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㉙ **Earth drilling system and method for controlling the direction of a borehole.**

㉚ A steerable rotary drilling system for drilling or coring holes in subsurface formations comprises a bottom hole assembly 11 including a drill bit 13 carrying a plurality of cutting structures 16, and a mud hammer 14 which applies repeated axial impulses to the bit at a frequency greater than its frequency of rotation. Operation of the mud hammer 14 may be modulated in synchronism with rotation of the drill bit 13 and in controllable phase relation thereto. The drill bit is asymmetrically arranged, for example by an asymmetric distribution of the cutters 16, so that by appropriate selection of the phase relation the bit may be steered in a desired direction.

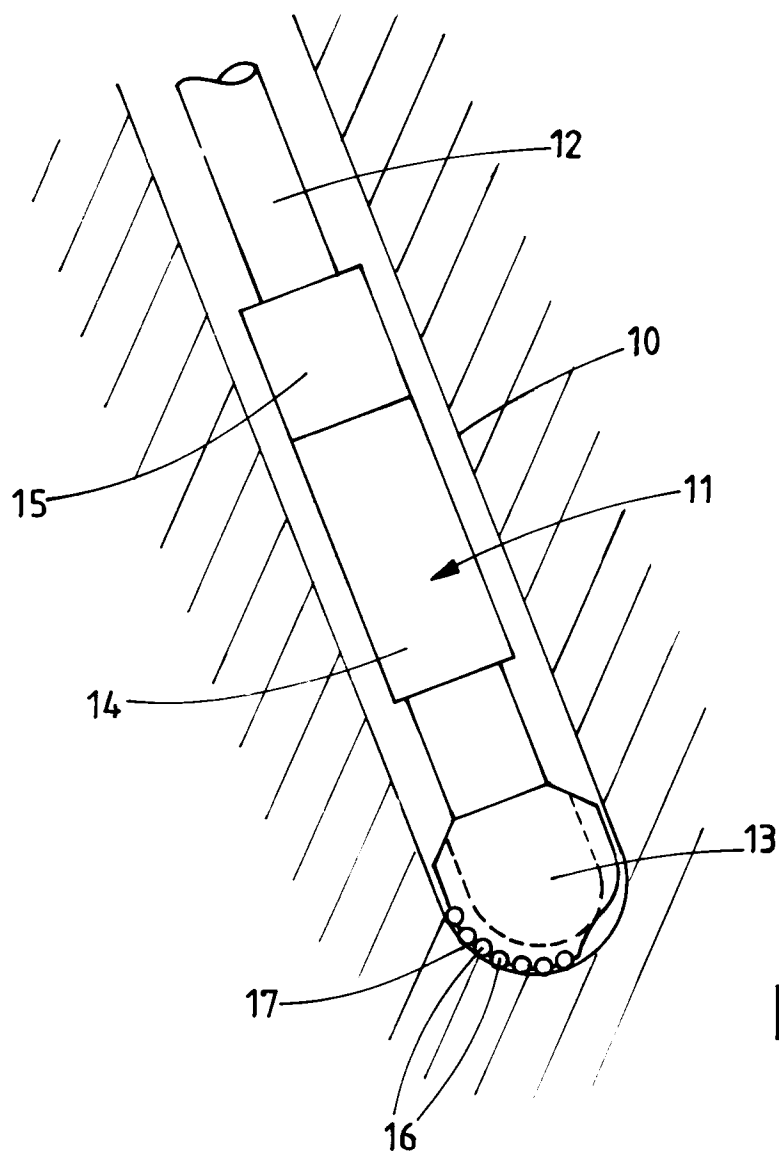


FIG. I.

When drilling or coring holes in subsurface formations it is sometimes desirable to be able to vary and control the direction of drilling, for example to direct the borehole towards a desired target, or to control the direction horizontally within the payzone once the target has been reached. It may also be desirable to correct for inadvertent deviations from the desired direction when drilling a straight hole, or to control the direction to avoid obstacles.

Hitherto, fully controllable directional drilling has usually required the drill bit to be rotated by a steerable downhole motor, either a turbine or PDM (positive displacement motor). In such an arrangement the downhole assembly includes an asymmetrical unit which rotates with the drill string and not with the drill bit. For example, the asymmetrical unit may comprise a motor having a "bent" housing, a "bent" sub-assembly above the motor, or an offset stabiliser on the outside of the motor casing. During normal drilling the effect of this asymmetry is nullified by continual rotation of the drill string, and hence the motor casing, as the bit is rotated by the motor. When variation of the direction of drilling is required, the rotation of the drill string is stopped with the bit tilted towards the required direction. Continued rotation of the drill bit by the motor then causes the bit to drill in that direction.

The rotational orientation of the motor casing is sensed by survey instruments carried adjacent the motor and the required rotational orientation of the motor casing (known as the tool face angle) for drilling in the appropriate direction is set by rotational positioning of the drill string, from the drilling platform, in response to the information received in signals from the downhole survey instruments.

Since this method of directional drilling requires the use of a downhole motor to drive the bit it is not applicable to so-called "rotary" drilling where the drill bit is fixedly connected to the drill string and the drill string is rotatably driven only from the drilling platform.

There are circumstances where rotary drilling is preferred. For example, the cost of rotary drilling tends, generally, to be less than the cost of using a downhole motor, and the life of the equipment used in the downhole assembly tends to be longer. Torque limits may also be higher. Furthermore, difficulties may arise, when using a steerable downhole motor, in controlling the tool face angle from the surface, due to wind-up in the drill string.

When carrying out rotary drilling, the established methods of directional control have involved variations in bit weight, rpm and stabilisation. However the directional control which can be exercised by these methods is limited and is insufficient for anything other than control during the drilling of tangent sections. Various other methods have therefore been proposed for effecting directional control of rotary drilling.

British Patent Specifications Nos. 2172324 A, 2172325 A and 2177738 A (Cambridge Radiation

Technology Limited) disclose arrangements in which lateral forces are applied to a drilling tube above the drill bit so as to impart a curvature to the drilling tube and thereby control the drilling direction. Such arrangements are complex and require large downhole assemblies.

International Specification No. W090/05235, (J. B. Noble) describes a directional drilling apparatus in which the drill bit is coupled to the lower end of a drill string through a universal joint which allows the bit to pivot relative to the string axis. The bit is contra-nutated in an orbit of fixed radius and at a rate equal to the drill string rotation but in the opposite direction. This speed-controlled and phase-controlled bit nutation keeps the bit heading off-axis in a fixed direction. Such arrangement requires the provision of a controlled servo of high power.

U.S. Specification No. 4995465 (J. L. Beck and L. D. Taylor) describes a rotary drilling system in which a bent-sub is connected behind the drill bit so that the bit extends angularly with respect to the drill rod. An actuator, such as an hydraulic ram, is provided at the surface for exerting thrust on the end of the drill rod which is transmitted along the rod to the drill bit. The thrust applied along the drill rod is pulsed to effect the desired trajectory of the drilling. The pulsing of the drill rod is based upon signals received from a downhole monitor. Although reference is made to the necessity of compensating for the existence of a certain amount of wind-up in the drill string, as well as for the reaction delay in transmitting a thrust pulse along the length of the drill string to the drill bit, the system is primarily contemplated for use in horizontal coal mine drilling where the length of the drill string, and hence the wind-up and reaction delay, are in practice considerably less than in oil well drilling. Since the bit is connected to the drill string through a bent sub, the bit does not rotate about the axis about which it was designed to rotate and does not therefore drill efficiently. When the bit is drilling normally, i.e. in a straight line, the bit dynamics are likely to be poor and only a part of the bit is likely to be cutting the formation.

U.S. Specification No. 4637479 (L. J. Leising) describes a roller-cone bit carried on a drilling tool in which a rotating flow-obstructing member controls the flow of drilling fluid to discharge passages in the drill bit. By varying the rate of rotation of the flow obstructing member, drilling fluid may be sequentially discharged from the bit passages into only a single peripheral sector of the borehole, and thereby divert the drill bit into a different path.

The present invention provides a novel system and method for directional drilling which is applicable to rotary drilling.

According to the present invention there is provided a drilling system for drilling or coring holes in subsurface formations comprising:

a) a bottom hole assembly including a drill bit

structure comprising a bit body carrying a plurality of cutting structures;

b) means for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof, said modifying means forming part of said bottom hole assembly so as to be located downhole during operation of the system;

c) means for periodically varying the operation of said modifying means, and hence the rate of penetration of the cutting structures modified thereby, in synchronism with rotation of the drill bit, and in selected phase relation thereto;

d) the bit structure being asymmetrically arranged whereby said variation of the rate of penetration of said cutting structures in synchronism with rotation of the drill bit causes the drill bit to become displaced laterally, as drilling continues, in a direction which is dependent on said selected phase relation between rotation of the drill bit and said periodic variation of the operation of said modifying means.

The operation of substantially all the cutting structures of the drill bit are preferably modified simultaneously by said modifying means. For example, the means for modifying the operation of the cutting structures may comprise means for cyclically varying an axial force applied to the bit body.

Said modifying means may comprise a hammer which applies repeated axial impulses to the bit at a frequency greater than the frequency of rotation thereof, means being provided for periodically varying the intensity of operation of the hammer in synchronism with the rotation of the drill bit. For example, the hammer may be switched on and off periodically in synchronism with the rotation of the drill bit.

The hammer may be a mud hammer including means for periodically restricting the flow of drilling fluid to the bit structure to create pulsations in said flow and thereby impart said repeated axial impulses to the bit structure.

In any of the above arrangements the required phase relation between rotation of the drill bit and periodic operation of the modifying means may be selected by determining the instantaneous rotational orientation of the drill bit and setting the phase angle to provide operation, or maximum operation, of the modifying means at the appropriate rotational position of the drill bit to achieve displacement in the required direction.

The means for determining the instantaneous rotational orientation of the bit body may include downhole sensing means responsive to the instantaneous rotational orientation of the bit body, which sensing means sends signals, indicative of said instantaneous rotational position, to control means, also located downhole, for controlling said modifying means.

Alternatively the instantaneous rotational orien-

tation of the bit structure may be determined from the rotational position of the rotary table on the drilling platform, suitable allowance being made for wind-up of the drill string.

In the case where both the sensing means and the control means are located downhole, selection of the particular phase relation between rotation of the drill bit and periodic variation of the modifying means, and hence selection of the direction of deviation of the borehole, may be effected automatically by a predetermined program responsive to information received from downhole surveying instruments supplying signals indicative of the direction of the borehole, the program being executed by processing means located downhole.

In an alternative arrangement the aforesaid means for controlling the phase relation between rotation of the drill bit and periodic variation of the modifying means may include a downhole clock controlling the periodic operation of the modifying means, and a substantially synchronised clock at the surface, means being provided for varying the rotation of the drill bit in relation to said surface clock in a manner to achieve a desired phase angle.

