of the drill string near the bit. In such an apparatus, the drill string above the bent sub is held stationary while the down hole motor turns the bit on the other side of the bent sub. If a variably bendable sub is used, the direction of drilling can be changed without withdrawing the drill string from the hole by changing the angle of the bending sub.

However, prior art variably bendable subs have not been suited for use in conventional drilling where the drill pipe is rotated from the surface to turn the drill bit because they have not been capable of maintaining the orientation of the portion of the drill string below the sub constant as the portion of the drill string above the sub is rotated. Therefore, it has not heretofore been possible using whip stock or bent sub techniques to directionally control a conventionally powered drill string without interrupting drilling operations.

SUMMARY OF THE INVENTION

This invention is a broad aspect comprises a method and apparatus for maintaining the orientation constant with respect to a non-rotating coordinate system of a laterally unsupported driven shaft (such as the portion of a drill string adjacent the bit) connected in end to end relationship with a non-coaxial driving shaft (such as a segment of drill pipe) as the driving shaft rotates to drive the driven shaft. The method comprises interconnecting the shafts through a universal joint means; applying controlled amounts of force to a plurality of elements which are fixedly positioned with respect to

one of the shafts and moveably connected to the other of the shafts; and controlling the amount and direction of the applied force in coordination with the rotation of the shafts to displace the elements with respect to the shaft to which they are moveably connected in a direction and amount substantially equal to the direction and amount of displacement the elements would undergo if the shafts were rotated with the driven shaft supported in the desired orientation with respect to the driving shaft.

An apparatus for maintaining the orientation constant with respect to a non-rotating coordinate system of a laterally unsupported driven shaft connected in end to end relationship with a non-coaxial driving shaft as the driving shaft rotates to drive the driven shaft comprises a plurality of control elements each of which is anchored on a first of the shafts and moveably connected to the second of the shafts; and means for applying controlled amounts of force to the elements in coordination with the rotation of the shafts to displace the elements with respect to the shaft to which they are moveably connected in a direction and amount substantially equal to the direction and amount of displacement the elements would undergo if the shafts were rotated with the driven shaft supported in an orientation desired to be maintained constant.

In another aspect this invention provides a method and apparatus by which a drill string rotated from the earth surface may be directionally controlled without withdrawing the drill string from the borehole for directional drilling. The method comprises the steps of affixing a drilling bit to one end of a lower pipe segment, attaching to the opposite end of the lower pipe segment a means for maintaining a selected angle of axial intersection and direction of deflection of the lower pipe segment with respect to an upper pipe segment constant with respect to a non-rotating coordinate system as the upper pipe segment is rotated to drive the lower pipe segment; attaching an upper pipe segment to the means for maintaining a selected angle of axial intersection and direction of deflection constant; extending the drilling bit, lower pipe segment, means for maintaining a selected angle of axial intersection and direction of deflection constant, and upper pipe segment into a well; and rotating the upper pipe segment with a rotary drive means at the earth surface to rotate the bit and thereby advance the well into the earth. The means for maintaining a selected angle of axial intersection and direction of deflection constant can be adjusted to control the direction in which the well is advanced into the earth. Advantageously, the direction in which the drill bit is advancing into the earth is measured while drilling is progressing so that deviations of this direction from that desired may be corrected by appropriately adjusting the means for maintaining a selected angle of axial intersection and direction of deflection constant.

A directionally controllable drill string which can be used in the practice of this method of directional drilling comprises an upper pipe segment adapted to be coupled to a conventional rotary drive means for transmitting rotation from the drive means into the bore hole. This upper pipe segment may be a conventional string of drill pipe or, according to a preferred embodiment, may be telemetering drill string in which segments of an insulated electrical conductor are built into each joint of drill pipe to carry electrical signals

through the drill pipe to the surface. Such a telemetering drill string is described in U.S. Pat. NO. 3,518,699, issued June 30, 1970, to J. E. Fontenot. The upper pipe segment is coupled in rotary driving relation to a lower pipe segment by a directional control sub which includes a universal coupling means, such as a heavy duty universal joint. The lower pipe segment is coupled to the drilling bit for transmitting rotation to the bit. Associated with the universal coupling means is a means for maintaining the angle of axial intersection of the two pipe carried by one of the pipe segments constant with respect to a non-rotating coordinate system as the drill string is rotated by the rotary drive means to drive the drilling bit.

