

Nov. 3, 1959

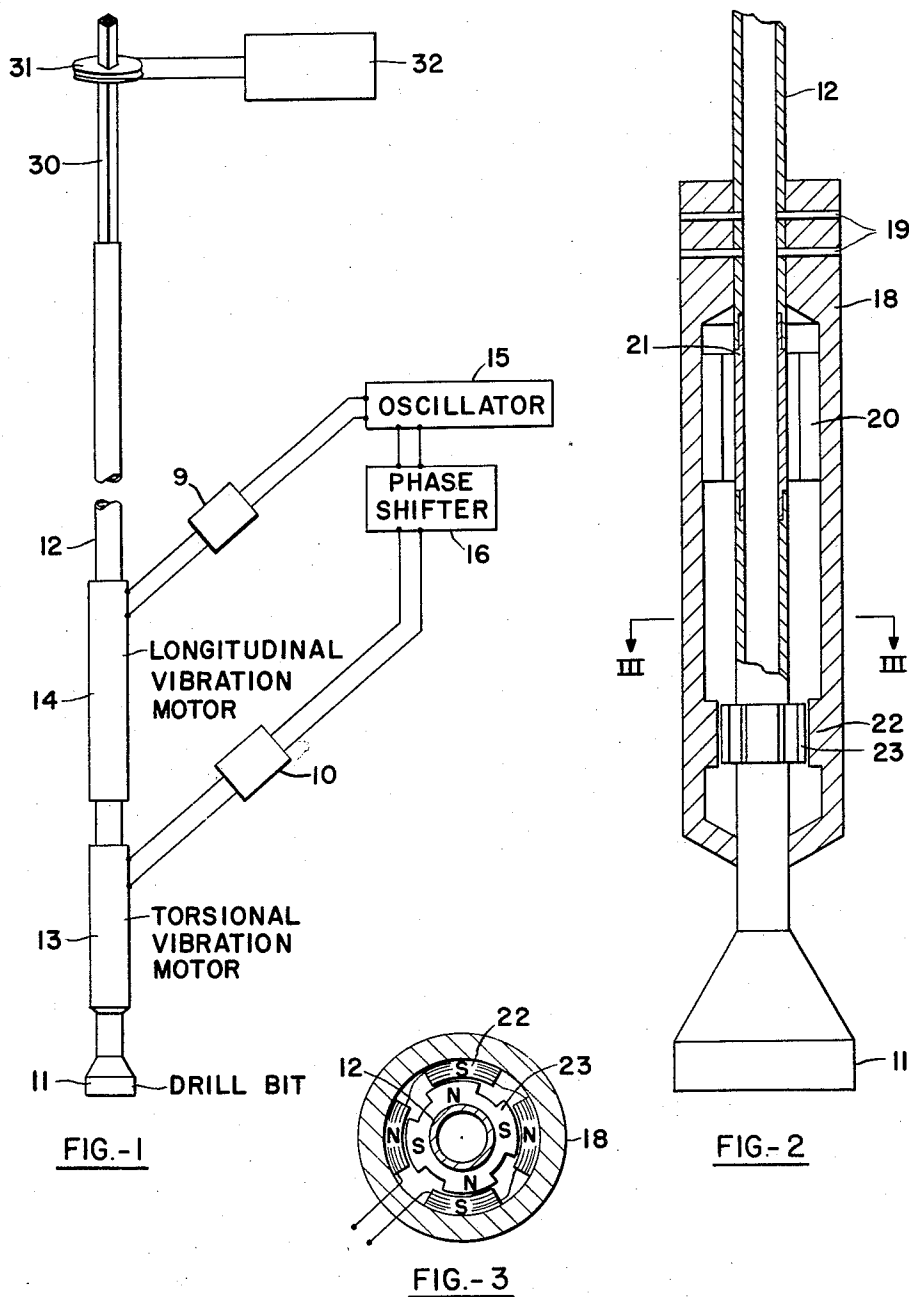
F. G. BOUCHER

2,911,192

VIBRATORY ROTARY DRILLING METHOD AND APPARATUS

Filed April 3, 1957

2 Sheets-Sheet 1



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VIBRATORY ROTARY DRILLING METHOD AND APPARATUS

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2 Sheets-Sheet 2

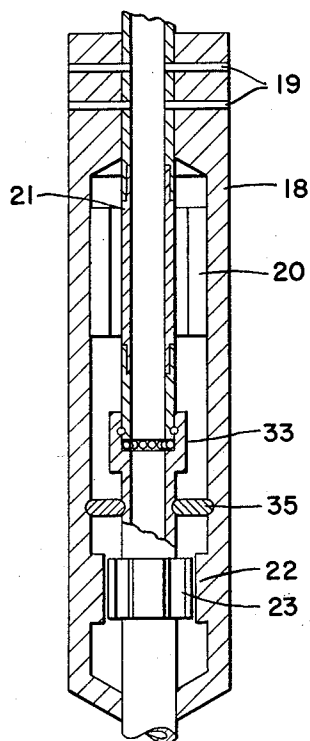


FIG.-4

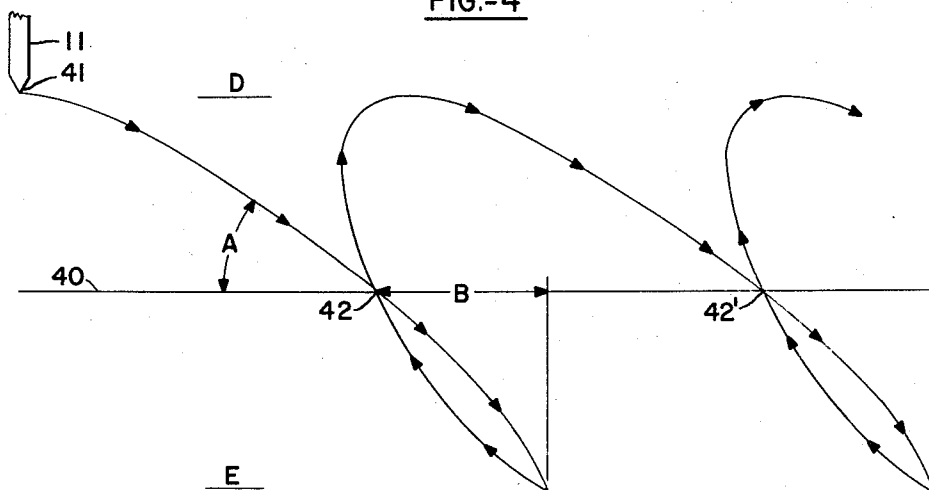


FIG.-5

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VIBRATORY ROTARY DRILLING METHOD AND APPARATUS

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Application April 3, 1957, Serial No. 650,386

17 Claims. (Cl. 255—1.8)

This invention concerns a method and apparatus for drilling a borehole in the earth. More particularly, the invention relates to a drilling method and apparatus which combines a longitudinal vibratory drilling action with a torsional vibratory drilling action. In an especially preferred form of the invention, a rotary drilling action is combined and coordinated with a percussive vibratory drilling action and a torsional vibratory drilling action. The invention finds particular application in drilling boreholes for petroleum exploration and production purposes.

This application is a continuation-in-part application based on Serial No. 394,423 filed in the name of Frank G. Boucher on November 25, 1953, now abandoned.

The principles of this invention may be appreciated by considering simple drilling tests. Thus, in shattering hard formations with a drill of the nature of the star drill, it can be readily established that the most effective penetrating force is achieved by imparting a combination torsional and percussive action to the drill bit. The resultant motion at the actual drill teeth or other cutting surfaces is downwardly inclined and results in an inclined force which serves to hammer and shear the formation encountered by the drill. Depending upon the composition of the formation to be drilled, the longitudinal and torsional components of the drill movement should be varied for best results. Again, depending on the composition of the formation to be drilled, the phase relationship between the downward and rotary motion of the drill should be varied. In this connection, it is a principal object of this invention to provide a simple and effective drilling apparatus capable of varying the phase and magnitude of the combined longitudinal and torsional vibrations that are applied to a drill bit. It is also an object of the invention to separately or jointly control the amplitudes of the vibrations.

In addition to the observation that a combination torsional and percussive action in a drill bit provides the most effective penetrating force, it has also been observed that other factors have pronounced effects upon the effectiveness and efficiency of a drilling apparatus or method. Furthermore, it has been found that these factors tend to differ markedly in their relative importance, depending upon the type of formation being drilled, the depth of the formation, etc.