The system may include a signal processor to which are supplied signals from said surface clock, as well as signals indicative of rotation of the drill bit and of the desired phase angle, said signal processor processing said signals and delivering to means controlling rotation of the bit a resultant signal to cause said means to vary rotation of the bit until said desired phase angle is achieved.

Preferably there are also supplied to the signal processor signals indicative of the wind-up in the drill string, the processor being adapted to modify said resultant signal in accordance therewith, so as to compensate for said wind-up in controlling said phase angle.

The invention includes within its scope a method of controlling the direction of a hole being drilled or cored in a subsurface formation by a drill bit structure which is asymmetrically arranged, and which includes a bit body carrying a plurality of cutting structures, the method comprising:

a) periodically varying, in synchronism with rotation of the drill bit, the operation of means located downhole for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof,

b) operation of said modifying means being periodically varied in selected phase relation to rotation of the drill bit, and

c) said asymmetrical arrangement of the bit structure being such that said variation of the rate of penetration in synchronism with rotation of the drill bit causes the drill bit to become displaced laterally, as drilling continues, in a direction which is dependent on said selected phase relation be-

tween rotation of the drill bit and said periodic variation of the operation of said modifying means.

The invention further provides a drilling system for drilling or coring holes in subsurface formations including:

- a) a drill bit, comprising a bit body carrying a plurality of cutting structures;
- b) means for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof; and
- c) means for periodically varying the operation of said modifying means, and hence the rate of penetration, in synchronism with rotation of the drill bit, and in selected phase relation thereto,
- d) said cutting structures being asymmetrically arranged on the bit body whereby said variation of the rate of penetration thereof in synchronism with rotation of the drill bit causes the drill bit to become displaced laterally, as drilling continues, in a direction which is dependent on said selected phase relation between rotation of the drill bit and said periodic variation of the operation of said modifying means.

The asymmetrical arrangement of the cutting structures may comprise an asymmetrical distribution of the cutting structures over the bit body.

In the case where the drill bit includes cutting structures which face laterally outwardly as well as axially of the bit body, the asymmetrical distribution of the cutting structures may be such that at least the major part of the cutting action of the drill bit is effected by outwardly facing cutting structures located in a region of the bit body which is offset to one side of a diametral axis thereof. In this case the profile of the surface generated by the cutting structures may be generally convex or conically shaped.

In the case where the drill bit includes some cutting structures which face laterally outwardly as well as axially of the bit body, and other cutting structures which face laterally inwardly as well as axially of the bit body, the asymmetrical distribution of the cutting structures may be such that at least the major part of the cutting action of the drill bit is effected by cutting structures which face generally in the same lateral direction.

Alternatively or additionally to any of the above arrangements, the asymmetrical arrangement of the cutting structures may be provided by the cutting structures being of different cutting characteristics in different regions of the bit body, so as to achieve an asymmetrical cutting pattern.

For example, cutting structures in some regions of the bit body may comprise polycrystalline diamond cutting elements designed to effect comparatively rapid cutting and penetration of the formation, while on other regions of the bit body the cutting structures are in the form of abrasive elements comprising studs which project from the bit body and have embedded

in the exposed end thereof natural or synthetic diamonds.

In the case where at least some of the cutting structures comprise preform polycrystalline diamond cutting elements, the asymmetrical arrangement of the cutting elements may be provided by cutting elements in some regions of the bit body being disposed at different angular orientations with respect to their normal forward direction of movement during drilling than cutting elements in other regions of the bit body.

The invention is particularly applicable to drilling systems where the cutting structures comprise preform cutting elements formed, at least in part, from polycrystalline diamond. However, the invention is also applicable to other forms of cutting elements. For example, the invention is applicable to roller cone bits. The invention is also applicable to arrangements where the cutting structures are in the form of jets of high pressure fluid. In this case, the modification of operation of the cutting structures may be achieved by increasing or reducing the fluid pressure in all the jets in synchronism with rotation of the bit. The modification might also be achieved by pulsing the jet, or by varying a normal rate of pulsation.

The following is a more detailed description of embodiments of the invention, reference being made to the accompanying drawings in which:

Figure 1 is a vertical section through the bottom portion of a borehole being drilled, showing diagrammatically a drilling system in accordance with the present invention,

Figure 2 is a graphical representation of the rotational orientation of the drill bit as it rotates through a number of revolutions,

Figure 3 is a diagrammatic cross-section through the bottom of the borehole showing the rotational orientation of the drill bit,

Figure 4 shows diagrammatically an arrangement for controlling a drilling system in accordance with the invention as described with reference to Figures 1-3,

Figure 5 is a diagrammatic representation of an alternative form of drilling system in accordance with the invention,

Figures 6 and 7 are diagrammatic representations of other typical asymmetrical drill bits, Figure 8 is a vertical section through a bit, similar to the bit of Figure 7, the bit being shown downhole,

Figure 8A is an end view of the bit of Figure 8, Figure 9 is a vertical section through an alternative form of bit,

Figure 9A is an end view of the bit of Figure 9, Figure 10 is a diagrammatic end view of a similar bit to that of Figure 8 to show the relative dispositions of the cutting elements,

Figure 11 is a diagrammatic representation of an alternative form of drilling system in accordance

with the invention,

Figure 12 is a diagrammatic representation of a further form of drilling system in accordance with the invention, and

Figure 13 is a diagrammatic representation of a still further form of drilling system according to the invention.

Referring to Figure 1 there is shown, down a borehole 10, a drilling system in which the bottom hole assembly 11 is connected to the lower end of a rotatable drill string, the first collar being indicated at 12. The bottom hole assembly 11 comprises an asymmetrical drill bit 13 connected to a mud hammer 14 there being mounted above the mud hammer a surveying instrument package indicated diagrammatically at 15.

The drill bit 13 may be of any kind having a bit body carrying a plurality of cutting structures, where the cutting structures are asymmetrically distributed over the cutting face, or otherwise asymmetrically arranged, in accordance with the present invention. In the example shown diagrammatically, the cutting structures comprise polycrystalline diamond preform cutting elements 16 mounted along substantially radially extending blades, one of which is shown at 17 in Figure 1.

The mud hammer 14 to which the bit 13 is connected is of known form and is so designed that as drilling mud is pumped through it at high pressure the mud hammer repeatedly applies axial hammer blows or impulses to the bit. Use of such a mud hammer will normally increase the rate of penetration of the bit.

The mud hammer may be of any suitable construction. For example it may be of the kind in which the hammer blows are created by periodically restricting the flow of drilling fluid, or mud, through a passage in a part of the downhole assembly, for example a housing mounted in the drill string above the drill bit. The periodic restriction creates a cyclical water-hammer effect.

One suitable mud hammer assembly of this type is described in U.S. Patent Specification No. 5009272, the content of which is incorporated herein by reference. In the arrangement described in that specification the means for periodically interrupting the flow comprise a venturi body within which a flap valve is freely pivoted at its downstream end, the arrangement being such that, as drilling fluid flows downwardly through the housing, the flap valve vibrates so as alternately to open and close the venturi and thus create shock waves in the drilling fluid above the flap, the resulting impulses being transmitted to the drill bit. It will be appreciated that, in such an arrangement, the pivoted flap might be replaced by some other form of movable element responsive to the differential pressures acting on the element as a result of the venturi effect. Alternative arrangements may be employed for periodically restricting the flow of the fluid, and those skilled in the art will also be

aware of other forms of mud hammer which could be employed.

The present invention also includes within its scope the use of other devices, apart from mud hammers, for imparting impulses to the drill bit. For example, the drill bit may be coupled to a downhole actuator such as an hydraulic actuator. In another arrangement impulses may be imparted to the bottom hole assembly by means of a percussion hammer or an axially oscillating mass carried in the bottom hole assembly.

Referring again to Figure 1, the instrument package 15 includes sensors, such as magnetometers and/or accelerometers, for sensing the rotation and instantaneous rotational orientation of the drill bit and providing signals indicative of such instantaneous rotational orientation. The instrument package 15 may also include other known forms of surveying equipment for enabling the position and direction of the borehole to be determined. Suitable forms of sensor are well known and may include accelerometers, magnetic fluxgates, gyroscopes, magnetic coils or pendulums. The specific details of the sensors and the instrumentation do not form part of the present invention and they will not therefore be described in detail.

Means are provided for selectively switching the mud hammer on and off periodically. Such control means may be under the direct control of information from the sensing instruments. Preferably the downhole instrument package 15 includes analogue and/or digital processing means for processing information concerning the position and direction of the borehole and passes instructions to the means controlling the mud hammer in accordance with a predetermined program. Alternatively operation of the mud hammer may be controlled from the drilling platform to control the direction of drilling in accordance with said information as to the position and direction of the borehole.

The method of control of the mud hammer is shown graphically in Figure 2. Referring to Figure 2: the sinusoidal curve 18 indicates the output from a magnetometer or other device for indicating the rotational orientation of the drill bit. Each cycle 19 indicates a single complete revolution of the drill bit through 360° from a datum. Superimposed is a graphical representation of the periods 20 when the mud hammer is operating. It will be seen that the mud hammer is switched on and off cyclically in phase relation to rotation of the drill bit.

Referring to Figure 3: this is a view looking axially down a borehole with the cardinal points being indicated at N, E, S and W. If it is required, for example, to cause the borehole to be deviated to the south east, the control means for the mud hammer may be instructed to switch the hammer on and off in such phase relation to rotation of the drill bit that the ham-

mer is switched on each time the cutter blade 17 reaches the position indicated at 21 in Figure 3, that is to say after the bit has rotated 45° from the datum position represented by north. The hammer remains switched on and operative while the drill bit rotates through 180° (clockwise in Figure 3) to the position indicated at 22 in Figure 3 and Figure 2 whereupon the hammer is switched off. This is repeated for each rotational cycle of the drill bit for as long as the deviation is required.

Although the mud hammer is shown in Figure 3 as being switched on through 180° of rotation of the drill bit, other pulse widths may be employed. The pulse width may be pre-set and constant, or may be varied in accordance with signals delivered to the signal processor.

Since the rate of penetration increases when the mud hammer is activated the portion of the bottom of the borehole which is cross-hatched in Figure 3 will be cut at a faster rate of penetration than the remainder of the borehole bottom, with the result that the drill bit will become increasingly displaced to the south east, as drilling proceeds, with consequent deviation of the borehole in the same direction.

It will be appreciated that a similar effect would be achieved if the mud hammer were to be normally activated during the whole of each revolution of the drill bit but were then to be periodically switched off each time the cutting elements rotated through the non-cross-hatched portion of the borehole bottom in Figure 3. The cross-hatched portion would then still be drilled at a faster rate than the rest of the borehole bottom, so that the deviation would still be in the required direction. Such arrangement is to be preferred since the overall rate of penetration will be greater with the mud hammer constantly in operation except when deviation of the borehole is required.

By appropriately selecting the phase relation between rotation of the drill bit and operation of the hammer the mud hammer can be activated or de-activated in any portion of the rotation of the bit and the borehole thereby deviated in any required direction.