The angle maintaining means can comprise an axial-piston machine, segments and operatively connected to a control flange which is affixed to the other pipe segment. In conventional applications of such a machine, the displacement of the pistons of the axial piston machine is controlled by varying the displacement of the control flange. In the apparatus of this invention, the angle of the plane of the control flange is controlled by varying the displacement of the pistons.

The axial-piston machine may comprise a plurality of pistons slideably mounted within a housing for reciprocating movement in a direction co-axial with the upper pipe segment. Each piston is connected by a connecting rod to the control flange on the lower pipe segment. The connecting rods maintain the point on the control flange at which they are mounted a fixed distance from the piston as the piston moves reciprocally in the housing. A variable amplitude drive means is preferably associated with the piston for reciprocally driving them within the housing. This drive means may be, for example, a mud turbine or differential-slip mechanism powered hydraulic motor, an electrically powered linear actuator, or a mechanically powered push-pull rod system operatively associated with a cranking mechanism. The variable amplitude drive means is preferably coupled to an amplitude controller at the surface via the telemetering drill string. If a conventional string of drill pipe is used the variable amplitude drive means is coupled to a programmed downhole controller which can be carried on the control sub adjacent the drive means.

A timing means is associated with the drive means for synchronizing the motion of the pistons. Preferably, the pistons complete one full reciprocating cycle each time the drill bit completes one revolution. In this way, the connecting rods maintain the control flange in a fixed plane with respect to a non-rotating coordinate system as the drill string is rotated to drive the drilling bit. The angle of intersection of the plane of the control flange with the axis of the upper pipe segment is a function of the amplitude of the reciprocal motion of the piston in the housing. The direction toward which the control flange is inclined is a function of the phase relationship between the reciprocating motion of the piston and the rotating of the drill string. The timing means preferably comprises remotely controlled means for adjusting this phase relationship coupled to a controller at the surface via the telemetering drill string.

An angle measuring means such as an inertial platform may be mounted on the lower pipe segment to measure the orientation of this pipe segment with respect to the vertical and the direction in which the pipe segment is deflected. The angle measuring means is preferably associated with signaling means of a type ca-

pable of signaling the measured angle to the surface. A preferred signaling means is an electrical transducer means coupled to a display means at the surface via a telemetering drill string.

The angle measuring means provides a signal from which the driller may be able to determine the direction and inclination of the drill pipe segment directly above the drill bit. The driller may adjust this orientation while drilling operations are in progress by adjusting the variable amplitude drive means to change the angle between the upper drill pipe segment and the lower drill pipe segment and by adjusting the phase relationship of the pistons to change the direction of deflection. Thus, the apparatus of this invention provides a drill string which is steerable from the earth's surface.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic view, partially in cross section, showing the steerable drill string of this invention in the operative position in a well bore.

FIG. 2 is a side view, partially in vertical cross-section, of an embodiment of the directional control sub of this invention.

FIG. 3 is a side view of the directional control sub of FIG. 2 in a deflected condition.

FIG. 4 is a partially cut-away side view of the control sub of FIG. 3 looking in the direction of arrow 65 of FIG. 3.

FIG. 5 is a block diagram showing the elements of a timing means of a type which may be used in the directional control sub of FIG. 2.

DESCRIPTION OF A PREFERRED EMBODIMENT

Referring to FIG. 1, we see a rotary drilling rig 10 of a conventional type drilling a well bore hole 11 with an embodiment of the drill string 12 of this invention. A drill bit 13 is affixed to the lower end of the drill string 12. The drilling bit 13 is driven by drill string 12 which transmits rotary power to the bit 13 from a rotary drive means, such as rotary table 14 on the earth's surface.

The drill string 12 comprises an upper pipe segment 15, which preferably is a string of telemetering drill pipe and drill collars having an insulated electrical conductor provided with the pipe, such as the telemetry drill pipe described in the aforementioned patent to Fontenot. The upper pipe segment 15 is joined to a preferably telemetering kelly 16 which is in turn driven by a kelly bushing 17 which matingly engages the rotary table 14. The drill string 12 can also comprise a lower pipe segment 20 adjacent the drill bit which may comprise one or more joints of drill pipe and/or one or more drill collars. The lower pipe segment 20 or the bit 13 is coupled in driven relationship to the upper pipe segment 15 by directional control or bending sub 21.