Persons skilled in the art have long recognized that different operating conditions and equipment are desirable when encountering different types of formations beneath the earth. For example, in drilling any given borehole or well, it is not unusual to find that a wide range of bit loadings, a great variety of bit designs, and a wide range of bit rotation or impact frequencies must be employed. Some of these adjustments or changes may be made quite readily, but some of them entail great expenditures of time and money. For example, the task of changing a bit at the bottom of a drill string necessitates a great deal of pipe handling before the old bit can be removed from the drill string and replaced with a new one. Even then, the operator is never absolutely

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sure that the new bit will drill the formation of immediate interest with any greater degree of success than did the previous bit.

Accordingly, it is one object of the present invention to provide a drilling method and apparatus which is superior to existing apparatus and methods in its ability to drill effectively and efficiently through a wide variety of earth formations. It is another object of the invention to provide a drilling method and apparatus which is much more readily adapted to changing drilling conditions than are conventional apparatus and methods. It is still another object of the invention to greatly reduce the time and money that is presently required in drilling a borehole by greatly reducing the time required to ascertain and adjust to the best drilling conditions for various formations and structures that are penetrated by the borehole.

These and related objects, which will be explicitly described or readily apparent in the following description, are attained in accordance with the present invention by the use of a drilling apparatus and method which utilizes a longitudinal vibratory drilling action in combination with a torsional vibratory drilling action. The objects of the invention are even more completely realized by the utilization of a rotary-type drilling action in combination with the longitudinal and torsional vibratory actions just mentioned.

More specifically, the objects of the invention are realized in accordance with one embodiment of the invention by repeatedly impacting a drill bit or equivalent rock-cutting element against a formation while simultaneously imparting a rotatory vibrational motion to the bit. The frequency of the rotary or torsional vibrations is maintained equal to the frequency of the percussive or longitudinal vibrations; and the phase relationship between the two types of vibrations is adjusted and controlled as desired. Thus, when using a predetermined frequency of percussive and torsional vibrations in any given drilling operation, drilling efficiency and effectiveness are increased simply by shifting the phase relation between the two types of vibration. Preferably, the frequency of the two sets of vibrations is adjustable in value; and the over-all system is operated at the resonant frequency of the mechanical system. Furthermore, the amplitudes of the two sets of vibrations are also adjustable—either separately or jointly.

In accordance with a preferred and unique aspect of the invention, a drill bit is simultaneously and vibrationally twisted and percussed against a formation in the manner just described, while at the same time the bit receives a continuous rotational movement in one direction. In other words, the bit is subjected to a progressive rotational advance while combined torsional and longitudinal vibratory movements are imparted to the bit. As with the previous embodiment of the invention, the frequencies of the two types of vibrations are maintained identical; and the phase relation between the frequencies is adjusted to obtain the optimum angle of bit contact with the formation being drilled. Concurrently, the bit is rotated about its axis so that the bit progresses around the bottom of the borehole. This progressive rotational advance of the bit around the borehole may be referred to as "indexing," a factor which has been determined and observed to be very important in attaining effective and efficient drilling.

At this point, it is well to recapitulate briefly and to note that factors of major importance in obtaining good drilling results include: (1) the amount of load imparted to a bit, (2) the angle at which the loading is impacted upon the formation, (3) the indexing distance between successive impacts, (4) the frequency of the impacts, and (5) the general dynamics and kinematics of the drilling

system. It has also been observed that all of these factors are effected to a greater or less degree by the number and types of formations that a drilling operation encounters, thereby necessitating frequent and empirical changes or adjustments in the system. The present invention is especially characterized by its ability to quickly and effectively maximize or minimize these various factors as desired. This is especially true for the embodiment of the invention in which continuous rotary motion of a drill bit is combined with simultaneous torsional and percussive vibrations of the bit.

The invention may be better understood by reference to the attached drawing in which:

Figure 1 diagrammatically illustrates the major components of a drilling apparatus which embodies the principles of this invention;

Figure 2 diagrammatically shows in cross-sectional elevation a suitable form for the longitudinal and torsional vibration motors that may be used in the invention;

Figure 3 is a cross-sectional view of Figure 2 taken along the line III—III and showing a particular arrangement of the torsional vibration motor;

Figure 4 diagrammatically shows in cross-sectional elevation another suitable arrangement for the longitudinal and torsional vibration motors that may be used in the invention;

Figure 5 schematically illustrates the action of a bit cutting element when it is rotated and simultaneously vibrated—both torsionally and longitudinally—in accordance with this invention.

