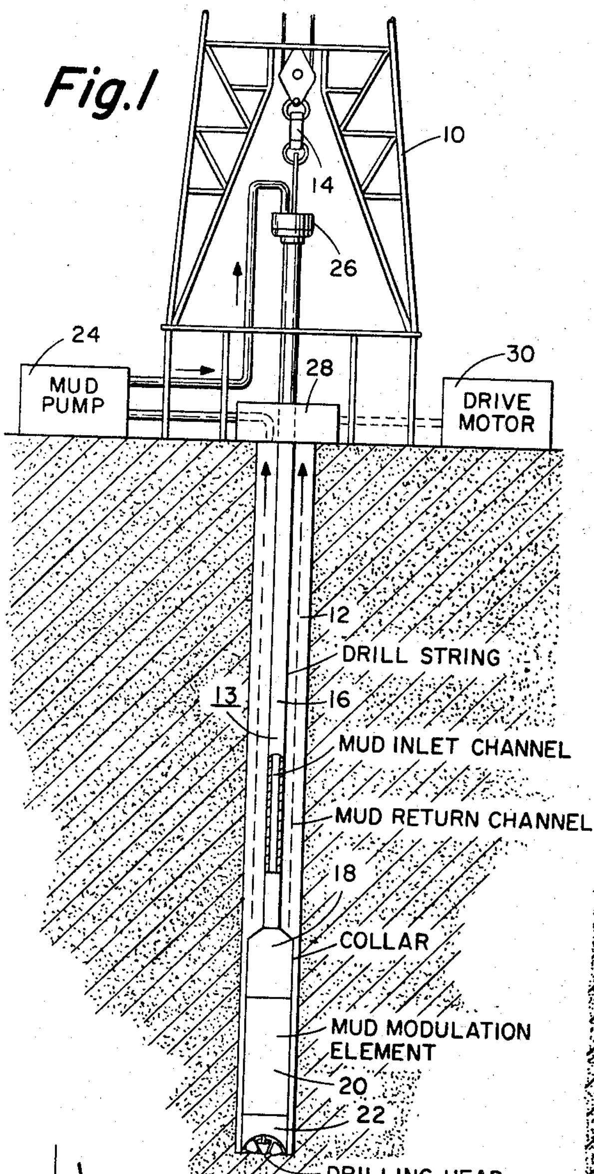
Oct. 10, 1967 J. V. BOUYOUCOS 3,346,058

ACOUSTIC APPARATUS

Filed May 29, 1964 3 Sheets-Sheet 1

Fig. 1



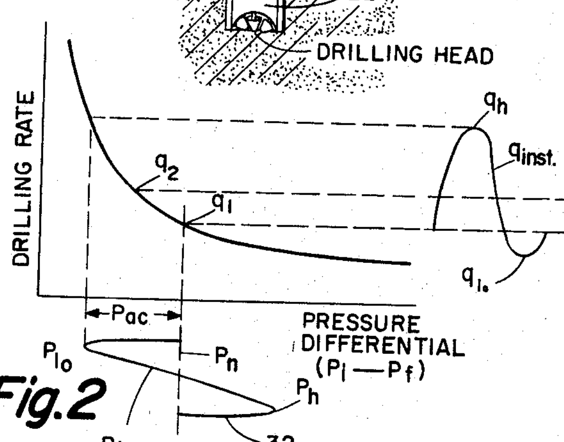


Fig. 2