The directional control sub 21 comprises a universal coupling capable of transmitting rotation from the upper pipe segment 15 to the lower pipe segment 20 when the pipe segments 15 and 20 are not co-linear. It additionally comprises means for adjusting the angle of axial intersection of the upper pipe segment 15 and the lower pipe segment 20, and means for maintaining a selected angle of intersection and direction of deflection constant with respect to a non-rotating coordinate system.

FIG. 2 illustrates one preferred embodiment of the directional control sub 21. The sub 21 of this embodiment comprises top portion 22 and bottom portion 23

provided with coupling means such as threaded connections 24 and 25 for coupling the sub 21 to the upper pipe segment 15 and the lower pipe segment 20. The top portion 22 of the sub 21 comprises an axial-piston at least four piston (see FIG. 4), such as piston 27 and 28 (FIG. 2), slideably mounted in a housing 29 for reciprocal motion in a direction parallel to the central axis of the top portion 22 of the sub 21. The pistons 27 and 28 are connected by connecting rods 31 and 32, respectively, to a control flange 30 which is affixed, as by welding, to the lower portion 23 of the sub 21. The control flange 30 may have a central opening or hole 30a through which drilling mud may pass. The connecting rods 31 and 32 may be pivotably attached to pistons 27 and 28 and are preferably pivotably attached to the control flange 30 for pivotable movement in any direction. For example, the connecting rod 31 and 32 may carry ball members 33 and 34 at the ends of the rods opposite the piston 27 and 28. The ball members 33 and 34 may be pivotably mounted in socket members 35 and 36 which are fixedly attached to the control flange 30. The axial-piston machine 26 preferably is provided with a central throughbore 37 through which drilling mud may pass.

The lower portion 23 of the sub 21 is connected to the upper portion 22 by means of a pivotable connection such as ball joint 38 which comprises a socket portion 39 carried by the upper portion 22 of the sub 21 and a hollow semi-spherical ball portion 39a affixed to the lower portion 23 and pivotably held by the socket 39. The diameter of the outer surface of ball 39a is preferably sufficiently smaller than the diameter of the inner surface of the socket 39 to allow some drilling mud to leak out of the sub 21 through the joint 38, thereby lubricating the joint 38.

The bottom portion 23 of the sub 21 preferably carries an angle measuring means such as inertial reference means 72 capable of sensing the orientation of the bottom portion 23 of the sub 21 with respect to vertical and north. It may be advantageous to dispose this inertial reference 72 in the lower pipe segment 20 near the bit 13 if the sub 21 is positioned a significant distance above the bit 13. The reference 72 may be coupled to a display means 61 (FIG. 1) at the surface by means of a circuit which comprises an insulated electrical conductor 62 in the sub 21 coupled to the electrical conductor of the telemetering upper pipe segment 15. The display means 61 is preferably of a type adapted to display the orientation of the bottom portion 23 of the sub 21 with respect to both vertical and horizontal axes. For example, the display means 62 may project a beam 63 on a round screen 64 which beams 63 moves radially away from the center of the screen 64 in the direction of deflection as the bottom portion 23 of the sub 21 is deflected from the vertical.

The pistons 27 and 28 are driven by a drive means such as a positive displacement pump 40, shown in block form on FIG. 2. The pump 40 discharges fluid at high pressure through a conduit 91 into an annular high pressure chamber 42. The high pressure chamber 42 opens into the cylinders 43 and 44 which house the pistons 27 and 28. Fluid flow from the high pressure chamber 42 into the cylinders 43 and 44 is controlled by inflow valves 45 and 46. The inflow valves 45 and 46, for example, can be poppet or reed valves or piston type valves affixed to valve stems 47 and 48 which are slideably mounted in the housing 29. The valves 45 and

46 are operatively connected to valve drive means for opening and closing the valves. For example, the valve drive means may include hydraulic means, electrical means, or mechanical means such as cams 49 and 50 which are adapted to open and close the inflow valves 45 and 46 under the control of an appropriate electrical signal.

The intake of the pump 40 draws fluid through a conduit (not shown) from an annular low pressure chamber 51 which is in fluid communication with, and acts as the fluid discharge from, the cylinders 43 and 44 of the axial-piston machine 26. Fluid flow from the cylinders 43 and 44 into the low pressure chamber 51 is controlled by exhaust valves 52 and 53 which can be, for example, poppet or reed valves or piston type valves affixed to valve stems 54 and 55. The valve stems 54 and 55 are slideably mounted in the housing 29 and are operatively connected to valve drive means for opening and closing the exhaust valves 52 and 53. The valve drive means may, for example, include hydraulic means, electrical means, or mechanical means such as cams 56 and 57 which are adapted to open and close the inflow valves 45 and 46.