The general drilling apparatus illustrated in Figure 1 comprises a drill bit 11 supported by a drill string 12 of conventional nature extending upward within a borehole to the surface of the earth. The drill bit may be any conventional type of rock bit such as a multi-cone rotary bit; but it is preferably of a type resembling a star drill, a chisel-type bit, or the like. For the purpose of this description it will be assumed that the drill bit illustrated in the drawing is a chisel-type bit. As pointed out above, the bit must be of a nature to withstand repeated percussions against a rock surface; and it is therefore preferably a percussive-type structure.

The drill string 12 may comprise the usual type of drill pipe or drill collars that are employed in drilling operations to support a bit and to transfer forces to the bit. In a preferred version of the invention, the upper end of the drill string 12 terminates in a kelly 30. The kelly passes through and engages the rotary table 31 which is driven by a conventional rotary-drive mechanism 32. The latter mechanism may be any conventional diesel, electric, steam, or other suitable and available source of power. Other conventional pieces of drilling equipment which may be used with the apparatus in Figure 1—but which are not illustrated in the figure for the sake of simplicity and clarity of presentation—include the usual derrick, drawworks, mud pumps, casing, swivel, cables, and the like.

Fixed to and about the lower portion of the drill string 12—preferably immediately above the drill bit 11—is a torsional vibration motor 13. This motor is adapted to vibrate the drill bit 11 in a torsional manner relative to its axis.

Positioned above—and also preferably near the drill bit 11—is a longitudinal vibration motor 14 which is adapted to vibrate the drill bit in an upward and downward manner within the borehole.

As illustrated in Figure 1, a single oscillator or equivalent drive means 15 may be employed to energize both vibration motors simultaneously. The oscillator may constitute an A.C. generator, or it may constitute an electronic voltage source—depending upon the frequency which is selected for operation of the two motors.

As noted above, both motors are preferably positioned just above the drill bit 11 in the borehole being drilled. The oscillator, generator, or other drive means 15 is

preferably positioned at the surface of the earth for ease of operation. Standard electrical cables and the like may be used to convey power from the oscillator 15 to the motors, and slip rings or equivalent devices may be used as necessary or desirable to enable the cables to remain stationary relative to a rotating drill string. Variable resistors or equivalent power control means 9 and 10 may be used to adjust the amplitudes of the vibrations of the longitudinal vibration motor 14 and the torsional vibration motor 13, respectively.

The oscillator 15 may be directly connected to one of the vibration motors, but it is preferably connected through a phase shifting means 16 to the other of the two motors. A conventional phase-shift system may be used and is not described herein, as this is not in itself the subject of this invention.

In employing this apparatus, it is simplest to determine the optimum frequency of vibration and the optimum relative phase between the longitudinal and torsional vibrations by experimentation directly at the actual drilling site. Ordinarily, the frequency of vibration in each instance will be fixed by design considerations relating to the type of longitudinal or torsional vibration motors employed. In this connection, the length and thickness of the drill string and associated elements are selected so that both the torsional and longitudinal vibration motors can be operated preferably at the resonant frequency of the mechanical system comprising the drill string and drill bit assembly.

As previously noted, a critical variable in drilling efficiency in this invention is the phase relation between the activation of the two vibration motors. This is preferably adjusted by trial and error until an optimum drilling rate is attained. In general, it may be stated that the torsional vibration should somewhat lag the longitudinal vibration in order to secure the best drilling efficiency, the exact phase relation depending as stated upon the particular nature of the formation encountered.

In employing the principles of this invention, a wide variety of mechanical drive means may be employed. Illustrated in Figure 2, however, is a preferred form of the invention. Here, both the longitudinal and torsional vibration motors are supported within a sleeve element 18 which is fixed to and about the drill string 12 at the upper portion of the sleeve 18 by means of suitable pins 19 or equivalent locking devices.