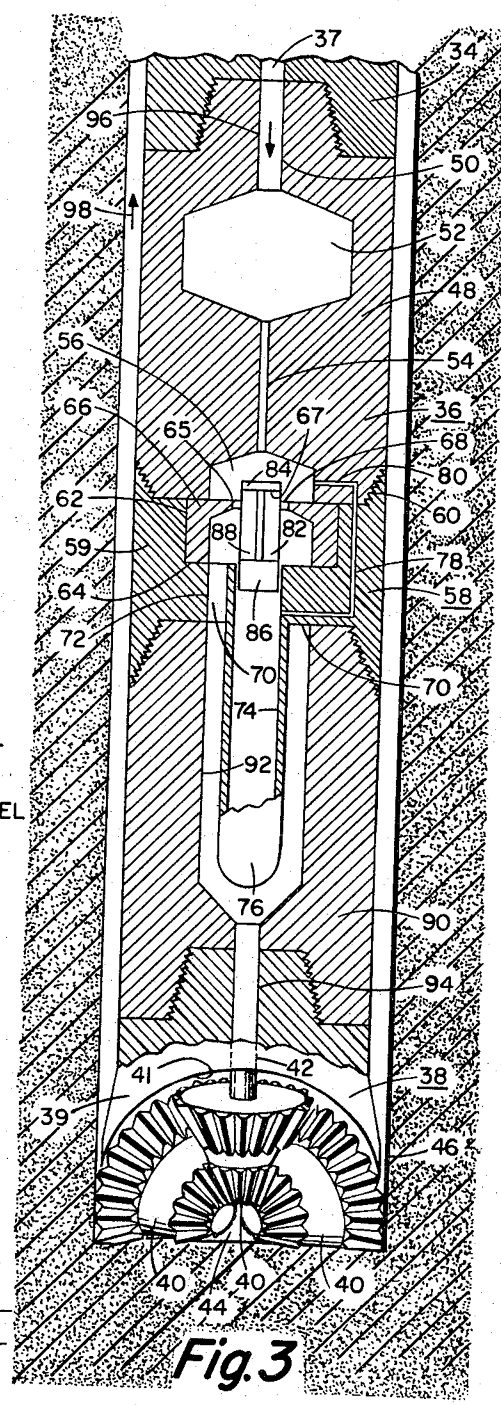


Fig. 3

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ACOUSTIC APPARATUS

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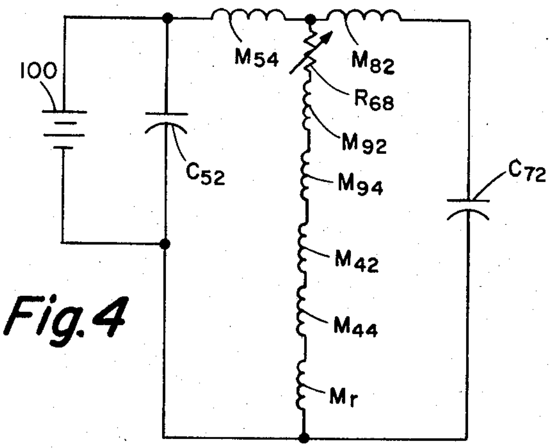