The positive displacement pump 40 is preferably driven by a downhole power source 58 of a conventional type. For example, the power source 58 can be a fluid turbine of the type which may be driven by drilling mud pumped down the drill string 12 and through the sub 21 from the earth surface, or the power source 58 can be a down hole electric motor of the type used in "electro-drilling". The particular power source used is not critical to the present invention.

The control sub 21 is advantageously provided with means for maintaining the pressure in the high pressure chamber 42 substantially constant regardless of the rate at which the pump 40 is pumping fluid. For example, the high pressure chamber 42 can be coupled to the low pressure chamber 51 by a conduit (not shown) in which an adjustable constant-pressure inlet valve is disposed. The adjustable inlet valve is preferably of a type which opens to fluid flow when the inlet pressure, i.e., the pressure in high pressure chamber 42, exceeds a preselected value.

The valve drive means, cams 49, 50, 56 and 57 in FIG. 2, preferably are operatively associated with a timing means 71 mounted in the sub 21 for synchronizing the motion of the pistons 27 and 28 both with one another and with the rotation of the sub 21. Preferably, the pistons complete one full reciprocating cycle each time the bottom portion 23 of the sub 21 completes one revolution. In this way the pistons maintain the control flange 30 in a fixed plane as the drill string 12 is rotated to drive the bit 13, the plane being fixed with respect to a non-rotating coordinate system such as the system defined by the central axis of the upper portion 22 and a pair of orthogonal lines intersecting this axis at right angles. If the top portion 21 is vertical, the pair of orthogonal lines may be north — south and east — west axes.

The manner in which the angle is maintained may be understood by referring to FIGS. 3 and 4 which show the sub 21 operating with the bottom portion 23 disposed at an angle Θ with respect to the top portion 22. FIG. 4 is a cut-away view looking in the direction of arrow 65 of FIG. 3 (i.e., north). We can see in FIG. 4 that the sub comprises four pistons 27, 28, 66 and 67 disposed in housing 29 which is mounted in the top por-

tion 22 of the sub 21. The pistons are connected by connecting rods, such as rods 31, 32 and 68, to the control flange 30.

In the embodiment of the sub 21 illustrated, as the top portion is rotated, torque is transmitted to the control flange 30 via the pistons and connecting rods. Therefore, the bottom portion 23 rotates with the top portion 22. Thus the axial-piston machine 26, control flange 30, and ball joint 38 in combination act as a universal coupling means for transmitting rotation from the top portion 22 to the non co-axial bottom portion 23 of the sub 21.

Additionally, the orientation of control flange 30 with respect to a reference non-rotating three dimensional coordinate system will be maintained constant if each of the pistons 27, 66, 28 and 67 is always in the same position relative to the cylinder 43, 69, 44, 70, respectively, in which it moves when that cylinder occupies a given position within the reference coordinate system. For example, if the reference coordinate system comprises vertical, north-south, and east-west axes and if in FIG. 4 cylinders 69 and 70 intersect the north-south axis and cylinders 43 and 44 intersect the east-west axis with cylinder 70 to the north, then the orientation of control flange 30 will remain constant with respect to the reference coordinate system as the sub 21 rotates if the piston in each cylinder attains the top of its reciprocating cycle (as has piston 67) as the center of that cylinder crosses the north axis and if the piston attains the other relative positions illustrated as the center of the cylinder crosses the east, south, and west axes, respectively. This means the pistons must complete one full reciprocating cycle each time the sub 21 turns once.

Therefore, to maintain the northward deflection of the bottom portion 23 of the sub 21 (as shown in FIGS. 3 and 4) as a cylinder, such as cylinder 43 in FIG. 4, rotates from north to south, the fluid inflow valve 45 of that cylinder should be open (and the exhaust valve 52 closed) to admit high pressure fluid from high pressure chamber 42 to drive cylinder 27 downward. Similarly as a cylinder, such as cylinder 44 of FIG. 4, rotates from south to north the exhaust valve 53 of that cylinder should be open (and the inflow valve 47 closed) to allow fluid to flow out of the cylinder 44 in a control manner into the low pressure chamber 51 so that the piston 28 may move upwardly relative to the cylinder 44.