The longitudinal vibration motor shown in Figure 2 comprises a section of pipe or equivalent conduit 21 which is constructed of magneto-strictive metal in combination with a coil 20 encircling the magneto-strictive section. The length of magneto-strictive metal is inserted within the drill string 12 and forms a part thereof. It is preferably joined to other conduit members of the drill string by conventional coupling means.

The coil 20 is supported by the sleeve 18 and is preferably insulated therefrom. Thus, as illustrated, a nickel coupling tube 21 may be fixed in the drill string 12 so as to be disposed within the electrical field created by energizing the coil 20. Application of a suitable oscillatory current to coil 20 therefore causes the magneto-strictive tube to vary in its length so as to longitudinally vibrate the lower portion of the drill string 12 and its attached bit 11. Alternatively, a pulsing-type current may be used to energize the magneto-strictive motor.

The torsional vibration motor employed in Figure 2 constitutes electromagnetic poles positioned and supported on the inside of sleeve 18 in combination with suitable magnetic armatures fixed to the drill string 12. The electro-magnetic poles are generally indicated by the legend 22, and the armature fixed to the drill pipe 12 is indicated by numeral 23. This arrangement is better illustrated and more apparent in Figure 3 which shows a cross section of the apparatus in Figure 2 taken at a position slightly above the torsional vibration motor. As indicated, the sleeve 18 is secured to the drill string 12

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by the pins 19 in a manner such that the relative position between the electro-magnetic poles 22 and the armature 23 is normally as illustrated in Figure 3—i.e., in the absence of energization of the motor. Consequently, when current is supplied to the electro-magnetic poles 22, a torque is applied to drill string 12 as the armature is pulled by the poles. In the form of the invention illustrated in Figure 2, torsional movement of the drill pipe is possible simply by exerting a torque on the pipe. This twisting in itself creates a restoration force within the drill pipe which causes the motor to return to the normal position illustrated in Figure 3 between periods of activation.

An alternative arrangement which may be used between the longitudinal and torsional vibration motors of Figure 2 to permit free rotation of the drill pipe is illustrated diagrammatically in Figure 4 and includes a rotary coupling 33 which is inserted in the drill string between the torsional and longitudinal vibration motors. The rotary coupling enables the section of the drill pipe which is attached to the drill bit 11 (not shown in Figure 4) to be torsionally vibrated relative to the portion of the drill pipe which extends through the longitudinal vibratory motor, while yet enabling the entire length of drill pipe to be vibrated longitudinally by the latter motor. In this instance, leaf springs or equivalent spring elements 35 which engage both the drill pipe and the sleeve 18 are preferably employed to bias the armature and field of the torsional vibration motor in the position shown in Figure 3.

As explained earlier, the present invention may be used in conjunction with the usual provisions for circulating drilling mud within a borehole. Thus, drilling mud may be passed downwardly through the drill string 12 and thence through the magneto-strictive section 21 to the drill bit 11 in a conventional manner. Fluid passages including jets and the like may be provided within the bit to enhance drilling efficiency and effectiveness. It will also be noted that amplifying equipment may be used between each vibration motor and the oscillator 15 as necessary to supply ample power to the motors. Again, it will be recognized that two separate electrical drive means may be employed—one for each vibration—provided suitable means are also used to synchronize the two drive means and to vary the phase between them.

To recapitulate briefly, then, it is necessary in the present invention to employ a drilling structure which includes a drill bit in conjunction with a torsional vibration motor and a longitudinal vibration motor. The two motors are driven at the same frequency by joint or separate drive means, and adjustable phase-shifting means is provided to vary the phase relation between the two types of vibrations to obtain optimum drilling conditions. The apparatus of the invention further includes suitable drill pipe or equivalent means for supporting the drill bit and the vibration motors within a borehole. The vibratory driving means, i.e., the means for supplying power to the vibratory motors, and the phase-shifting means are preferably located at the top of the borehole to facilitate their control and adjustment.

In an especially preferred version of the invention, the apparatus of the invention also includes means for rotating the drill bit steadily in one direction simultaneously with the longitudinal and torsional vibrations. As noted earlier, conventional rotary drilling equipment including rotary tables and the like may be used for this aspect of the invention.