Figure 4 shows diagrammatically an arrangement for controlling a drilling system in accordance with the invention as described with reference to Figures 1-3.

As previously explained, control of the system requires measurement of the instantaneous rotational position of the drill collar and such measurements must be taken continuously while the drill collar is rotating. As a result there may be difficulty in obtaining uncorrupted signals. With the drill collar rotating, the principle choice is between having the whole instrument package fixed to the drill collar and rotating with it, (a so-called "strapped-down" system), or having at least the sensors of the instrument package fixed to a component which remains essentially stationary as the drill collar rotates around it (a so-called "roll stabilised" system). Figure 4 illustrates diagrammatically a

roll stabilised system in which the dotted line 101 represents a component, such as an axially extending shaft, which is normally controlled to remain essentially stationary as the drill collar rotates around it. Such an arrangement is described in British Patent Application No. 9113713.3.

The shaft 101 is driven relatively to the drill collar by a torquer 102 at such a rotational velocity in relation to the drill collar that it remains essentially stationary at an angular position dependent on the direction of the deviation required. The sensors mounted on the stationary, or roll stabilised, component comprises a three-axis accelerometer 103, a three-axis magnetometer 104 and an angular accelerometer 105. In known manner the accelerometer 103 outputs three signals G_x , G_y and G_z indicative of mutually orthogonal components of the earth's gravitational field, and the magnetometer 104 outputs three signals H_x , H_y and H_z indicative of three mutually orthogonal components of the earth's magnetic field.

These signals are fed to a processor 106 (for example a digital processor) which produces an output signal A indicative of the azimuth of the portion of the borehole in which the instrument package is located, a signal I indicative of the angle of inclination of the portion of the borehole, and a signal R indicative of the spatial roll angle (or tool face angle).

The desired azimuth A_0 and inclination I_0 for a given well depth are subtracted from the signals A, I respectively, indicative of the actual azimuth and inclination, to give signals $(A - A_0)$ and $(I - I_0)$ indicative of the changes in azimuth and inclination required to bring the borehole to the required direction. The signals A_0 and I_0 may be preset, or derived from a pre-determined program defining the required path of the borehole, or they may be signals passed downhole from an operator-controlled transmitter located at the surface.

The signals $(A - A_0)$ and $(I - I_0)$ are fed to a processor 107 which outputs a signal 108 indicative of the desired modulation phase angle of the mud hammer relative to the tool face angle. This is compared with the actual tool face angle R to produce a signal 109 indicative of the roll angle error of the sensor package. This signal passes through a filter 110 to attenuate noise and is fed to the torquer 102 to control the rotational position of the roll stabilised shaft 101.

To stabilise the servo loop controlling the shaft 101 there is mixed with the signal 109 a signal 111 from the angular accelerometer 105.

The output from the roll stabilised system is provided by the rotational position (or shaft angle) of the shaft 101 itself and the shaft can therefore simply be mechanically connected to the modulation system for the mud hammer as indicated diagrammatically at 112.

For example the shaft 101 may be connected to a control valve for controlling the flow of drilling fluid

through the mud hammer. In such an arrangement no electrical connections, power source or electromechanical devices may be required to modulate the mud hammer, thus simplifying the control system.

As previously mentioned, the pulse width of the modulation of the mud hammer may be preset and constant, but alternatively further control may be provided by allowing the pulse width to be varied. In this case the processor 107 may be arranged to produce a signal, as indicated at 113, indicative of the modulation pulse width and adapted to control the pulse width, i.e. the proportion of each rotation of the drill bit during which the mud hammer is in operation.

Alternatively, the signal 113 may be a control signal dependent on $(A - A_0)$ and $(I - I_0)$. When the signals $(A - A_0)$ and $(I - I_0)$ are both at or below a predetermined level, indicating that the direction of the borehole is correct, the control signal 113 is arranged to switch off the modulation of the mud hammer, for example by switching off the torquer 102. Preferably the arrangement is such that the torquer is switched off in a position where the mud hammer is on, so that the mud hammer continues to operate, but is unmodulated. The torquer is then switched on at periodic intervals, for example under the control of a clock, to allow the system to check whether the signals are still below the predetermined level or whether further correction of the direction of drilling is necessary.

Instead of being controlled in accordance with the instantaneous rotational orientation of the drill bit, the required phase relation between operation of the mud hammer and rotation of the drill bit may be selected by a trial and error method. That is to say, the mud hammer is first operated in an initial phase relation to rotation of the bit, the resultant deviation of the borehole is determined by the surveying instrumentation, and the phase relation is then adjusted through the angle necessary to bring the deviation to the required direction. Such feedback and adjustment may be handled by the digital processor.

Although, in this example, the mud hammer is described as being cyclically switched on and off it may instead be continuously in operation, its intensity of operation being continuously varied cyclically to vary the rate of penetration of the cutting elements in synchronism with rotation of the drill bit.

Although the embodiment of the invention described above utilises a mud hammer for modifying the operation of the cutting structures to vary their rate of penetration, this is only one example of various ways in which the rate of penetration of the cutters might be varied. Thus, it is well known that a change of the rate of penetration may be effected by other factors, such as the weight-on-bit or the geometry of the cutting elements. Accordingly, any such variable may be periodically modified in synchronism with rotation of the drill bit to achieve a greater or lesser rate of penetration during only a portion of each revolution of the bit.

Figure 5 shows an arrangement where the rate of penetration of the cutting structures is varied cyclically by cyclically varying the weight-on-bit.

Referring to Figure 5: the bottom hole assembly includes, above the drill bit 30 an hydraulic actuator 31 of a kind generally similar to the type of assembly known as a "shock sub". An actuator of this type normally comprises a piston and cylinder arrangement pressurised by the drilling mud to apply a downward load to the drill bit. The normal purpose of the conventional shock sub is to absorb axial vibrations of the drill bit and prevent such vibrations being transmitted to the rest of the drill string.

The mud pressure applied to the hydraulic actuator contributes to the weight-on-bit, i.e. the axial load pressing the drill bit downwardly against the bottom of the borehole. In accordance with the present invention, the downward load applied by the hydraulic actuator is cyclically varied in synchronism with rotation of the drill bit, and the drill bit is asymmetrically arranged, for example as previously described, so as to become displaced from the longitudinal axis of the existing borehole as drilling continues with cyclic operation of the hydraulic actuator. As in the previously described arrangement, a surveying instrument package 32 is included in the bottom hole assembly. It is shown above the hydraulic actuator 31 but might equally be below the hydraulic actuator.

In accordance with normal practice drilling mud is delivered from a mud pit 33 by a mud pump 34 through a stand pipe 35 and hose 36 to the upper end of the kelly 37 through which the mud is delivered to the drill pipe. The mud pumped down the drill string emerges through the hydraulic system of the drill bit 30 and passes back up the annulus between the drill string and the borehole to be returned to the mud pit 33 through a pipe 38, via a shale shaker, hydrocyclones etc., as indicated diagrammatically at 38a.

As previously described, during normal operation a substantially constant mud pressure is applied to the hydraulic actuator 31 which in turn applies a downward load on to the drill bit. According to the present invention, the hydraulic pressure of the mud is cyclically varied in synchronism with rotation of the drill bit so that the hydraulic actuator 31 applies a cyclically varying downward load on the drill bit. To this end a bypass conduit 39 is connected between the standpipe 35 and the mud pit 33 and is controlled by a main valve 40. Also disposed in the bypass conduit 39 is a further valve 41 which is coupled to the rotary table 42, through a differential gearbox 43. The connection may be of any suitable form, e.g. mechanical, electrical or hydraulic, and is such that the valve 41 opens and closes once for each revolution of the kelly 37. The differential 43 enables the phase angle to be adjusted, i.e. enables the valve 41 to be opened and closed during any selected portion of each revolution of the kelly.

The valve 41 may be continuously cyclically operated but has no effect so long as the main valve 40 is closed. In this case the drilling assembly operates normally. When it is required to effect deviation of the drilling direction, the valve 40 is opened so that during a portion of each revolution of the drill bit the mud flow is bypassed directly to the mud pit 33. The resultant cyclical drop in hydraulic pressure is transmitted to the hydraulic actuator 31 so that the axial load applied by the actuator to the drill bit 30 also varies cyclically.

The pulses in the drilling mud at the drilling platform will be in phase relation to the rotation of the drill bit 30 and the actual phase angle will depend both on the wind-up in the drill string and on the time taken for each pulse to be transmitted down the borehole. The necessary phase angle to achieve deviation of the borehole in a required direction may be determined from signals provided by the surveying instrument package 32 regarding the instantaneous rotational orientation of the drill bit, as in the previously described arrangement. Such information may therefore be used to control adjustment of the differential 43, to give the required direction of deviation of the drill bit.

Alternatively, the phase angle may be determined from a calculation of the wind up of the drill string and of the phase lag due to the transmission of the pulse to the hydraulic actuator.

Since the wind up of the drill string is dependent on the rotary table torque, the differential 43 for adjusting the phase angle may have an automatic input from the rotary table torque multiplied by a setting for the estimated effective drill string compliance. The adjustment for phase lag will depend on the depth of the borehole and of the speed of sound in the drilling mud.

Alternatively, the required phase angle may be determined by the trial and error method previously described.

The two latter methods are preferred since the system is not then dependent on any signals from the surveying instrument package 32, which is then required only to provide information enabling the position and direction of the borehole to be determined.

Instead of the main valve 40 being provided, means may be provided to interrupt the link between the valve 41 and the rotary table 42 so that the valve 41 is only operated cyclically when a deviation in drilling direction is required.

Mud pulses originating at the surface will become substantially attenuated in the course of transmission down the borehole to the hydraulic actuator 31 and this must be allowed for in the design of the system.

The required asymmetrical arrangement of the cutting structures may be achieved in a variety of ways. Figure 1 shows diagrammatically a suitable form of drill bit where the surface generated by the profile of the cutting elements is generally convex so that the cutters face laterally outwardly as well as axially of the bit body. As will be seen from Figure 1, the

elements 16 are provided in a region which is offset to one side of a diametral axis of the cutting face.

Figure 6 shows a drill bit having a generally conical cutting face 25 where the cutting structures are similarly offset.

Figure 7 shows diagrammatically a drill bit, of a common "double cone" type, where the cutting structures are asymmetrically distributed to provide the effect of the present invention. In this case the profile of the bit body is in the form of two convex portions 27 and 28 on opposite sides of the central axis of the bit. The cutting structures are asymmetrically distributed, partly over the radially outwardly facing surface of the left hand convex portion 27 and partly over the radially inwardly facing surface of the right hand convex portion 28. (In this context "inwardly" and "outwardly" refer to the direction with respect to the central longitudinal axis of the drill bit). However, the cutting structures are mounted on regions of such surfaces which face generally in the same lateral direction, i.e. to the left in Figure 7. Such arrangement ensures that the variation in rate of penetration of the two regions has a similar effect on the drill bit, i.e. causes it to become displaced in the same direction (to the left in Figure 7).