Fig. 4

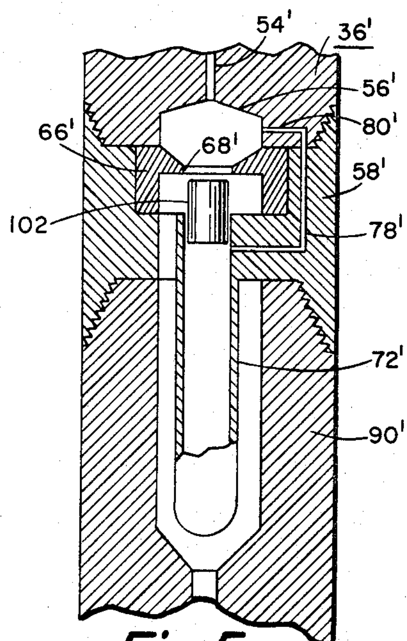

Fig. 5

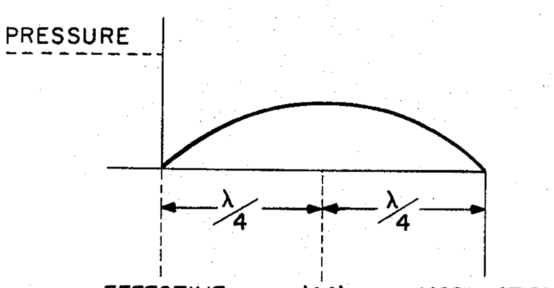

Fig. 6

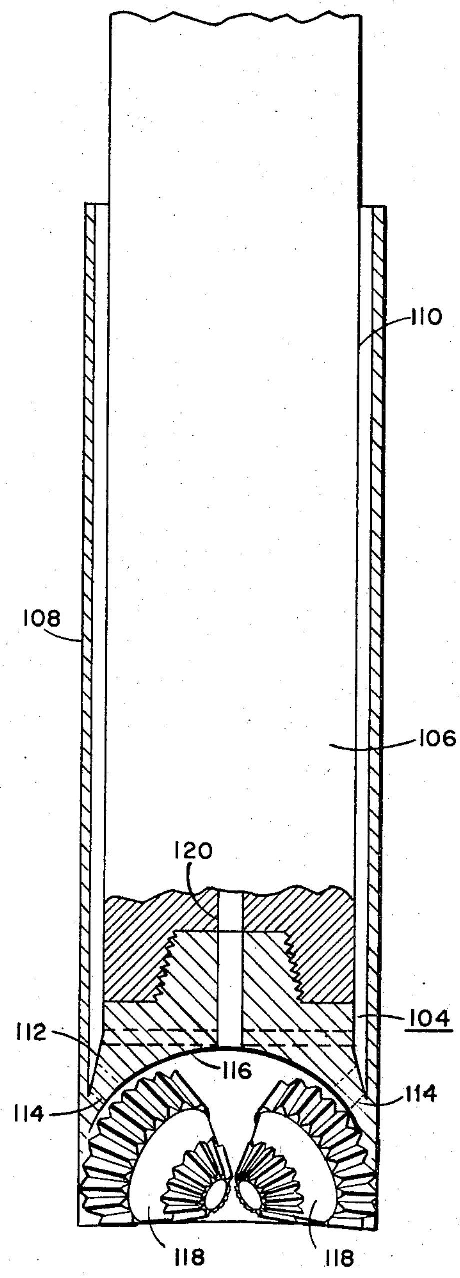

Fig. 7

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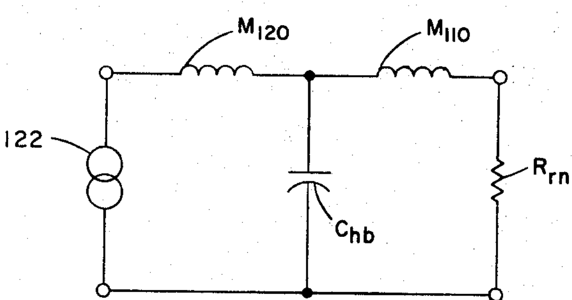

