This invention relates to the drilling of boreholes in the earth. More particularly, the invention is concerned with drilling apparatus in which a periodic percussive force is applied to the rock bit, or other cutting element, while the bit is being rotated in a conventional manner. Specifically, the invention relates to rotary percussive drilling apparatus wherein a resonant hammer mechanism is actuated by dynamic vertical oscillatory motions generated by rotating the bit against rock formations.

It is well known that the addition of percussive forces to the bit during rotary drilling greatly increases the penetration rate, particularly when hard rock formations are being drilled. A number of devices have been disclosed for generating such percussion action. One such device is the hammer, or self-hit, wherein an auxiliary hammer is used to impart additional percussion to the bit. Various means have been suggested for providing automatic hammering action simply by providing a pendulum or shock mechanism to strike the bit against the borehole bottom, since a cone of conventional design undergoes one and one-half revolutions about its own axis during each revolution of the bit assembly. The amplitude of each such displacement is determined by the difference between that elevation of the bit assembly which corresponds to the simultaneous contact of two rows of teeth with the borehole bottom, and that elevation which corresponds to the contact of a single row of teeth with the borehole bottom at the time when the axis of the cone lies directly above the point of contact.

It is particularly significant that the amplitude of the hammer stroke at resonance is greater than the amplitude of the displacement which actuates or excites the spring-hammer system.

Although a spring-mass system of suitable design is readily actuated or excited by the vertical displacement amplitudes characteristic of a conventional roller cone bit, a preferred embodiment of the invention comprises the combination of a spring-mass system with a special vibratory bit, or "vibrabit," capable of generating high-amplitude, periodic displacements.

In accordance with one embodiment of the invention, the vibrabrammer is incorporated in a drill string immediately above the bit, and a vibration isolator or filter is placed just above the hammer. This embodiment minimizes the transfer of vibrations generated at the bit-rock interface to the remainder of the drill string and other equipment at the surface.

On the other hand, by placing the vibration filter or "vibrofilter" a critically selected distance above the bit, it is possible to utilize the natural resonance of a length of drill pipe or collar intermediate the bit and vibrofilter to supplement the percussive force generated by the hammer mechanism. The vibrabrammer in this embodiment is located immediately above the bit, and the vibration filter is located at a level in the drill string such that the length of the drill pipe or collar intermediate the filter and the bit corresponds to:

$$L = \frac{V}{4f}$$

where \(L\) is length, \(V\) is the velocity of the compressional wave generated in the drill string, and \(f\) is the frequency of vibration characteristic of the spring-mass system, which is tuned to the forcing frequency of the bit.

A still further embodiment of the invention again places the vibrofilter in the drill string above the vibrabit, such that the length of drill pipe or collar intermediate the two is equal to \(V/4f\). In this embodiment the vibrabrammer is placed immediately below the vibrofilter.

FIGURE 1 is a longitudinal sectional view of the self-excited hammer device of the invention.

FIGURE 2 is a transverse sectional view of the tool, taken along the line 2-2 of FIGURE 1.

FIGURE 3 is a transverse sectional view of a roller cone of the vibrabit taken along line 3-3 of FIGURE 1.

FIGURE 4 is a transverse sectional view of a special drill bit roller cone, having a preferred configuration for generating dynamic oscillatory motions upon successive contacts with the borehole bottom.

FIGURE 5 illustrates an embodiment of the invention which corresponds to the embodiment of FIGURE 1, in combination with a vibration filter located a critically selected distance above the bit.

FIGURE 6 is a graphic representation of variations in bit load versus time, corresponding to the operation of the combination illustrated in FIGURE 5.

FIGURE 7 illustrates an embodiment of the invention wherein the percussive hammer is located a substantial distance above the vibrabit at a critically selected level in
the drill string, in combination with a vibration filter immediately thereabove.

FIGURE 8 is a graphic illustration of load variations experienced by the bit during the operation of the embodiment illustrated by FIGURE 7.

FIGURE 9 illustrates an embodiment of the invention wherein a vibration filter is located immediately above the percussive mechanism, which in turn is located immediately above a vibribit.

FIGURE 10 is a graphic illustration of load variations experienced by the bit in the operation of the embodiment shown in FIGURE 9.

Referring specifically to FIGURE 1, the illustrated embodiment of the invention includes thick-walled tubular elements 11 and 12 having thread box 13 at one end and threaded pin 14 at the opposite end, for connection in a conventional drill string. Annular space or chamber 15 is thereby provided between the walls of the tool, wherein hammer 16 is suspended by means of coil springs 17 and 18.