Figure 8 is a vertical section through a drill bit, shown downhole, of the double-cone type similar to that shown in Figure 7. Figure 8 shows the drill bit in a part of the revolution thereof during which the rate of penetration is increased. The cutting elements 50 are substantially all facing in the same lateral direction, i.e. to the left in Figure 8, so that the increased penetration will always occur on the left facing side of the bottom of the borehole, as indicated diagrammatically in dotted lines at 51 in Figure 8. As drilling proceeds, therefore, the bit will become increasingly displaced to the left of the central axis 52 of the existing borehole.

Figure 8A is a diagrammatic end view of the bit shown in Figure 8 and it will be seen that the end face of the bit comprises six blades 53, on which the cutting elements 50 are mounted, separated by waterways 54 leading to junk slots 55. In conventional manner drilling mud is delivered to the waterways 54 through nozzles 56. Wear pads 57 are provided on the gauge portion of the bit body and, as best seen in Figure 8, due to the asymmetry of the drill bit, wear pads 57 are only required on the portion of the gauge opposite to the direction in which the cutting elements face. In Figure 8 the wear pads 57 are shown on the cylindrical part of the gauge, but it may be preferable for the wear pads to be on the conical part of the bit face, as indicated at 58. In this case the wear pads 57 on the gauge portion may be omitted, as shown in the modified bit of Figures 9 and 9A. The provision of asymmetrical wear pads, as shown, may serve to stabilise the bit in the borehole.

Figure 10 is a diagrammatic representation of the end view of the drill bit of Figures 8 and 8A, to show

the asymmetrical distribution of the cutters.

Referring to Figure 10: the end face of the drill bit comprises three annular zones A, B and C. The outer zone A faces radially outwardly away from the axis 52 of the drill bit. The intermediate zone B faces generally axially of the drill bit and the inner zone C faces radially inwardly towards the axis 52.

Cutters are distributed generally symmetrically around the intermediate zone B since such cutters, facing axially, have little effect on the asymmetry of the drill bit. However, in order to achieve the asymmetry required for the present invention, cutters are mounted only on that portion of the outer zone A which is to the left of the diametral axis 59, and cutters are only mounted on that portion of the inner zone C which is to the right of the diametral axis 59. This has the result that all of the cutters in the zones A and C face in the same lateral direction with respect to the drill bit, that is to say to the left in Figure 10.

In any of the arrangements according to the invention, and in particular in the arrangements shown in the accompanying drawings, each cutting structure may include a cutting element of superhard material. For example, each cutting element may be in the form of a circular or part-circular tablet including a cutting table of superhard material, such as polycrystalline diamond or cubic boron nitride, bonded to a substrate of less hard material, such as cemented tungsten carbide. The preform cutting element may be directly mounted on the bit body or may be bonded to a stud or other carrier, for example of cemented tungsten carbide, which is received in a socket in the bit body. The bit body may be machined from metal, usually steel, or may be formed from an infiltrated tungsten carbide matrix by a powder metallurgy process.

In certain of the arrangements shown in the drawings, the required asymmetry is provided by omitting cutting structures from some parts of the bit body. However, as previously mentioned, a similar asymmetrical effect can be achieved by the cutting structures being of different cutting characteristics in different regions of the bit body. For example, some of the cutting structures may comprise so-called "impregs", which are studs of cemented tungsten carbide or other hard material which are mounted in sockets in the bit body and have embedded in their exposed outer ends natural diamonds or small elements of polycrystalline diamond. The mounting of such impregs on some areas of the bit body, instead of omitting cutting structures altogether from such areas, has the effect of improving the overall stability and dynamics of the drill bit, while at the same time providing the asymmetrical cutting pattern necessary for the present invention.

According to another arrangement in accordance with the invention the different cutting characteristics of the cutting structures in different regions of the bit

body may be achieved by varying the angular orientation of the cutting faces of the cutting structures. As is well known in the art, a polycrystalline diamond preform cutting element of the kind described above normally has a flat cutting face and this cutting face will be disposed at a negative back rake angle with respect to the normal forward direction of movement of the cutting element during drilling, and also a side rake angle. The cutting effectiveness of such a preform cutting element will depend to a certain extent on its angular orientation, i.e. the magnitude of the negative back rake angle and of the side rake angle, and the asymmetric arrangement of cutting characteristics required by the present invention may therefore be achieved by disposing preform cutters in different regions of the bit body so as to have different negative back rake angles and/or different side rake angles.

It is also possible for the required asymmetry to be achieved by the disposition or characteristics of other elements of the bottom hole assembly instead of being provided by the cutting structures themselves. Figure 11 shows diagrammatically such an arrangement.

Referring to Figure 11, there is shown an arrangement where a conventional drill bit 60, which may have cutting structures substantially symmetrically distributed about its own axis, is connected to the mud hammer or hydraulic actuator 61 by a bent sub assembly 62. The angle of inclination of the drill bit 60 provided by the bent sub 62 is exaggerated in the drawing.

As previously explained, a bent sub is normally used in conjunction with a motor and the effect of the tilt of the drill bit is nullified during normal drilling by rotating the motor casing. In the arrangement of Figure 11, where a motor is not employed and the drill bit is rotated through the drill string, the tilt effect of the bent sub 62 is also normally nullified during drilling by the rotation of the drill string and hence of the bent sub with the drill bit. However, when the mud hammer is set in cyclical operation in synchronism with rotation of the drill bit this will have the effect, as previously explained, of increasing the rate of penetration during a portion of each revolution of the bit. Due to the asymmetry of the drill bit 60, as a result of its tilt, such increase in the rate of penetration during a portion of each rotation will cause the drill bit to become increasingly displaced from the central axis of the borehole (to the left in Figure 11) as drilling continues.

Such arrangement has the disadvantage, referred to earlier, that the tilted drill bit is unlikely to drill efficiently since it is not rotating about the axis about which it was designed to rotate. However, in this arrangement the drill bit may be of virtually any type, symmetrical or unsymmetrical, and there may be advantage in being able to use a standard bit when steering.

Although the use of known surveying instrumen-

tation has been referred to above as the means for sensing the instantaneous rotational orientation of the bit, where this is used for controlling the mud hammer or other modifying means, any other suitable sensing method may be employed. For example, if suitable compensation is made for wind-up of the drill string in the case of rotary drilling, the instantaneous rotational orientation of the drill bit might be determined at the drilling platform from the instantaneous rotational orientation of the upper end of the drill string, and instructing signals sent to the mud hammer or other modifying device accordingly. Alternatively, the hammer or other modifying device could be directly controlled by a mechanical rotational orientation sensing device, such as a pendulum, a series of pendulums or a gyroscope, rotatable with the drill bit and arranged to switch the device on and off automatically at predetermined points in each rotation of the drill bit. Although it is preferred that the hammer or other modifying device be continuously controlled by signals from the drilling platform or from downhole computing means, the invention does not exclude arrangements where a control device for the modifying means requires to be preset for a particular required deviation of the hole, before the drilling system is introduced into the hole.

Figure 12 shows a further arrangement for controlling a mud hammer to vary the rate of penetration during only a portion of each revolution of the bit.

Referring to Figure 12: the bottom hole assembly includes an asymmetrical drill bit 70 connected to a mud hammer 71, there being mounted above the mud hammer a control module 72. As in the previously described arrangements, the drill bit 70 may be of any kind having a bit body carrying a plurality of cutting structures, where the bit structure is asymmetrically arranged in accordance with the present invention.

The mud hammer 71 to which the bit 70 is connected is also of any known form, and the particular construction of the mud hammer does not form part of the present invention. Although this embodiment of the invention will be described in relation to the use of a mud hammer, it will be apparent that the system may be modified by replacing the mud hammer by an hydraulic actuator, or "shock sub", of the kind described in the embodiment of Figure 5.

The arrangement of Figure 12 depends on the provision of two synchronised clocks in the downhole assembly and at the surface respectively. In Figure 13 the downhole clock is indicated diagrammatically at 73, in the control module 72, and the synchronised surface clock is indicated diagrammatically at 74.

Cyclical operation of the mud hammer 71 is arranged to be under the control of the downhole clock 73, as indicated diagrammatically by a control link 75. Since the surface clock 74 is synchronised to the downhole clock 73, it is also in synchronism with operation of the mud hammer and may therefore be

used as a reference to permit adjustment of the phase angle between rotation of the bit 70 and the cyclical operation of the mud hammer. The means for achieving this will be described in relation to the block diagram included in Figure 12.

Signals from the surface clock 74 are fed to a signal processor 76 which also receives signals indicative of other parameters affecting the phase angle, as will be described. The processor 76 may be a digital computer or an appropriate analogue device.

There is associated with the rotary table 80 a rotation sensor 81, of any appropriate form, which supplies to the signal processor a signal 82 indicative of the rotation and rotational orientation of the rotary table 80. This signal 82 is processed, together with the signal from the surface clock 74, to indicate the actual phase angle between the rotation of the rotary table 80 and the operation of the mud hammer 71, since the latter is generally in synchronism with the surface clock 74. This actual phase angle is then compared by the signal processor 76 with a desired phase angle which is input to the signal processor, by an operator, as indicated diagrammatically at 83. (In fact, as far as the operator is concerned, the input 83 will be in the form of a desired direction of deviation of the bore hole, since such deviation is dependent on the phase angle, as previously explained.) This comparison carried out by the processor 76 results in a phase error signal and a corresponding output signal 77 is sent to a speed controller 78 which, in response to such signal, controls the motor 79 driving the rotary table 80 in such manner as to reduce this phase error to zero and thereby achieve the desired phase angle.

As described above in relation to the Figure 5 embodiment, however, the actual phase angle between the cyclical operation of the mud hammer and the rotation of the drill bit 70 will partly depend on the wind-up in the drill string. Accordingly, it is also necessary to supply the signal processor 76 with signals from which the wind-up can be determined and allowed for in determining the actual phase angle.

The wind-up of the drill string is dependent on the rotary table torque and on the angular compliance of the drill string. There is therefore also supplied to the signal processor 76 a signal 84 which is indicative of the motor current, and hence of the rotary table torque. The angular compliance of the drill string is dependent on the section and the length of the drill string and signals 85 and 86, indicative of these parameters respectively, are therefore also supplied to the signal processor 76. The signal processor is arranged to process these signals in a manner to compensate for wind-up of the drill string in calculating the actual phase angle.

Although the clocks 73 and 74 will initially be in synchronism, it is possible that they will drift out of synchronisation during operation. For example, the downhole clock 73 is likely to be subject to elevated

temperatures which may affect its time-keeping. Accordingly, the clock 73 may be temperature controlled and a signal, indicated diagrammatically at 87, may be supplied to the signal processor 76 to provide an empirically determined correction for drift of the clocks out of synchronism due, for example, to temperature or other factors.