Fig. 9

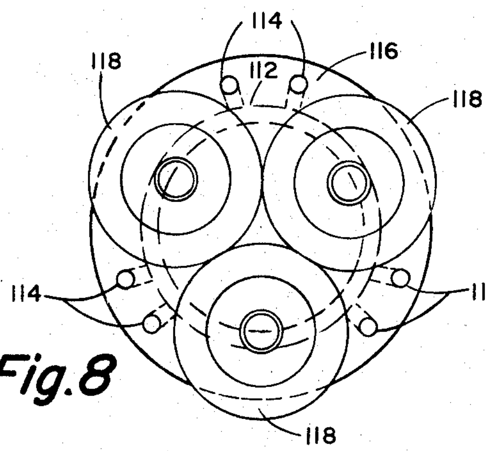

Fig. 8

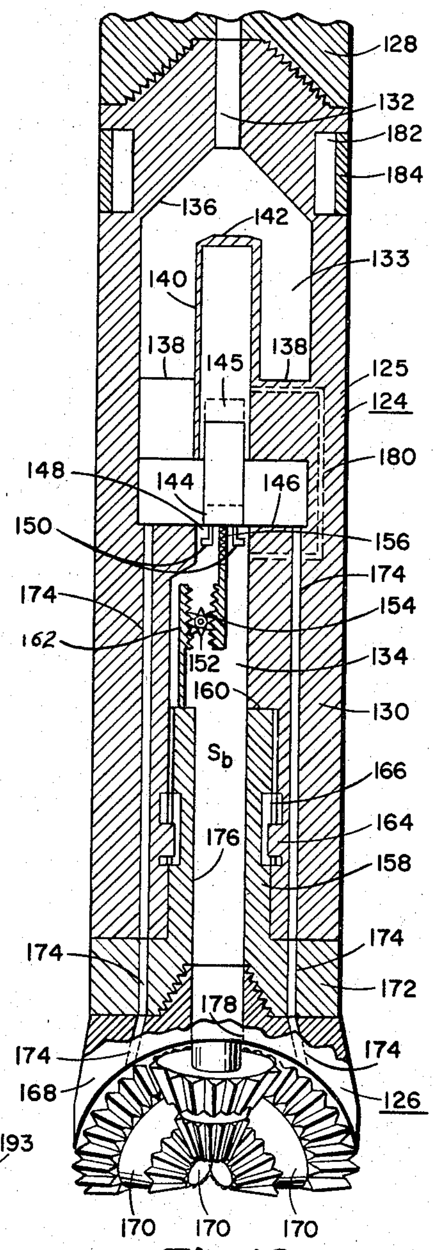

Fig. 10

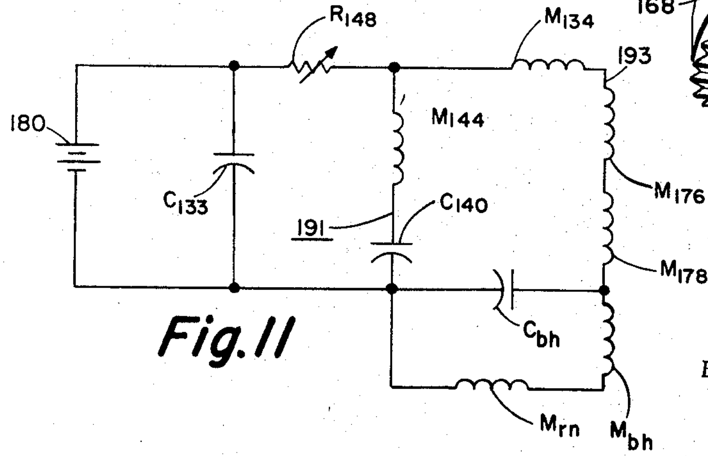

Fig. 11

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United States Patent Office

3,346,058

Patented Oct. 10, 1967

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3,346,058

ACOUSTIC APPARATUS

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Filed May 29, 1964, Ser. No. 371,202
11 Claims. (Cl. 175—56)

This invention relates to acoustic apparatus, and more particularly to methods of and apparatus for drilling or boring holes in the earth with the aid of acoustic apparatus of the type adapted to operate with drilling fluids.

The invention is especially suitable for use in oil well drilling and other apparatus where deep boreholes are drilled into the earth with the assistance of drilling fluids, such as are known in the oil well drilling art and referred to as "drilling muds."

At the bottom of deep holes the pressure due to the weight of the drilling mud in the borehole may exceed the pressure exerted by the earth formation on the bottom of the hole. The interface between the formation and the bottom of the hole becomes significant. The excess pressure exerted on the bottom hole formation interface may prevent or retard the removal of chips and other debris which are excavated by the drill bit. On the other hand, the pressure on the side-hole formation interface may be desirable to support the side-hole against collapse. Especially significant is the effect of the bottom hole pressure in holding down the chips broken off the earth formation by the drill bit. If the chips are not removed, immediately after they have been formed, the drill bit will continue to waste energy in crushing the chips thereby leading to increased drill bit wear and reduction of drilling rate. Worn bits need replacement. Frequent bit replacement appreciably increases drilling time.

It is an object of the present invention to provide methods and apparatus for drilling holes which afford faster drilling than is the case with known drilling methods and apparatus.

It is another object of the present invention to provide improved tools for forming boreholes in the earth especially at great depths.

It is a further object of the present invention to provide improved methods and apparatus for earth drilling and boring which improves the drilling process by facilitating the removal of material, such as chips and the like from the bottom of boreholes.

It is a still further object of the present invention to provide methods of and apparatus for earth boring and drilling which minimize the development and retention of caked drilling mud and other debris between the drill bit and the formation which can hinder the drilling process.

It is a still further object of the present invention to provide improved apparatus for modulating the flow of drilling fluids so as to assist in drilling.

It is a still further object of the present invention to provide improved acoustic vibration generating apparatus, especially suitable for use in drilling and boring tools.