Having generally outlined the structural aspects of this invention, attention is now directed briefly toward a consideration of the best mode contemplated for carrying out the operation of the invention. As noted earlier, it is considered that the best operating conditions for any given rock formation are best ascertained directly while drilling the formation rather than any method of prede-

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termination. Rock formations in the earth vary so greatly from one stratum to another and even within any given stratum that it is difficult to accurately predict what type of drilling conditions are optimum in any given instance. Just as with presently conventional drilling techniques, it is expected that the best drilling conditions to be followed in practicing the present invention may be determined directly at the drilling site. It is, in this connection, a particular advantage and feature of this invention that the equipment and the process may be very easily and quickly adapted to whatever conditions are necessary to provide the most efficient and effective drilling results possible.

While empirical procedures are contemplated to be the best and most practical way of ascertaining the best drilling conditions to be observed in this invention, nevertheless it is contemplated that several basic principles may be enunciated. And, to facilitate such a discussion, attention is directed to Figure 5 of the drawing wherein a kinematic chart has been prepared showing the motion of a fixed point on a drill bit which is subject to simultaneous continuous rotation as well as longitudinal and torsional vibrations. Figure 5 is a portion of an expanded view of the circular path that a point on the periphery of the bit describes in rotating around the axis of the bit—i.e., the axis of the borehole. In this figure, the legend 40 depicts the centerline of the vertical or longitudinal vibrations of the bit. If it is assumed that the bit contacts a formation for 50 percent of the time, then legend 40 in a sense corresponds to the surface of the formation underlying a borehole. The legend 41 depicts a point on a cutting surface of the bit 11. Rotational movement of the bit and the point 41 around the borehole is indicated by the arrows.

Point 41 of the bit 11 in Figure 5 vibrates vertically—i.e., longitudinally—between the two limits identified by the legends D and E. It also vibrates torsionally—i.e., laterally in the expanded view shown in Figure 5—but this action is masked in the figure by virtue of the simultaneous uniform rotation of the drill pipe. In any event, point 41, as it rotates around the borehole, progresses downwardly until it encounters formation 40 at the point 42. At this instant, it exerts a thrust vertically into the formation as well as longitudinally in a forward direction. The maximum forward penetration of the point 41 within the formation is indicated by the legend B. Then, depending upon the relative magnitudes and the phase relation between the torsional and longitudinal vibration frequencies, the bit removes itself from the formation and—as shown in Figure 5—may actually pass the level 40 at a point identical to the point of entry. The angle at which the point 41 engages the formation 40 is indicated by the legend A.

In view of the fact that the present invention may be varied in its operation throughout a wide range of operating variables, it will be recognized that a very large number of cutting actions—such as shown in Figure 5—may be realized. Thus, the value of the entering angle A may be adjusted by either adjusting the phase relation between the longitudinal and torsional vibrations or by changing the rotational speed of the drill bit. Changes in the angle of entry may also be readily realized by simply changing the relative amplitudes of the two types of vibrational movement.

Control of the rotational speed of the bit also makes it possible to vary as desired the indexing distance between successive points of impact 42 and 42'. As explained earlier in this description, it has been observed that the indexing distance in a drilling operation has a very marked effect upon the efficiency and effectiveness of the drilling results.

It is also of interest at this point to note that continuous rotation of a bit in conjunction with longitudinal and torsional vibrations of the bit enables the bit in time to engage substantially all portions of a formation under-

lying the borehole. It is not expected that any particular effort need be made to coordinate rotational movement of the bit with the vibratory movements for the purpose of deliberately obtaining uniform contacting between the bit and a formation, since minor variations in drill string elasticity normally occurring during drilling operations will generally suffice to insure such a result.

Still referring to Figure 5, it will be recognized that the amount of time that a bit is in contact with a formation may be controlled to a degree by simply raising or lowering the bit within the borehole overlying the formation. In the figure, the bit is shown to be in contact with the formation for approximately 50 percent of the time.