In order to cease steering the drill bit, and begin drilling a straight borehole, it is merely necessary to run the bit asynchronously by increasing the rate of rotation by a significant amount, for example by 50%.

The arrangement of Figure 12 has the advantage, when compared for example with the arrangement of Figure 5, that adjustment of the phase angle does not depend on the transfer of data to the surface from downhole instrumentation.

Figure 13 illustrates a further embodiment of the invention in which the phase angle between the operation of the mud hammer and rotation of the drill bit is dependent on the rotational frequency of the bit, so that the phase angle, and hence the direction of deviation, may be adjusted to a required value simply by varying the speed of rotation of the bit.

Referring to Figure 13: the bottom hole assembly again includes an asymmetrical drill bit 90 connected to a mud hammer 91, there being mounted above the mud hammer a control module 92. As in the previously described arrangements, the drill bit 90 may be of any kind having a bit body carrying a plurality of cutting structures where bit structure is asymmetrically arranged in accordance with the present invention. Also, an hydraulic actuator, or "shock sub", may be employed instead of a mud hammer.

The control module 92 includes a sensor 93 of a kind which detects the rate of rotation of the drill bit and supplies to a signal processor 94 a signal, indicated at 95, indicative of the frequency of rotation.

The sensor 93 may be of any known kind which can provide a signal which fluctuates for each revolution of the drill bit, for example it may comprise an accelerometer and/or a magnetometer.

The signal processor controls the mud hammer 91 through a control link indicated diagrammatically at 96 in such manner as to control and vary the phase angle between cyclical operation of the mud hammer and rotation of the drill bit in accordance with the rate of rotation detected by the sensor 93. The rate of rotation of the drill bit, (averaged over a long enough period of time to cancel out the effect of any torsional oscillations of the drill string), is equal to the rate of rotation of the rotary table 97, which is controlled from the surface. The rate of rotation of a drill bit is not normally particularly critical and may be varied by up to, say, 10 rpm without any significant effect on performance. The signal processor 94 is arranged to adjust the phase angle between operation of the mud hammer and rotation of the drill bit in dependence on the rate of rotation, within a predetermined range.

Thus, the desired phase angle may be selected from the surface by increasing or decreasing the rate of rotation of the rotary table 97, and hence of the drill bit 90, by a predetermined amount. Since, as previously described, the direction of deviation of the asymmetrical drill bit is determined by such phase angle, the direction of deviation may be selected by selecting an appropriate rate of revolution of the rotary table 97, within a predetermined range.

Means may be provided to switch the mud hammer (or the modulation thereof) on or off in response to signals from the surface. For example, the signal processor 94 may be adapted to switch the mud hammer (or its modulation) on and off in response to a predetermined sequence of operations detectable by the sensor 93.

The signal processor 94 may be of any suitable kind for controlling the phase angle of the mud hammer in response to variation in rotational frequency as detected by the sensor 93. For example, it could include a frequency meter which compares with a clock the frequency of signals from the sensor 93 and delivers a corresponding adjusting signal to a time lag device which controls the phase angle between the operation of the mud hammer and rotation of the drill bit, in response to signals from the rotation sensor 93.

Alternatively, the signal processor may incorporate a resonant component, for example electronic or mechanical, which is tuned to a frequency close to that of the datum frequency of rotation of the drill bit whereby the phase angle varies steeply in response to deviations from that datum frequency.

The arrangement of Figure 13 has the advantage that, since the phase angle is dependent solely on the frequency of rotation of the drill bit, no allowance requires to be made for a wind-up in the drill string, and it provides a convenient way of transmitting signals from the surface to the downhole assembly.

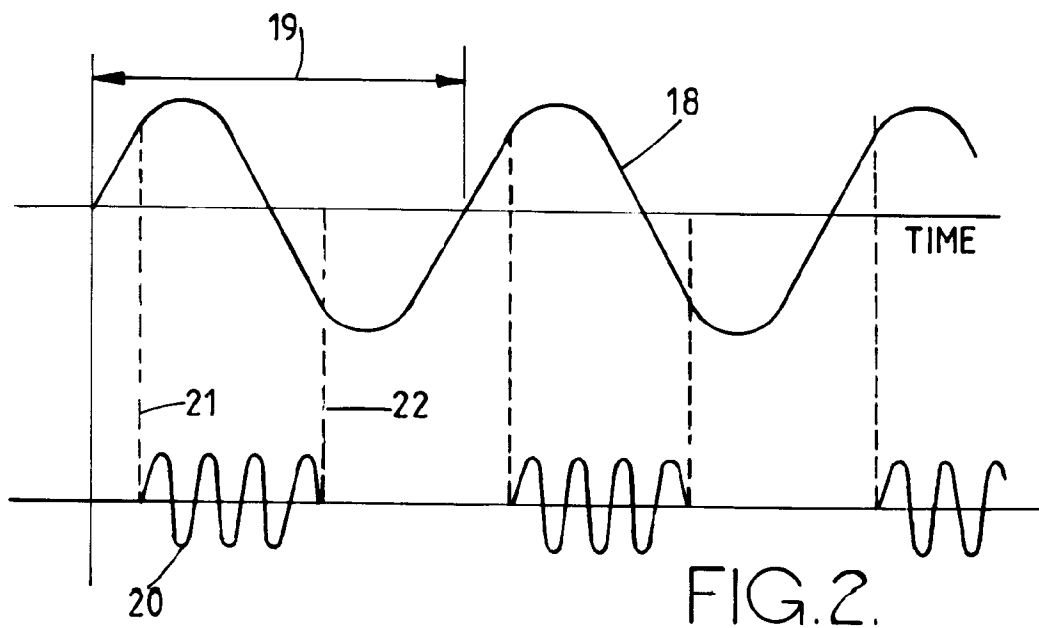
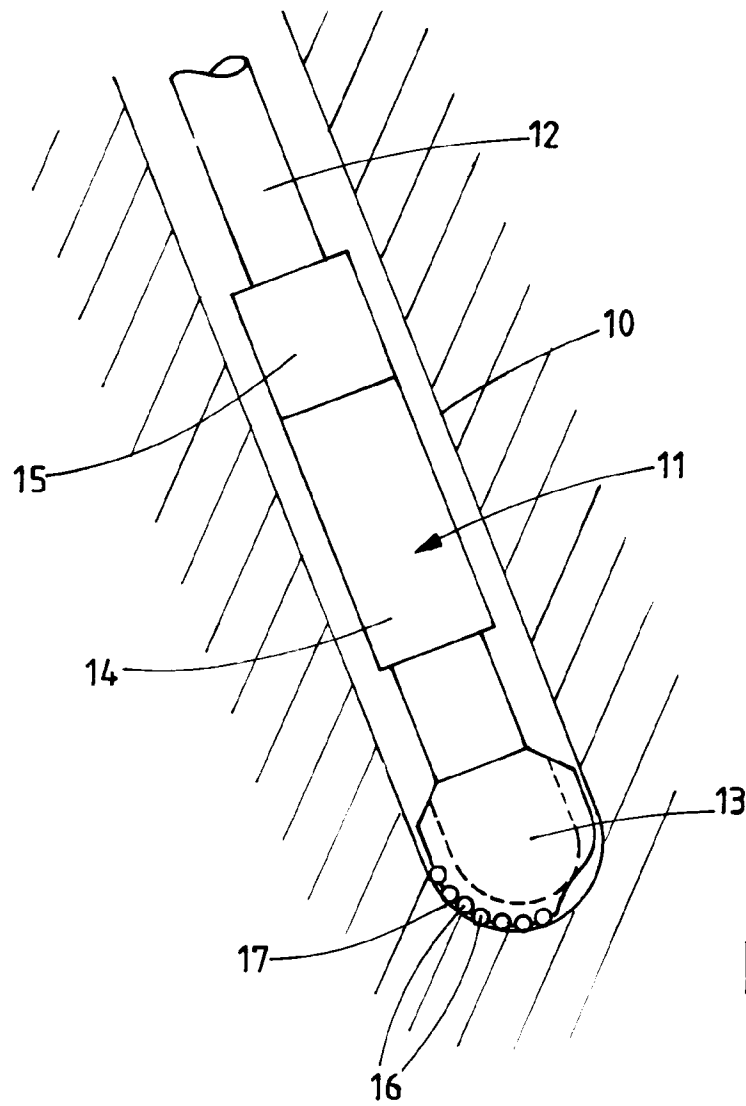
Claims

1. A drilling system for drilling or coring holes in sub-surface formations comprising:
 - a) a bottom hole assembly including a drill bit structure comprising a bit body carrying a plurality of cutting structures;
 - b) means for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof, said modifying means forming part of said bottom hole assembly so as to be located downhole during operation of the system;
 - c) means for periodically varying the operation of said modifying means, and hence the rate of penetration of the cutting structures modified thereby, in synchronism with rotation of the drill bit, and in selected phase relation

thereto;

- d) the bit structure being asymmetrically arranged whereby said variation of the rate of penetration of said cutting structures in synchronism with rotation of the drill bit causes the drill bit to become displaced laterally, as drilling continues, in a direction which is dependent on said selected phase relation between rotation of the drill bit and said periodic variation of the operation of said modifying means.
2. A drilling system according to Claim 1, wherein the operation of substantially all the cutting structures of the drill bit is modified simultaneously by said modifying means.
3. A drilling system according to Claim 2, wherein the means for modifying the operation of the cutting structures comprise means for cyclically varying an axial force applied to the bit body.
4. A drilling system according to Claim 3, wherein said modifying means comprise a hammer which applies repeated axial impulses to the bit at a frequency greater than the frequency of rotation thereof, means being provided for periodically varying the intensity of operation of the hammer in synchronism with the rotation of the drill bit.
5. A drilling system according to Claim 4, wherein the hammer is switched on and off periodically in synchronism with the rotation of the drill bit.
6. A drilling system according to Claim 5, wherein said hammer is a mud hammer and includes means for periodically restricting the flow of drilling fluid to the bit structure to create pulsations in said flow and thereby impart said repeated axial impulses to the bit structure.
7. A drilling system according to any of Claims 1 to 6, wherein the required phase relation between rotation of the drill bit and periodic operation of the modifying means is selected by determining the instantaneous rotational orientation of the drill bit and setting the phase angle to provide operation, or maximum operation, of the modifying means at the appropriate rotational position of the drill bit to achieve displacement in the required direction.
8. A drilling system according to Claim 7, wherein the means for determining the instantaneous rotational orientation of the bit body includes downhole sensing means responsive to the instantaneous rotational orientation of the bit body, which sensing means sends signals, indicative of said instantaneous rotational position, to control means, also located downhole, for controlling said modifying means.
9. A drilling system according to Claim 7, wherein the instantaneous rotational orientation of the bit structure is determined from the rotational position of the rotary table on the drilling platform, suitable allowance being made for wind-up of the drill string.
10. A drilling system according to Claim 8, wherein selection of the particular phase relation between rotation of the drill bit and periodic variation of the modifying means, and hence selection of the direction of deviation of the borehole, is effected automatically by a predetermined program responsive to information received from downhole surveying instruments supplying signals indicative of the direction of the borehole, the program being executed by processing means located downhole or by downwards telemetry.
11. A drilling system according to any of Claims 1 to 6, wherein the aforesaid means for controlling the phase relation between rotation of the drill bit and periodic variation of the modifying means include a downhole clock controlling the periodic operation of the modifying means, and a substantially synchronised clock at the surface, means being provided for varying the rotation of the drill bit in relation to said surface clock in a manner to achieve a desired phase angle.
12. A drilling system according to Claim 11, wherein there is provided a signal processor to which are supplied signals from said surface clock, as well as signals indicative of rotation of the drill bit and of the desired phase angle, said signal processor processing said signals and delivering to means controlling rotation of the bit a resultant signal to cause said means to vary rotation of the bit until said desired phase angle is achieved.
13. A drilling system according to Claim 12, wherein there is also supplied to the signal processor signals indicative of the wind-up in the drill string, the processor being adapted to modify said resultant signal in accordance therewith, so as to compensate for said wind-up in controlling said phase angle.
14. A method of controlling the direction of a hole being drilled or cored in a subsurface formation by a drill bit structure which is asymmetrically arranged, and which includes a bit body carrying a plurality of cutting structures, the method comprising:
 - a) periodically varying, in synchronism with