It is a still further object of the present invention to provide improved acoustic vibration generating apparatus which operates with drilling fluids, such as muds.

It is a still further object of the present invention to provide improved apparatus for forming boreholes in earth formations which will not damage the side walls of the hole.

Briefly described, the invention may be included with a tool which is adapted to drill a hole in earth formations by the generation and removal of chips and other debris from the bottom of the hole. The drilling fluid is circulated into and out of the bottom hole region. Acoustic

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vibrations are established, utilizing the energy of the circulating fluid, to modulate the pressure of the fluid in the bottom hole region. Periodic variations in bottom hole pressure are generated which oppose periodically the hold-down forces which tend to prevent the removal of chips or other debris. The drilling rate is increased since the adverse effect of these chip hold-down forces are periodically counteracted. The acoustic vibrations may be generated by oscillation of a valve mechanism which is disposed in the circulating fluid stream. The flow of fluid is modulated such that the maximum fluid pressure variations occur in the bottom hole region thereby effectively assisting the drilling process.

The invention itself, both as to its organization and method or operation, as well as additional objects and advantages thereof will become more readily apparent from a reading of the following description in connection with the accompanying drawings in which:

FIG. 1 is a diagrammatic view of an oil well drilling system which incorporates the present invention;

FIG. 2 is a graph illustration the improvement in drilling rate obtained through the use of the invention;

FIG. 3 is a diagrammatic sectional view of a drill tool incorporating the present invention, in accordance with one embodiment thereof, in section being taken along a transverse plane through the longitudinal axis of the tool;

FIG. 4 is a schematic diagram of the acoustic circuit of the apparatus shown in FIG. 3;

FIG. 5 is a fragmentary sectional view of a drilling tool in accordance with another embodiment of the present invention, the section being taken along a transverse plane through the longitudinal axis of the tool;

FIG. 6 is a graph showing the pressure distribution along the axis of the borehole drilled by a tool embodying the invention;

FIG. 7 is a fragmentary, diagrammatic sectional view of a drilling tool, similar to the tool shown in FIG. 3, which incorporates means for providing increased protection against damage of the side walls of the borehole;

FIG. 8 is a bottom view of the tool shown in FIG. 7;

FIG. 9 is an acoustic circuit of a portion of the apparatus shown in FIG. 7;

FIG. 10 is a sectional view of a drilling tool in accordance with still another embodiment of the present invention, the section being taken along a transverse plane through the axis of the tool; and

FIG. 11 is a schematic diagram of the acoustic circuit of the tool shown in FIG. 10.

Referring to FIG. 1, a derrick **10** is situated over the hole **12** which is bored in the earth in an effort to find oil, a gas, or similar deposits. A hoist **14**, such as a block and tackle, is attached to the top of a drilling apparatus **13** for the purpose of raising and lowering the apparatus in and out of the hole. The apparatus **13** itself includes a drill string **16**, of the type which is used in the oil well drilling art, such as a hollow pipe or plurality of pipe sections coupled to each other. The bottom of the drill string is connected to a drill collar **18**. Following one or more of these collars, or between successive collars, is a drilling mud modulation element **20**. The element **20** modulates the mud by generating acoustic vibrations therein so as to periodically vary the pressure of the mud in the bottom hole region, as will be explained more fully hereinafter. A drilling head **22**, which may be of the type adapted to be rotated, is attached to the modulation element **20** or to the last of the collars **18**. By drilling head is meant bits, housing, flow couplings, mechanical attachments and other parts constituting an assembly, the purpose of which is excavation at the bottom of the hole. A mud inlet channel is provided by communicating passages through the drill string **16**, the collar **18**, the element **20** and the head **22**. The mud passes through the region adjacent to the head **22** at the bottom of the hole. The mud returns to the surface through a channel between the outer periphery of the drill string **16**, the collars **18** and the element **20** and the periphery of the hole **12**.

Mud is pumped into the inlet channel by means of a mud pump **24** which may receive mud from a suitable sump or reservoir and pump this mud into an inlet **26** at the top of the drill string **16**. Mud is returned from the mud return channel into the mud pump or sump for recirculation by the pump to the drill string, after suitable filtration to remove debris carried up by the mud.