FIG. 5 shows in block form the elements of a timing means of a type which may be used to synchronize the motion of the pistons 27, 28, 66 and 67. The timing means 71 comprises a position signal generating means which is capable of generating a signal proportional to the angular position of a point of interest on the rotating sub 21 with respect to a reference such as the center of a gimbled gyroscopic platform. For example, the inertial reference 72 in addition to functioning as an angle measuring means may generate a signal which varies as the angular displacement of a reference point, for example a cylinder such as cylinder 44 of the axial piston machine 26, varies with respect to the center of the timing means 71.

The inertial reference 72 is coupled to a valve control signal generator 73 which is in turn coupled to the various valve drive means such as cams 49, 50, 56 and 57. The valve control signal generator 73 is preferably a pre-programmed device for generating appropriate

signals to the respective valve drive means in response to the angular position of reference cylinder 44 as indicated by the inertial reference output. For example, in response to a signal which indicates that cylinder 44 is rotating past a north-directed axis, the valve control signal generator 73 may generate an appropriate signal to couple the cams 49, 50, 56, and 57 (FIG. 2) with a power source 74 in such a way that the cams move causing inflow valve 45 and exhaust valve 53 to open and exhaust valve 52 and inflow valve 46 to close so that piston 27 is forced downwardly and piston 28 moves upwards in a controlled manner in the housing 29. The power source 74, for example, may be a source of electrical power 93 at the earth surface coupled to the valve control signal generator 73 by means which include telemetering upper pipe segment 15 or may be a generator driven by down hole power source 58. Similarly in response to a signal which indicates cylinder 44 is rotating past a south-directed axis the valve control signal generator 73 may generate an appropriate signal to couple the cams 49, 50, 56 and 57 with the power source 74 in such a way that the cams move causing inflow valve 45 and exhaust valve 53 to close and exhaust valve 52 and inflow valve 46 to open so that piston 28 is forced downwardly and piston 27 moves upwardly in the housing 29. Thus the timing means 71 controls the valves in such a way that the pistons 27 and 28 complete one reciprocating cycle each time the sub 21 completes one revolution. It should be understood that pistons 66 and 67 are controlled in a similar manner by valve control means 73 in cooperation with appropriate valve drive means for these cylinders.

As can be seen in FIG. 4, and as described above, the deflection of the bottom portions 23 of the sub 21 with respect to the top portion 22 will be to the north if each of the pistons 27, 28, 66 and 67 reaches the peak of its reciprocating cycle as it rotates past north. To change the direction of the deflection of the bottom portion 23 with respect to the top portion it is necessary to change the phase of the reciprocal movement of the pistons with respect to the rotation of the sub 21 so that each piston reaches the peak of its reciprocating cycle as it rotates past the desired direction of deflection. Such a phase change may be achieved by associating with the valve control signal generator 73 a phase adjust means 75 capable of adjusting the phase of signals generated by the valve control signal generator with respect to the angular rotation of the sub 21. The phase adjust means 75 may be, for example a delay circuit capable of delaying the signal from inertial reference 72 for a time corresponding to the angular rotational phase delay desired. Another example of a suitable phase adjust means is an adjustable detector means or sensor capable of detecting a signal from the inertial reference 72 indicating a desired direction of deflection and generating an appropriate signal to the respective valve drive means (via the valve control signal generator 73) to orient the sub 21 in the desired direction.

The phase adjust means 75 is advantageously coupled by appropriate circuit means to phase controller 76 at the earth surface. The circuit means may comprise the insulated conductor of telemetering upper pipe segment 15.

The angle of deflection of the directional control sub 21 may be adjusted by regulating the amplitude of the reciprocating motion of the pistons. This can be achieved by adjusting the amount of the fluid allowed

to flow into and out of the cylinders 43, 44, 69 and 70. Such an adjustment may be made by adjusting the length of time of opening and closing of the valves 45, 46, 52 and 53 to allow greater or lesser amounts of fluid to enter or leave the cylinders. An amplitude adjust means 59 can be associated with the valve control signal generator for adjusting this length of time. The amplitude adjust means 79 advantageously is coupled via electrical conductor 62 and telemetering upper pipe segment 15 with a deflection amplitude controller 92 at the earth surface. The amplitude controller is preferably associated with a display means coupled to the inertial reference 72 on the sub 21.