- rotation of the drill bit, the operation of means located downhole for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof, b) operation of said modifying means being periodically varied in selected phase relation to rotation of the drill bit, and c) said asymmetrical arrangement of the bit structure being such that said variation of the rate of penetration in synchronism with rotation of the drill bit causes the drill bit to become displaced laterally, as drilling continues, in a direction which is dependent on said selected phase relation between rotation of the drill bit and said periodic variation of the operation of said modifying means.
15. A drilling system for drilling or coring holes in sub-surface formations including:
- a) a drill bit, comprising a bit body carrying a plurality of cutting structures;
 - b) means for modifying the operation of at least some of the cutting structures in a manner to vary the rate of penetration thereof; and
 - c) means for periodically varying the operation of said modifying means, and hence the rate of penetration, in synchronism with rotation of the drill bit, and in selected phase relation thereto,
 - d) said cutting structures being asymmetri- cally arranged on the bit body whereby said variation of the rate of penetration thereof in synchronism with rotation of the drill bit causes the drill bit to become displaced later- ally, as drilling continues, in a direction which is dependent on said selected phase relation between rotation of the drill bit and said periodic variation of the operation of said mod- ifying means.
16. A drilling system according to Claim 15, wherein the asymmetrical arrangement of the cutting structures comprises an asymmetrical distribu- tion of the cutting structures over the bit body.
17. A drilling system according to Claim 16, wherein the drill bit includes cutting structures which face laterally outwardly as well as axially of the bit body, and wherein the asymmetrical distribution of the cutting structures is such that at least the major part of the cutting action of the drill bit is effected by outwardly facing cutting structures located in a region of the bit body which is offset to one side of a diametral axis thereof.
18. A drilling system according to Claim 17, wherein the profile of the surface generated by the cutting struc- tures is generally convex or conically shaped.
19. A drilling system according to Claim 16, wherein the drill bit includes some cutting structures which face laterally outwardly as well as axially of the bit body, and other cutting structures which face laterally inwardly as well as axially of the bit body, and wherein the asymmetrical distribution of the cutting structures is such that at least the major part of the cutting action of the drill bit is effected by cutting structures which face generally in the same lateral direction.
20. A drilling system according to any of Claims 15 to 19, wherein the asymmetrical arrangement of the cutting structures is provided by the cutting struc- tures being of different cutting characteristics in different regions of the bit body, so as to achieve an asymmetrical cutting pattern.
21. A drilling system according to Claim 20, wherein cutting structures in some regions of the bit body comprise polycrystalline diamond cutting ele- ments designed to effect comparatively rapid cut- ting and penetration of the formation, while on other regions of the bit body the cutting structures are in the form of abrasive elements comprising studs which project from the bit body and have embedded in the exposed end thereof natural or synthetic diamonds.
22. A drilling system according to Claim 20, wherein at least some of the cutting structures comprise preform polycrystalline diamond cutting ele- ments, and wherein the asymmetrical arrange- ment of the cutting elements is provided by cutting elements in some regions of the bit body being disposed at different angular orientations with respect to their normal forward direction of movement during drilling than cutting elements in other regions of the bit body.
23. A drilling system according to any of Claims 15 to 22, wherein the operation of substantially all the cutting structures of the drill bit is modified simul- taneously by said modifying means.
24. A drilling system according to Claim 23, wherein the means for modifying the operation of the cut- ting structures comprise means for cyclically varying an axial force applied to the bit body.
25. A drilling system according to Claim 24, wherein said axial force is applied by a hammer which applies repeated axial impulses to the bit at a fre- quency greater than the frequency of rotation thereof, means being provided for periodically varying the intensity of operation of the hammer in synchronism with the rotation of the drill bit.



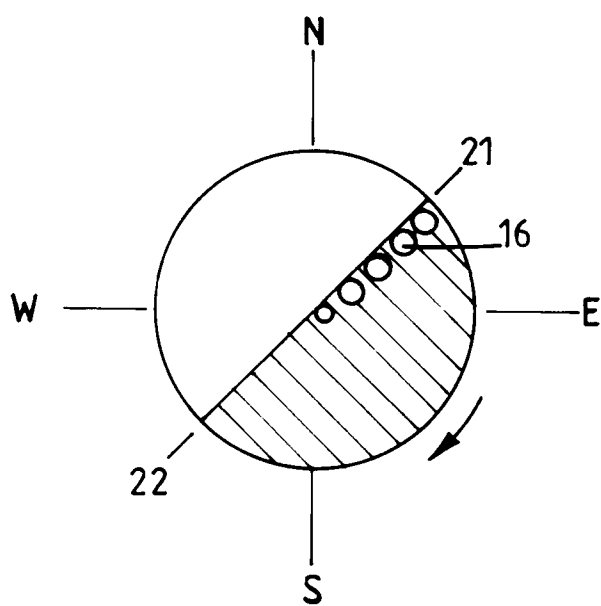


FIG. 3.

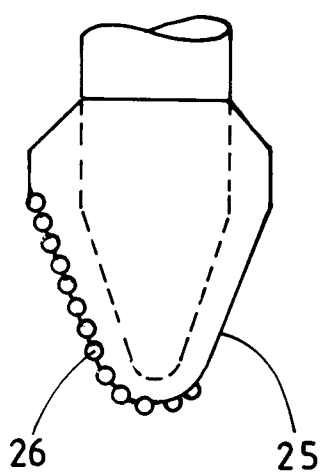


FIG. 6.

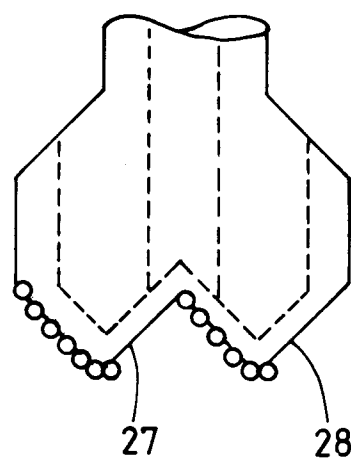


FIG. 7.

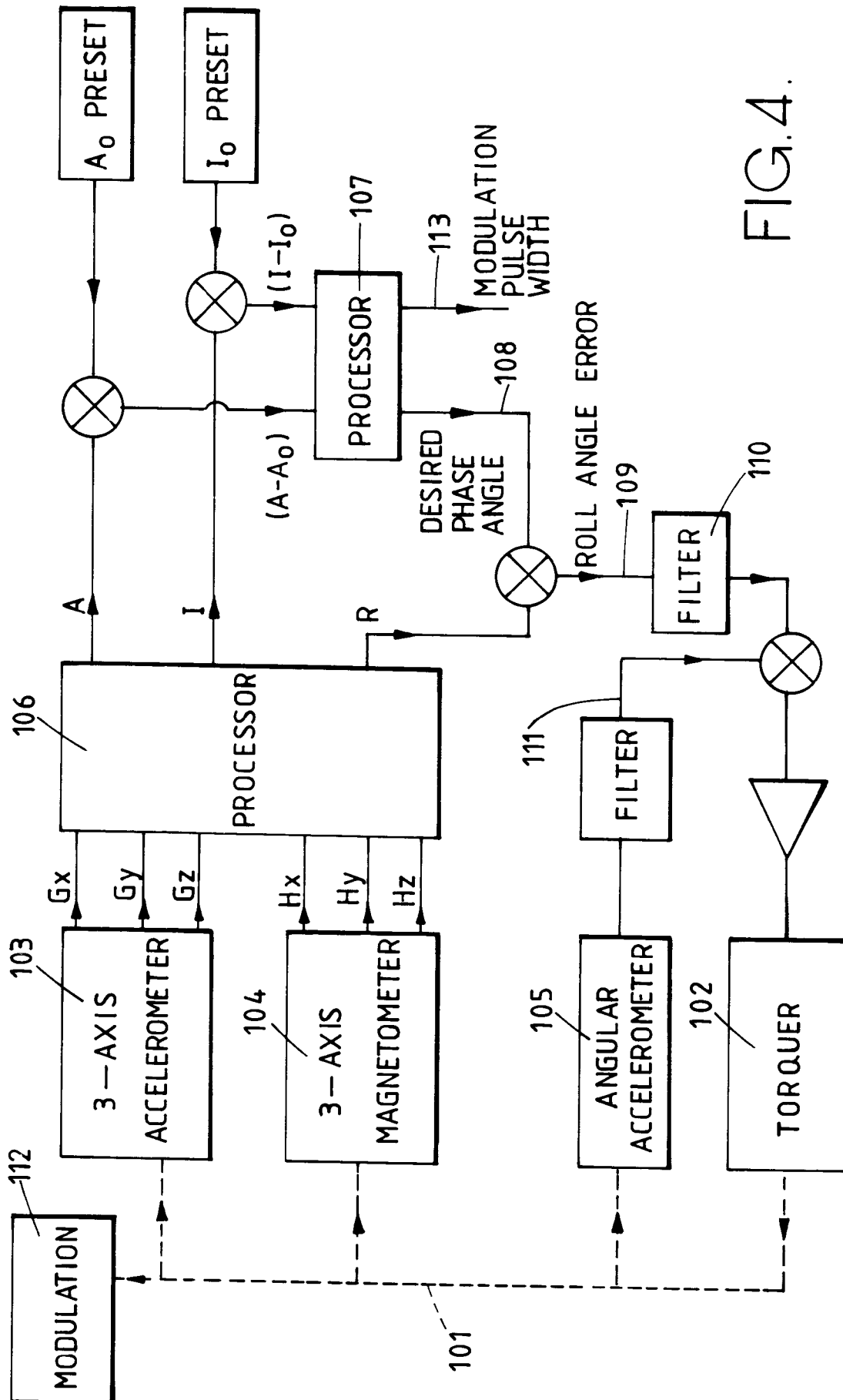


FIG. 4.