A rotary table **28** coupled to the drill string **16** and driven by a drive motor **30** rotates the drilling apparatus. As the drilling head **22** rotates, material is excavated from the formation at the bottom of the hole. This material may be in the form of the chips. The action of the drilling mud normally is to carry away the removed material by washing or flushing.

As the drill bit penetrates deeper and deeper into the earth formation, the hydrostatic pressure at the bottom of the hole principally due to the weight of the vertical column of drilling mud continually increases. When the internal pressure (P_i) in the drilling mud at the bottom of the hole exceeds the subsurface; pressure (P_f) exerted through the earth formation on the bottom of the hole, the removal of chips excavated by the drilling head is retarded. The positive pressure differential, $P_i - P_f$, exerted across the bottom hole formation interface acts hydraulically to hold down chips that are formed, instead of allowing them to be flushed away by the action of the drilling mud. Also, the pressure differential can cause a mud cake to be formed between the bit and the bottom hole region, particularly in the case of porous formations. Accordingly, the drilling rate will decrease with an increase in the positive differential pressure, $P_i - P_f$, across the bottom hole formation interface. The bit is retarded because it first crushes chips already formed before reaching the virgin bottom hole formation.

The decrease in drilling rate with increasing pressure differential is illustrated in the graph shown in FIG. 2. The drilling rate decreases monotonically with increasing pressure differential, the decrease being rapid at first up to a point after which the decrease in drilling rate with increasing pressure differential tends to level off asymptotically to a low substantially constant rate as the pressure differential is further increased.

The mud modulating element utilizes the energy in the pressurized mud flowing through the mud inlet channel to generate acoustic vibrations in the mud. These acoustic vibrations are coupled to the bottom hole region and periodic variation or pulsation in internal pressure (P_i) results. This variation in internal pressure (P_i) is indicated by the sine wave **32** in FIG. 2 of peak amplitude P_{ac}, which is superimposed upon a nominal or average value of pressure differential P_n. P_n, in turn, is associated with a nominal or average value of drilling rate q_1. The resultant time variation in the instantaneous value of bottom hole pressure P_{inst} gives rise to a time variation in the instantaneous value of drilling rate shown as q_{inst} in FIG. 2. It is to be noted that as P_{inst} swings toward a low value of pressure differential, P_{lo}, q_{inst} swings toward a high value of drilling rate, q_h. As P_{inst} swings toward a high value of pressure differential, P_h, q_{inst} swings toward a low value of drilling rate q_{lo}. Since the characteristic drilling rate vs. pressure differential curve is not a straight line, it can be seen that the peak increase in drilling rate, $q_h - q_1$, occurring during the first portion of the cycle shown, is considerably greater than peak decrease in drilling rate $q_{lo} - q_1$, occurring during the second portion of the cycle shown in FIG. 2. As a result, the average drilling rate, which is the time average of q_{inst} in FIG. 2, has moved from the value q_1 to q_2, indicating a net increase in drilling rate as a result of the applied time variation in pressure differential. Accordingly, the modulation of the mud pressure has effectively increased the drilling rate from the value q_1 to q_2.

The applied pressure modulation as shown in FIG. 2, is not sufficient to cause the instantaneous pressure differential $P_i - P_f$ to go negative over any portion of the cycle. If however, P_{ac}, is made large enough for $P_i - P_f$ to become negative over a significant portion of a half-cycle, the resultant reversal in bottom hole pressure differential can actually force chips away from the bottom of the hole, thereby increasing substantially the drilling rate.

In FIG. 3 one embodiment of an oil well drilling tool incorporating the invention is illustrated. A cylindrical drill collar **34** is shown connected to the upper end of a mud modulating element housing **36** which may be cylindrical in shape. The collar has a hole **37** therethrough which provides the mud inlet in the collar **34**. The mud is not shown in place in the apparatus to simplify the illustration. Muds or other hydraulic drilling fluids of the type known in the art may be used. Screw connections between the collar **34** and the housing **36** are shown. It will be appreciated that bolt and flange or other connecting means may be provided if desired between the collar **34** and the housing **36** or between the collars and drill string sections, if desired.