It will also be recognized in Figure 5 that the points at which a bit enters and leaves the formation 40 may be adjusted by changing the phase relation between the torsional and longitudinal vibratory movements of the bit. As noted earlier, a phase relation in which the horizontal vibrations follow the longitudinal vibrations in time is preferred for the purposes of the invention. By way of definition, it may be noted that—for the purposes of the present description—the longitudinal and torsional vibrations of a bit are considered to be in phase with one another (relative to the longitudinal vibrations) when the bit is simultaneously at the extreme points of the two vibrational movements. For example, the vibrational frequencies are defined to be in phase when the bit is at the lowermost limit of its longitudinal vibrations, when it is also at the extreme position of its torsional vibrations said extreme position being directed from the midpoint of the torsional vibrations in the direction of drill pipe rotation. The phase angles between the two types of vibrations are measured relative to the longitudinal vibrations.

As an example of the manner in which this invention may be carried out, the following conditions are given for drilling a 9 $\frac{5}{8}$ -inch diameter borehole in Oklahoma marble. From analyses made on this material, it is contemplated that the optimum impact angle for a bit to percuss against such material is from about 70 to 90 degrees with respect to the surface of the marble. Very effective drilling results should be obtained when using a horizontal and vertical vibratory frequency of 300 cycles per second with a 60 r.p.m. uniform rotation when using the following combinations of phase angles and horizontal-to-vertical amplitude ratios. The maximum amplitude in all instances is assumed to be 0.1 inch.

Horizontal/vertical amplitude ratios:	Phase angle
1.0 -----	80° lag. to 110° lag.
0.66 -----	80° lag. to 120° lag.
0.33 -----	60° lag. to 180° lag.

These and other studies indicate that the following ranges of operating conditions appear to be suitable for use in drilling various types of rock formations.

- (1) Phase angles: 60° lead to 240° lag (with reference to vertical).
- (2) Vibrational frequencies: 10 c.p.s. to 600 c.p.s.
- (3) Vibrational amplitudes: 0.01 inch to 0.50 inch.
- (4) Rotational speeds: 20 r.p.m. to 400 r.p.m.

While the invention has thus been described with reference to specific ranges of operating conditions and preferred embodiments of the invention, it is apparent that other forms of the invention may also be used without departing from the spirit or scope thereof. In order to obtain the benefits of the invention, it is necessary only to apply suitable longitudinal and torsional drive means to a drill bit. As indicated earlier, it is especially preferred to superimpose a steady rotational movement on the drill bit, since extremely attractive and flexible drilling conditions and operations may thereby be obtained. In using the principles of the invention, it is

extremely important to properly phase the torsional and longitudinal vibrations of the drill so as to obtain the best drilling results. It is specifically contemplated that operating conditions (i.e.—phase angles, vibration frequencies, amplitudes, etc.) other than those within the ranges set forth above may be employed without departing from the scope of this invention.

The invention claimed is:

1. A drilling apparatus comprising in combination a drill bit, first reciprocative drive means fixed to said drill bit and adapted to longitudinally oscillate said drill bit, second reciprocative drive means fixed to said drill bit and adapted to torsionally oscillate said drill bit, said first and second drive means having the same drive frequency, and means to vary the phase between the longitudinal and torsional oscillations developed by said first and second drive means.
2. A drilling apparatus comprising in combination a drill bit, first reciprocating drive means positioned near said bit and adapted to drive said bit in a longitudinal vibratory manner, second reciprocating drive means positioned near said bit and operable simultaneously with said first drive means and adapted to drive said bit in a torsional vibratory manner, means to control the frequencies of both said drive means at equal values, and means to control the phase relation between the vibrations developed by said two drive means.
3. A drilling apparatus for drilling boreholes, comprising in combination a drill bit, first reciprocative drive means positioned within said borehole and adapted to vibrate said bit longitudinally, second reciprocative drive means positioned within said borehole and adapted to vibrate said bit torsionally, said first and second drive means vibrating said bit simultaneously and at equal frequencies, and means to control the phase relation between the vibrations developed by the two drive means.
4. In a drilling apparatus, the combination which comprises a drill bit, means positioned near said bit for longitudinally vibrating said bit, means positioned near said bit for simultaneously torsionally vibrating said bit, means for controlling said longitudinal vibrations and said torsional vibrations at equal frequencies, and phase-shift means to control the phase relation between said longitudinal and said torsional vibrations.
5. In a method of drilling a borehole through the earth by means of a drill bit, the improvement which comprises in combination vibrationally percussing the bit against the earth, simultaneously torsionally vibrating the bit, maintaining the percussive frequency equal to the torsional frequency, and shifting the phase relation between the percussive vibrations and the torsional vibrations.
6. In a method of drilling a borehole within the earth by means of a drill bit, the improvement which comprises vibrating the bit against the earth in a percussive manner, simultaneously vibrating the bit in a torsional manner, maintaining the percussive and torsional vibrations equal to one another in frequency, and shifting the phase relation between the percussive and vibrational frequencies.
7. An apparatus for drilling a borehole in the earth which comprises a drill bit, a first reciprocative motor positioned near said bit and adapted to percuss said bit vibrationally against the bottom of the hole, a second reciprocative motor positioned near said bit and adapted to vibrate said bit torsionally, means connected to each motor to drive both motors simultaneously and thereby drive said bit against the borehole bottom in a combined torsional-percussive manner, and means for shifting the phase relation between the two vibrations.
8. An apparatus for drilling a borehole in the earth comprising a drill string, a drill bit attachable to the lower end of the drill string, a sleeve surrounding the lower portion of said drill string and attached near its upper end to said drill string, first reciprocative drive