Hammer 16 is an annular mass having an upper shoulder 19 and a lower shoulder 20, engaging springs 17 and 18 respectively. In operation, hammer 16 generates a percussive force by repeatedly striking anvil 21. The "air cushion" effect experienced by conventional air hammer drills is preferably eliminated in the present tool by evacuating chamber 15.

Bit assembly 22, including roller cones 23, is shown adjacent to the hammer means. However, other embodiments of the invention place the vibrammer elsewhere within the drill string, as hereinafter described. Any conventional rotary bit may be used in combination with the novel vibramer of the invention. However, a vibratory bit designed to induce relatively large, periodic dynamic vertical oscillations in the drill string as it is rotated at a constant speed during its normal operation, is preferably employed.

FIGURE 2 illustrates the relative simplicity of the central section of the vibrammer. At this level the device consists essentially of three coaxial tubular members. The outer member 11 and inner member 12 remain relatively fixed, while hammer 16 is induced during operation to undergo vigorous vertical oscillatory motion, striking anvil 21 with a frequency which corresponds to that of the bit assembly. Longitudinal grooves 24 are provided in the hammer to facilitate the flow of air within chamber 15 caused by each stroke of the hammer, in case the chamber is not completely evacuated.

FIGURE 3 illustrates a suitable vibratory configuration of teeth in a rotary cone bit drill. In operation, the contact of successive axial rows of cutter teeth with the borehole bottom causes a rhythmic rise and fall of the bit assembly, which motion is transmitted up the drill string to the spring-annul system of the invention. The amplitude of each vertical displacement is the distance between arrows d₁.

FIGURE 4 is a transverse sectional view of another preferred type of cutting element used in a vibratory roller-cone bit for the generation of dynamic vertical oscillations substantially greater than can be obtained with conventional roller-cone bits. Whereas a conventional roller-cone bit has right circular conical cutter elements with teeth situated in a rather random order, the cone illustrated in FIGURE 4 is substantially hexagonal. Each row of cutter teeth has a triangularoid configuration. Heel teeth row 31 is 60° "out of phase" with the adjacent row of teeth 32. The third row and successive alternate rows, if any, are aligned with the heel row, while any remaining rows are aligned with row 32. Conical cutters having this arrangement cause six vertical displacements of amplitude d₂ per revolution, and therefore generate nine such displacements for each revolution of the complete bit assembly. It is also possible to generate suitable displacements by employing conical cutting elements having tooth configurations which would generate a higher frequency of vertical displacements per revolution. However, this could be accomplished only by sacrificing the maximum amplitude delivered by the bit. It is considered optimum to maintain a relative low amplitude with a low number of displacements per revolution of the bit assembly, since increased frequency is readily obtained by increasing the rate at which the drill string is rotated. Thus, for example in using hexagonal cones, as illustrated by FIGURE 4, rotation of the bit assembly at 60 r.p.m. generates 540 vertical displacements of amplitude d₂ per minute, when all cones are in phase. Accordingly, a mass-spring-annul system characterized by a natural resonant frequency of 540 cycles per minute would be stimulated optimally by rotating such a drill bit at 60 r.p.m.

It is significant that the axial rows of teeth in the cone of FIGURE 4 also impart relatively low amplitude, high-frequency displacements to the bit action, in addition to the major displacements of amplitude d₁. This secondary vibration is of little consequence, however, since the vibrammer "sees" only those displacements having a frequency which matches, or substantially matches the natural resonant frequency of the spring-hammer system.

An additional example of a suitable vibratory bit is disclosed in a copending application of Othar M. Kiel, Serial No. 119,105 filed June 23, 1961, now Patent No. 3,126,973.

FIGURES 5 and 6 illustrate an embodiment of the invention wherein vibrammer 41 is employed in combination with a vibribit 42 such as illustrated by FIGURE 4, and also in combination with a vibrofilter or shock isolator 43 of known design, an example of which is described in U.S. 3,099,918. The location of the shock isolator is selected to provide a length of drill pipe or drill collar 44 intermediate the vibribit and the vibrofilter corresponding to the following equation:

\[ L = \frac{\sqrt{V}}{f} \]

where \( L \) is the length of drill pipe or collar, \( V \) is the velocity at which a compressional wave is propagated in the drill pipe or collar, and \( f \) is the vibration frequency. In this embodiment, as before, the drill string is rotated at a particular speed whereby the number of vertical displacements per second generated by the bit corresponds to the natural resonant frequency of the vibrahammer. In addition to the percussive force generated by the hammer, there is a supplementary force generated by the resonant length of drill pipe or collar.