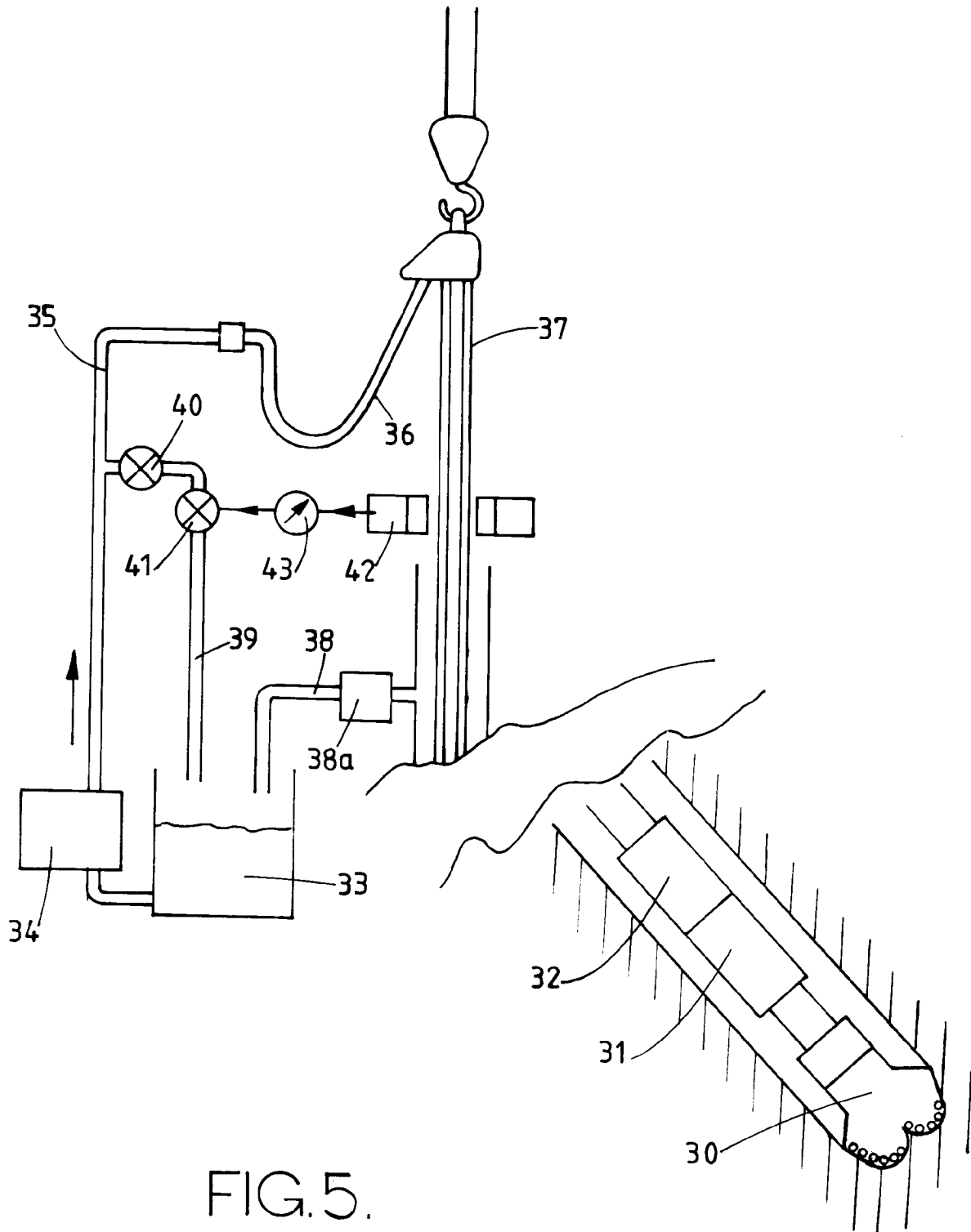


FIG.5.

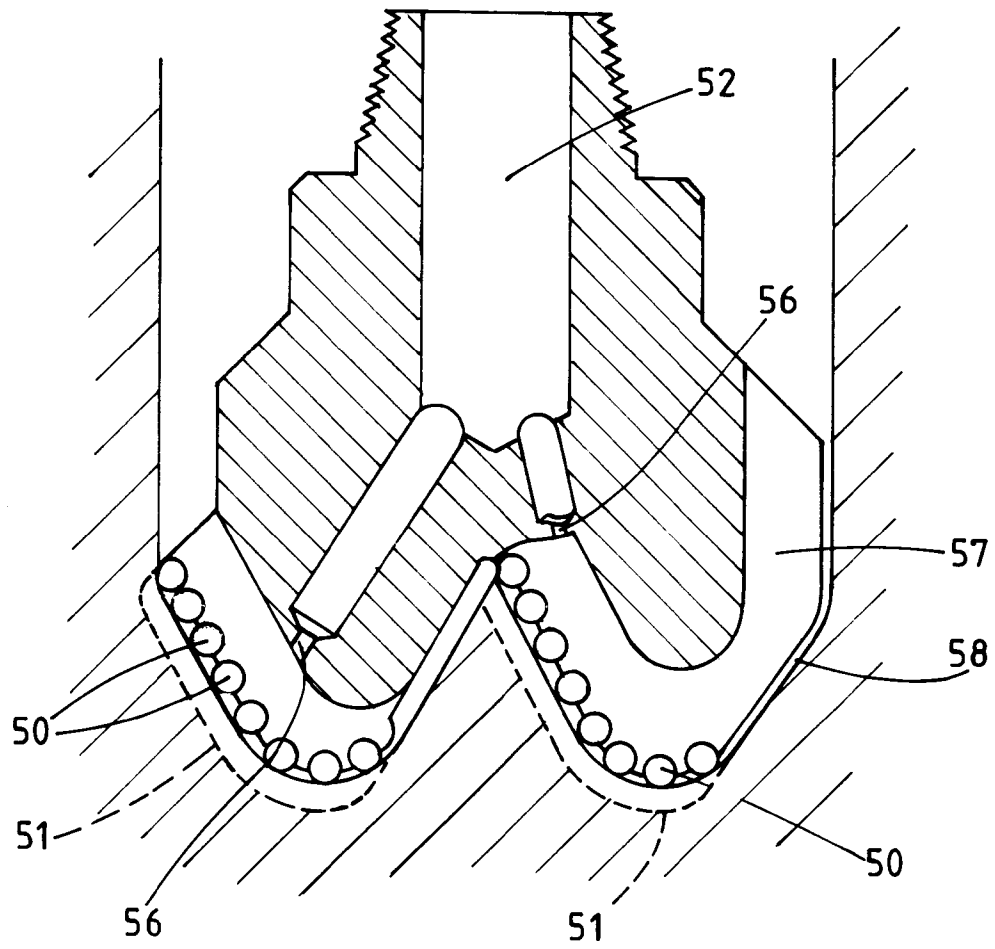


FIG. 8.

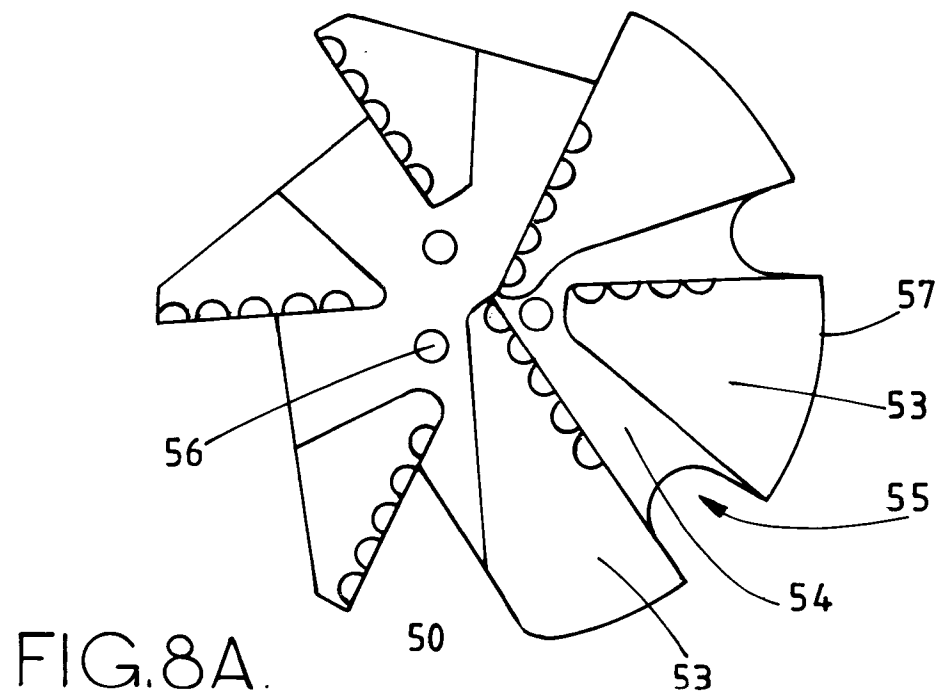


FIG. 8A.

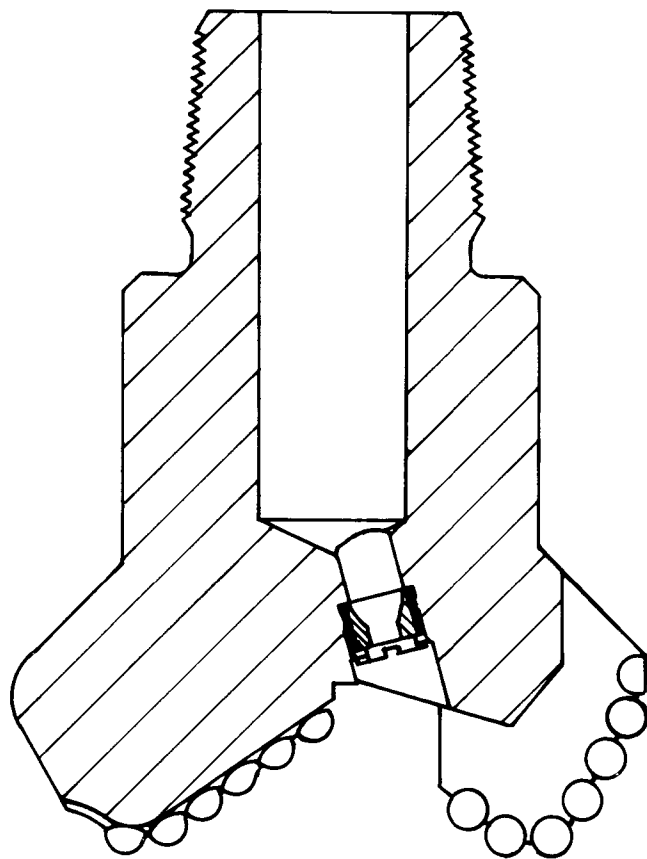


FIG. 9.