The power source 93, phase control 76 and deflection amplitude control 92 may, if desired, all be coupled to the sub 21 by means of a signal electrical circuit in the telemetering upper pipe segment 15 via a multiplex transmitting means of a well known type.

To practice the method of this invention with the above-described apparatus, the drill string 12 and bit 13 are lowered into the well bore hole 11. The rotary table 14 is turned to rotate the drill string 12 and bit 13 and thereby advance the bore hole 11 into the earth. While drilling is progressing signals from the deviation sensor in the bottom portion of the directional control sub 21 are telemetered up the upper pipe segment 15 and displayed on display means 61. When the displayed angle or direction of deflection of the bending sub 21 indicates that the bore hole 11 is deviating from the desired path or when a change in path is desired, the deflection amplitude control 92 or phase control 76 can be appropriately adjusted to change the angle or direction of deflection of the bending sub 21 to direct the drill string 12 in the desired direction.

I claim as my invention

1. A method for maintaining the orientation constant with respect to a non-rotating coordinate system of a laterally unsupported driven shaft, connected in end to end relationship with a non-coaxial driving shaft as the driving shaft rotates to drive the driven shaft comprising the steps of

interconnecting the shafts through a universal joint means;

applying controlled amounts of force to at least one element which is anchored to one of the shafts and moveably coupled to the other of the shafts;

and controlling the amount and direction of the applied force in coordination with the rotation of the shafts to displace the element with respect to the shaft to which it is moveably connected in a direction and amount substantially equal to the direction and amount of displacement the element would undergo if the shafts were rotated with the driven shaft supported in the orientation desired to be maintained constant.

2. A method for directionally drilling a well into a subsurface earth formation comprising the steps of affixing a drilling bit to one end of a lower pipe segment;

attaching to the opposite end of the lower pipe segment a means for maintaining a selected angle of axial intersection and direction of deflection of the lower pipe segment constant with respect to a reference non-rotating coordinate system as the lower pipe segment is rotated;

attaching an upper pipe segment to the means for maintaining a selected angle of axial intersection and direction of deflection constant;

extending the drilling bit, lower pipe segment, means for maintaining a selected angle of axial intersection and direction of deflection constant, and upper pipe segment into a well;

rotating the upper pipe segment with a rotary drive means at the earth surface to rotate the bit and thereby advance the well into the earth;

while rotating the upper pipe segment, applying controlled amounts of force to at least one element of the means for maintaining a selected angle of intersection and direction of deflection constant, the element being anchored to one of the pipe segments and slidably coupled to the other of the pipe segments; and

controlling the amount and direction of the force applied to the element in coordination with the rotation of the upper pipe segment to displace the element with respect to the pipe segment to which it is moveably connected in a direction and amount substantially equal to the direction and amount of displacement the element would undergo if the pipe segment were rotated with the lower pipe segment supported at the angle of inclination and direction of deflection at which it is desired to advance the drilling bit into the earth formation.

3. The method of claim 2 including the step of adjusting the for maintaining a selected angle of inclination and direction of deflection by sending a signal via a telemetering drill string from the earth surface to a control means carried by the means for maintaining a selected angle of axial intersection and direction of deflection constant.

4. The method of claim 2 including the step of measuring the orientation of the lower pipe segment while the lower pipe segment is in the operative position to determine the direction in which the well is advancing into the earth.

5. The method of claim 4 including the step of signaling the measured orientation of the lower pipe segment to the earth surface via a telemetering drill string.

6. Apparatus for maintaining the orientation constant with respect to a non-rotating coordinate system of a laterally unsupported driven shaft connected in end to end relationship with a non-coaxial driving shaft as the driving shaft rotates to drive the driven shaft comprising:

universal coupling means coupling the driving shaft to the driven shaft;

a plurality of control elements each of which is anchored on a first of the shafts and moveably connected to the second of the shafts; and

means for applying controlled amounts of force to the control elements in coordination with the rotation of the shafts to displace the control elements with respect to the shaft to which they are moveably connected in a direction and amount substantially equal to the direction and amount of displacement the control elements would undergo if the shafts were rotated with the driven shaft supported in an orientation desired to be maintained constant.

7. The apparatus of claim 6 including:
a housing mounted on a first of the shafts; and
a control flange affixed to the second shaft;

and wherein the plurality of control elements comprise

a plurality of pistons slideably mounted within the housing for reciprocating movement in a direction coaxial with the first shaft; and

a plurality of connecting rods, each connecting rod connected to one of the pistons at one end of the rod and pivotably mounted on the control flange at the other end of the rod for maintaining the point of mounting of the rod on the control flange a fixed distance from the piston as the piston moves reciprocally within the housing.