means mounted on said sleeve and said drill string to vibrate said bit longitudinally relative to said sleeve, second reciprocative drive means mounted on said sleeve and said drill string and adapted to vibrate said bit torsionally relative to said sleeve, means for maintaining the frequencies of said torsional and said longitudinal vibrations equal to one another, and means for phasing one of said types of vibrations relative to the other type of vibrations.

9. A method of drilling a borehole in the earth which comprises striking the earth with simultaneous percussive and torsional vibrations, maintaining the frequencies of the percussive and torsional vibrations equal to one another, varying the phase between the percussive and torsional vibrations, and superimposing a continuous rotational movement upon the percussive and torsional vibrations within the borehole.

10. In a method of drilling a borehole within the earth by means of a drill bit, the improvement which comprises vibrating the bit against the earth in a percussive manner, simultaneously vibrating the bit in a torsional manner, maintaining the percussive and torsional vibrations equal to one another in frequency, shifting the phase relation between the percussive and vibrational frequencies, and continuously rotating the bit.

11. A drilling apparatus comprising in combination a drill bit, first reciprocative longitudinal drive means fixed to said drill bit and adapted to longitudinally oscillate the drill bit, second reciprocative drive means fixed to said drill bit and adapted to oscillate said drill bit torsionally, said first and second drive means having the same operating frequency, means to vary the phase between the longitudinal and torsional oscillations developed by said first and second drive means, and rotary drive means adapted to rotate said drill bit.

12. In a drilling apparatus, the combination which comprises a drill bit, means effectively connected to the bit for longitudinally vibrating said bit, means effectively connected to the bit for simultaneously torsionally vibrating said bit, means for controlling said longitudinal vibrations and said torsional vibrations at the same frequency, phase-shift means to control the phase relation between said longitudinal and said torsional vibrations, and means to rotate said drill bit.

13. An apparatus for drilling a borehole in the earth comprising a drill string, a drill bit attachable to the lower end of the drill string, a sleeve surrounding the lower portion of said drill string and attached near its upper end to the drill string, first reciprocative drive means mounted on said sleeve and said drill string adapted to vibrate said bit longitudinally relative to said sleeve, second reciprocative drive means mounted on said sleeve and said drill string and adapted to vibrate said bit torsionally relative to said sleeve, means for maintaining the torsional and longitudinal vibrations at the same frequency, means for phasing one of the types of vibrations relative to the other type of vibrations, and means to rotate said bit continuously in one direction.

14. In a drilling apparatus including a drill string and a drill bit attached to the lower end thereof, the improvement which comprises means to rotate said bit in one direction, first reciprocating drive means supported by said drill string and adapted to vibrate said bit longitudinally relative to said drill string, second reciprocative drive means supported by said drill string and adapted to vibrate said bit torsionally relative to the drill string, means to operate said first and second reciprocative drive means at the same vibrational frequency, means to adjust the phase relation between the frequencies of said first and second reciprocative drive means.

15. An apparatus as defined in claim 1 including means to vary the amplitude of the vibrations of at least one of said reciprocative drive means.

16. A method as defined in claim 10 in which the amplitude of at least one type of vibrations is varied.

17. An apparatus as defined in claim 11 including means to vary the amplitude of one of said types of vibrations.

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