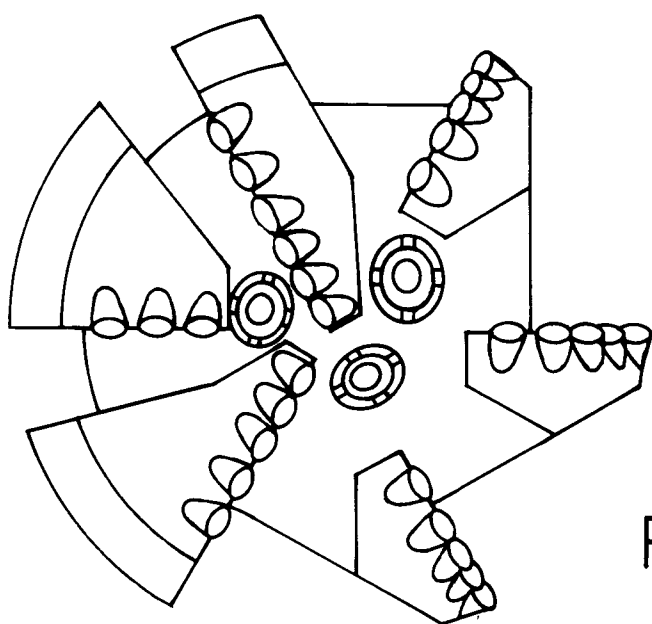


FIG. 9A.

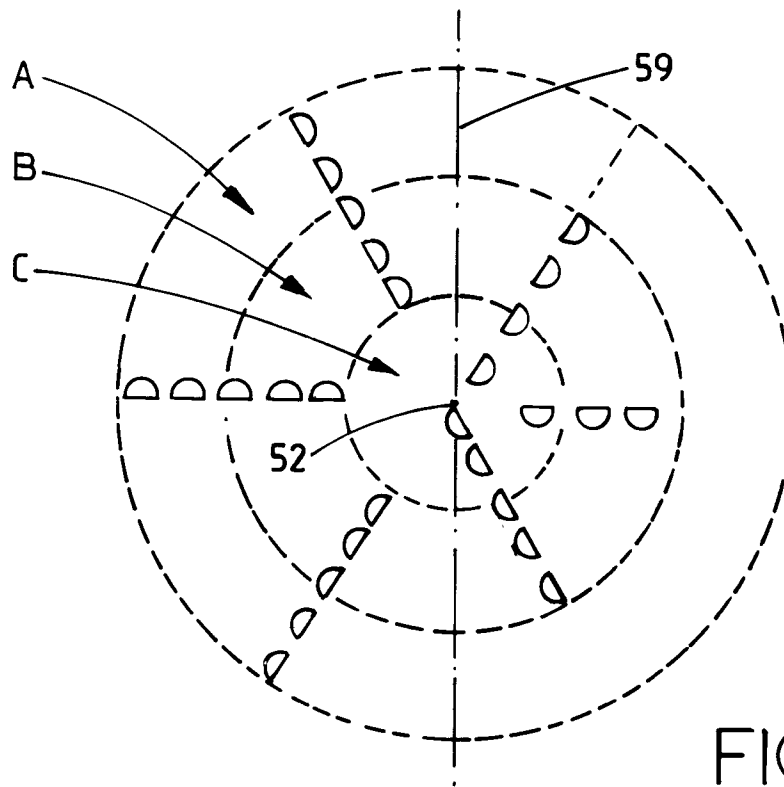


FIG. 10.

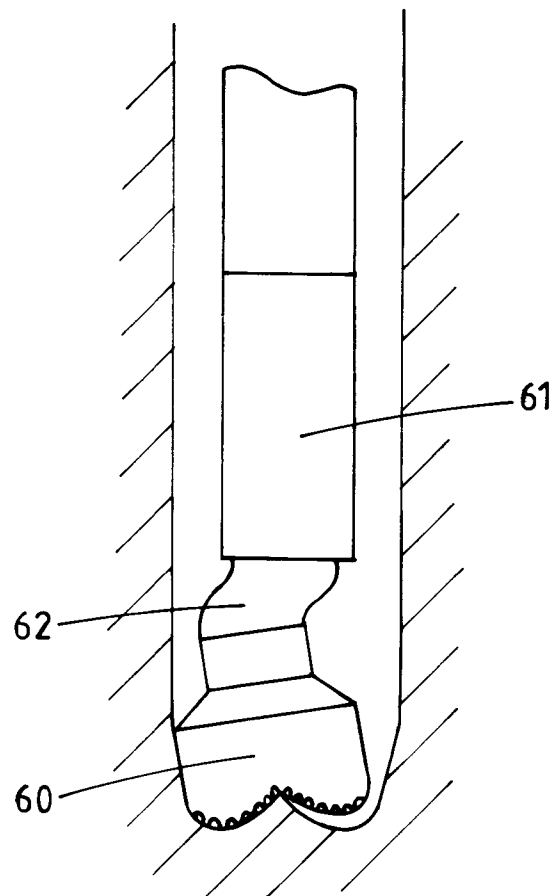


FIG. 11.

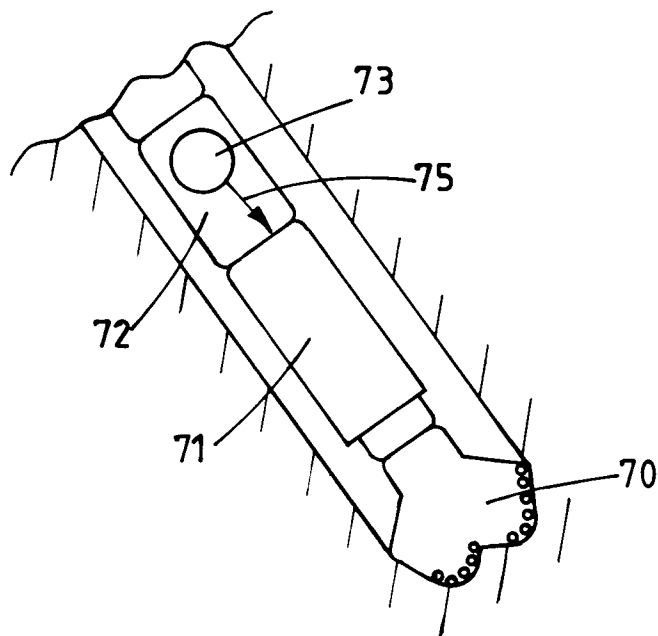
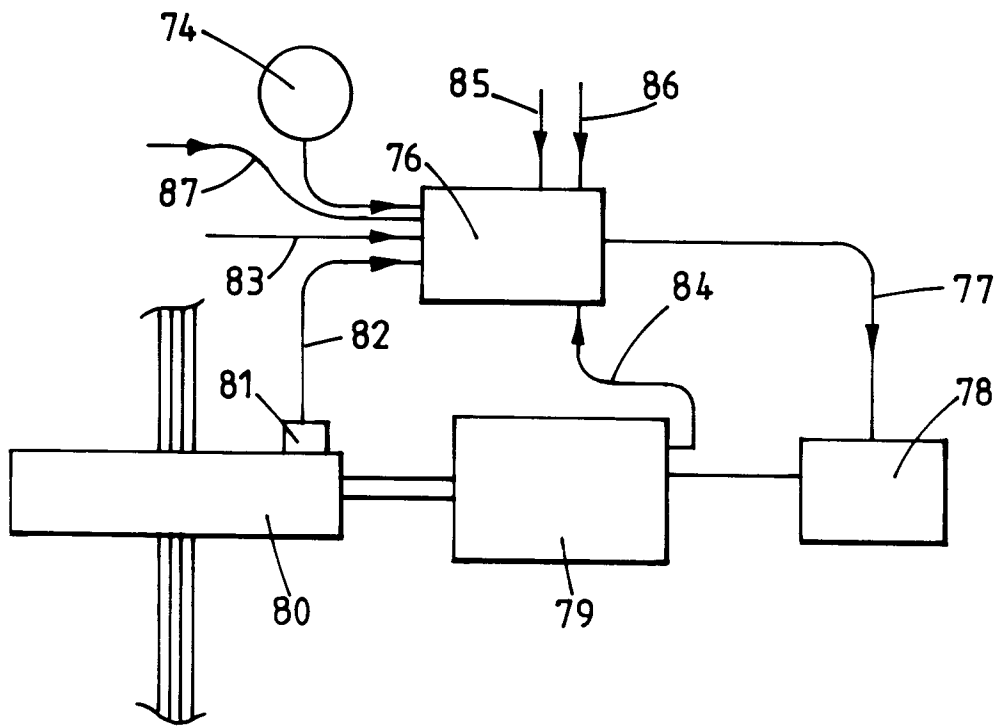


FIG. 12.

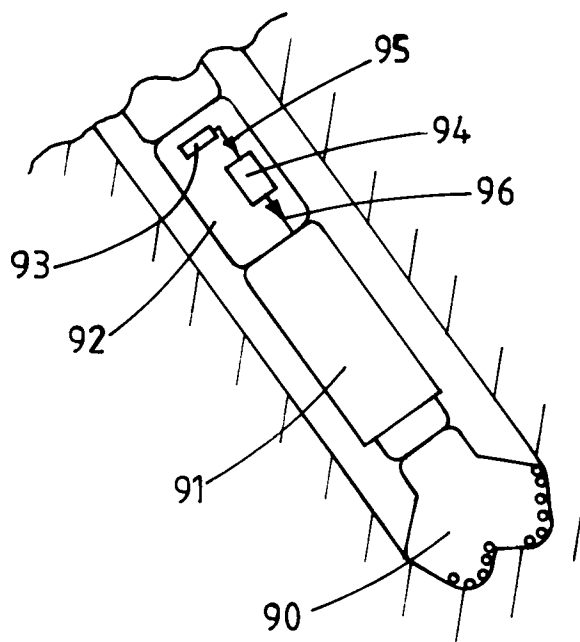
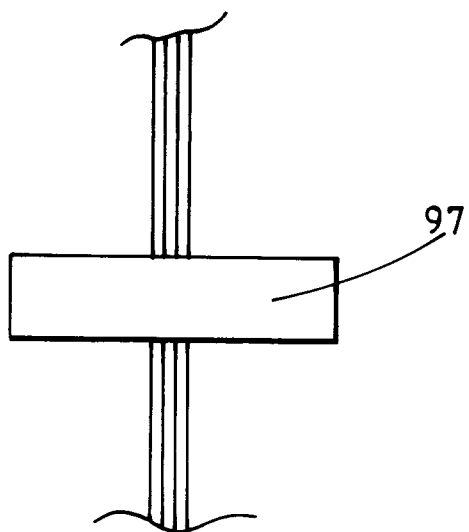


FIG.13.