8. The apparatus of claim 7 wherein the means for applying controlled amounts of force to the control elements in coordination with the rotation of the shafts comprises:

variable amplitude drive means for reciprocally driving the pistons within the housing; and

timing means associated with the drive means for timing the motion of each piston to complete one full reciprocating cycle each time the driven shaft completes one revolution whereby the connecting rods maintain the orientation of the control flange substantially constant with respect to a non-rotating coordinate system as the driving shaft is rotated to drive the driven shaft.

9. The apparatus of claim 8 wherein the variable amplitude drive means comprises a pump.

10. The apparatus of claim 8 wherein the timing means comprises an inertial reference means.

11. A directionally controllable well drill string for connecting rotary drive means on the earth surface in driving relationship to a drill bit in a well borehole comprising:

an upper pipe segment adapted to be coupled to the rotary drive means for transmitting rotation from the rotary drive means;

a lower pipe segment adapted to be coupled to the drilling bit for transmitting rotation to the bit;

universal coupling means coupling the upper pipe segment in rotary driving relationship to the lower pipe segment; and

means for maintaining a selected angle of axial intersection and direction of deflection of the lower pipe segment with respect to the upper pipe segment constant with respect to a non-rotating coordinate system as the drill string is rotated by the rotary drive means to drive the drilling bit, the means for maintaining a selected angle of axial intersection and direction of deflection constant comprising an axial piston machine carried by one of the pipe segments and a control flange affixed to the other of the pipe segments, the axial piston machine being operatively connected to the control flange to maintain the control flange in a substantially fixed plane with respect to a non-rotating coordinate system.

12. The apparatus of claim 11 including: means for adjusting the selected angle of axial intersection of the upper pipe segment with the lower pipe segment from the earth surface while the drill string is operatively positioned in the well bore hole.

13. The apparatus of claim 12 including: means mounted on the lower pipe segment for mea-

suring the angle of the axis of the lower pipe segment with respect to the vertical;

means operatively connected to the angle measuring means for signaling to the surface the angle measured by the angle measuring means; and

means at the earth surface operatively connected to the signaling means for displaying the angle measured by the angle measuring means.

14. The apparatus of claim 13 wherein the signaling means comprises circuit means disposed in the upper pipe segment.

15. The apparatus of claim 11 wherein the axial-piston machine comprises:

a housing;

a plurality of pistons slideably mounted within the housing for reciprocating movement in a direction co-axial with the pipe segment upon which the housing is carried;

variable amplitude drive means for reciprocally driving the pistons within the housing;

a plurality of connecting rods, one connecting rod connected to each of the pistons at one end of the rod and pivotably mounted on the control flange at the other end of the rod for maintaining the point of mounting of the rod on the control flange a fixed distance from the piston as the piston moves reciprocally in the housing; and

timing means associated with the drive means for timing the motion of each piston to complete one full reciprocating cycle each time the drilling bit completes one revolution whereby the connecting rods maintain the control flange in a substantially fixed plane with respect to a non-rotating coordinate system as the drill string is rotated to drive the drilling bit, the angle of intersection of the fixed plane with the axis of the pipe segment upon which the axial-piston machine is carried being a function of the amplitude of the reciprocal motion of the pistons in the housing.

16. The apparatus of claim 15 wherein the variable amplitude drive means comprises a pump.

17. The apparatus of claim 15 wherein the timing means comprises an inertial reference means.

18. The apparatus of claim 15 including means for controlling the amplitude of the variable amplitude drive means from the earth surface and thereby controlling the angle of intersection of said fixed plane with the axis of the pipe segment upon which the axial-piston machine is carried.

19. The apparatus of claim 15 wherein the timing means includes means for adjusting the phase of the reciprocating motion of the pistons with respect to the rotation of the drilling bit thereby rotating the plane of the control flange within the non-rotating coordinate system to change the direction of deflection of the lower pipe segment with respect to the upper pipe segment; and wherein

the means for adjusting the phase of the reciprocating motion of the piston is coupled to a phase control means at the earth surface for activating the means for adjusting the phase of the reciprocating motion of the pistons to change the deflection of the lower pipe segment with respect to the upper pipe segment.

* * * * *