Referring specifically to FIGURE 6, the curve representing variations in bit load versus time is generally sinusoidal. However, when resonance is achieved in the vibrahammer and in the length of drill pipe 44 (FIGURE 5), the impact of the hammer plus the impact of the vibrating drill collar generates a sharp pulse 51 coincident with each maximum of the base curve. It is of particular significance that the percussive impacts do coincide with these maxima, since it is known that increased penetration rate from percussive impact can be achieved only by generating dynamic loads which exceed the maximum load obtained in the absence of percussive impact.

The embodiment of FIGURE 7 is distinguished from that of FIGURE 5 by locating vibrahammer 41 at the upper, rather than the lower end of a resonant length of drill pipe or drill collar. In the operation of this embodiment, the drill string and bit are rotated at a speed which generates a frequency of vertical dynamic displacements at the vibribit which corresponds to the natural resonant character of the vibrahammer, as well as that of the drill pipe or drill collar 44 intermediate the bit and the vibrofilter 43. Similarly, as in the embodiment of FIGURE 5, the force generated by the hammer mechanism is supplemented by the force generated in the resonating column of drill pipe. There are two important distinctions, however, over the previous embodiment. First, the actuating displacement amplitude which serves to excite the ham-
The percussive mechanism is increased by an amplification factor larger than one, depending on isolator stiffness and collar size. Thus the percussive force which can be developed in the hammer is increased by approximately the same amplification factor. But the impact reaches the bit out of phase with the normal load variations stimulated by the bit and the resonating column. That is, the percussive impact reaches the bit at the minimum rather than the maximum dynamic load.

Since the amplitude of displacements reaching the vibrohammer may be six-fold greater than the vibrations generated by the bit, it follows that the force potentially generated by percussive impact of the hammer is approximately six-fold greater than can be achieved by operating in accordance with the embodiment of FIGURE 5. It does not follow, however, that the embodiment of FIGURE 7 can generate a dynamic load variation six-fold greater than the embodiment of FIGURE 5, since the percussive load is out of phase with the static load variations achieved in the absence of percussive impact. This is graphically illustrated by FIGURE 8 which shows the percussive load peak 61 to be coincident with the sinusoidal minima, rather than the maxima as shown in FIGURE 6. Thus it becomes apparent that the embodiment of FIGURE 7 is not always superior to the embodiment of FIGURE 5.

FIGURES 9 and 10 illustrate still another embodiment of the invention, wherein vibrofilter 43 is located immediately above the vibrohammer 41, which in turn is located immediately above a vibratory bit 42, preferably as illustrated in FIGURE 4. This embodiment has the desirable feature of isolating the percussive vibrations in the immediate vicinity of the drill bit, thereby minimizing dynamic stresses in the lower sections of drill pipe or drill collar. This prolongs the life of the lower drill string, although possibly at the expense of penetration rate.

Referring specifically to the graph of FIGURE 10 it is significant that the percussive peaks 71 are coincident with maximum loads obtained in the absence of percussive impact. In this regard the load curve of FIGURE 10 is similar to that of FIGURE 6, differing essentially in that load variations are minimized.

As a specific example of the invention, hammer 16 (FIGURE 1) is constructed of steel having a density of 488 lbs. per cu. ft. It has an outside diameter of 6.5 inches, an inside diameter of 3.5 inches, a height of 45 inches, and weighs approximately 300 lbs. Each of springs 17 and 18 has a nominal coil diameter of 5 inches, and is comprised of 4 coils of 0.8 in. diameter steel wire. The stiffness of each spring is 1240 lbs. per inch, and the resonant frequency of the system is 540 cycles per minute.

While various embodiments have been specifically described, other variations and modifications will occur to those skilled in the art, without departing from the proper scope and spirit of the invention.

What is claimed is:

1. A percussive force generator adapted for rigid connection in a rotary drill string, comprising two substantially coaxial tubular walls forming a closed annular chamber, anvil means at the lower end of said chamber, spring means within said chamber, and hammer means suspended by said spring means within said chamber in a position to strike said anvil means, said chamber being free of any obstruction to a resonant action of said spring and hammer.

2. A self-resonating hammer and anvil system comprising a thick-walled tubular body member adapted for rigid connection in a rotary drill string, the wall of said body member having an annular chamber therein; an annular hammer suspended within said chamber near the lower boundary thereof; and spring means within said chamber supporting said hammer, said spring means and hammer being free of any obstruction to a resonating motion.

3. A rotary percussive drilling apparatus comprising a tubular drill column, a rotary drill bit attached to the end of the column, said bit comprising means for imparting to said tubular drill column an axial vibratory oscillation upon rotation of said drill column about a borehole bottom, and a percussive force generator within said drill column, said generator comprising anvil means; hammer means suspended in a position to strike said anvil means; and spring means supporting said hammer means; said generator being capable of resonating at a frequency inducible by the operation of said bit.

4. A rotary percussive drill string assembly comprising a tubular drill column, a vibratory drill bit comprising means for inducing axial vibrations in said drill column upon rotation against a borehole bottom, and a percussive force generator within said column adapted to resonate at the frequency of vibrations induced by the operation of said bit, said generator comprising anvil means; hammer means suspended in a position to strike said anvil means; and means for transmitting said axial vibratory oscillations from said drill column to said hammer means, said means for transmitting said oscillations being capable of causing said hammer means to strike said anvil means repeatedly and to resonate with the frequency of vibrations induced by the operation of said bit.

5. A rotary drilling apparatus comprising a tubular drill column, a vibrofilter, a vibrabit attached to the end of said drill column and comprising means for imparting axial vibratory displacements to said drill column upon rotation against a borehole bottom, and a percussive force generator intermediate said filter and said bit, said percussive force generator comprising anvil means; hammer means; and spring means engaging said drill column, and said hammer means for transmitting said vibrating displacements from said drill column to said hammer means; said spring means having a natural resonant frequency within the range corresponding to the number of vertical displacements generated by rotating said vibra bit 30-300 r.p.m.

6. A tubular drill column comprising a vibra bit, a vibrofilter, and a vibrohammer intermediate said bit and filter; said vibra bit comprising a body and a plurality of conical cutters axially mounted thereon, each of the axes of said cutters being inclined and said cutters having a polygonal cross section; said vibrohammer comprising a thick-walled tubular body, the wall of said body having a sealed chamber therein, a hammer suspended within said chamber, and spring means engaging said drill column and supporting said hammer, said spring means and hammer having a resonant frequency within the range corresponding to the frequency of vertical displacements imparted to said drill column by the rotation of said bit.

7. A rotary percussive drilling apparatus comprising a tubular drill column, a vibratory drill bit attached to the end of the column, said bit comprising a plurality of rotary conical cutting elements, each having a plurality of circumferential rows of teeth, corresponding teeth of each row being aligned to define a plane with the cone axis, and a percussive force generator within said drill column, said generator comprising an anvil; hammer means; and spring means suspending said hammer means and engaging said drill column for transmitting axial vibrations from said drill column to said hammer means, said spring-mass system being capable of resonating at a frequency inducible by the rotation of said bit against a borehole bottom.

8. A tubular drill column comprising a vibra bit, a vibrofilter, and a vibrohammer intermediate said bit and filter; said vibra bit comprising a body and a plurality of conical cutters axially mounted thereon, each cutter axis being inclined, and said cutters having a polygonal cross section; said vibrohammer comprising a thick-walled tubular body, the wall of said body having a sealed chamber therein; a hammer suspended within said chamber, and spring means engaging said tubular body and supporting said hammer; said vibra bit and said vibrofilter being...
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separated by a length of drill column equal to \( V/4f \), where \( V \) is the velocity at which compressional waves are propagated longitudinally in said column, and \( f \) is the resonant frequency of said vibrahammer.

9. A tubular drill column comprising a vibra(bit, a vibro-filter, and a percussive force generator intermediate said bit and filter; said vibrabit comprising a body and a plurality of rotary conical cutters axially mounted thereon, said cutters being inclined and having a polygonoidal cross section; said generator comprising a thick-walled tubular body, the wall of said body having a sealed chamber therein, a hammer suspended within said chamber, spring means engaging said tubular body and supporting said hammer; said vibrofilter and said vibrabit being separated by a length of drill column equal to \( V/4f \), where \( V \) is the velocity at which compressional waves are propagated longitudinally in said column, and \( f \) is the resonant frequency of said generator.

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