The housing **36** is interposed between the collar **34** and a drilling head **38**. The head **38** includes a shaped housing **39** having a cupped end face **41** to which three drill bits **40** of the conical type are attached one hundred twenty degrees apart from each other. The head **38** also has a passage hole **42** therethrough through which the mud may flow into a region **44** adjacent at the bottom of a borehole **46**.

The housing **36** includes three successive cylindrical sections **48**, **58**, and **90** which are screw threaded for attachment one to another. The section **48** has a passage therethrough formed by an upper hole **50**, a cavity **52**, a narrow bore **54**, which may be of smaller diameter than the hole **50**, and a chamber **56**, all along the axis of the housing **36** and coaxial therewith. The upper hole **50** is circular in cross-section and communicates with the mud channel hole **37** in the collar **34**. The cavity **52** and the chamber **56** both have cylindrical side walls, the upper and lower ends of which may be conical in shape to reduce turbulence in the flow path.

The intermediate section **58** is an assembly of parts including cylinder **59** which has a hole **62** of circular cross-section coaxial with the housing **36** bored into its upper face. The bottom of this hole **62** defines a shoulder **64**. A cup shaped member **66** is inserted into the hole **62** and rests on the shoulder **64**. The bottom of this cup shaped member **66** has a circular hole **68** concentric with the axis thereof and also concentric with the axis of the housing **36**. The member **66** provides a stator port for a valving mechanism and the hole **68** through the member **66**, with a valve member **82** to be described more fully hereinafter, define a valve orifice. Thus, the members **66** and **82** are desirably formed from tungsten carbide or other hardened material to improve their wear characteristics.

Three webs **70**, two of which are shown in FIG. 3, extend from the walls of a passage hole **72** through the bottom face of cylinder **59**. These webs support an elongated tube **74** which is closed at its bottom end **76**. An L-shaped channel **78** in the cylinder **59** and a communicating L-shaped channel **80** in the lower portion of the upper cylinder **48** communicate the interior of the tube **74** and the interior of the cavity **56** with each other, for valve centering purposes, as will be explained more fully hereinafter.

A valve **82** is located in the intermediate assembly **58** and is a cylindrical body having a relatively thin disc-like portion **84** and a relatively thick disc-like portion **86** respectively at the upper and lower ends thereof. These disc portions are separated by ribs **88**. The thin disc portion **84** is adapted to move through the hole **68**. The upper circular edge **65** of the stator member **66** and the lower circular edge **67** of the disc portion **84** control and throttle the flow of mud and cooperatively define the valve orifice referred to henceforth by the same reference numeral (**68**) as the stator hole **68**. The valve **82** oscillates in a self-excited mode in response to the passage or circulation of the drilling mud and establishes acoustic-vibrations therein, as will be explained in greater detail hereinafter.

The cylinder **59** is attached to a cylinder **90** constituting the lower-most of the sections. The cylinder **90** is axially bored with upper and lower circular holes **92** and **94**, respectively of larger and smaller diameter and coaxial with the housing **36**. The lower hole **94** joins the mud channel hole **42** in the drilling head **38**. The tube **74** is disposed partially within and coaxial with the upper hole **92**. When the drilling head **38** is attached to the bottom of the cylinder **90**, by means of the threads in their mating faces, the holes **94** and **42** communicate with each other. A passage for the circulation of drilling mud therefore extends along the axis of the drill collar **34**, the housing **36** and the drilling head **38**. This mud flows, acoustically modulated, into the bottom region **44** of the borehole **46**. The mud is returned to the surface in the channel between the inner periphery of the hole **46** and the outer periphery of the head **38**, housing **36**, collar **34**, and drill string sections. The inlet and return flow paths are, respectively, illustrated by two arrows **96** and **98**.

When the pressurized drilling mud flows into housing **38** through the upper hole **50**, it fills the cavity **52**. The cavity **52** acts like a large acoustical compliance effectively isolating the portion of the drilling apparatus including the collar **34** and the rest of the drill string from the valving mechanism **66–82**. Accordingly, strong acoustic vibrations generated in the modulating element **36** do not pass upwardly beyond the cavity **52**.

The drilling mud circulates through the cavity **52** into the narrow bore **54**. The bore **54** is dimensioned so that, when filled with drilling mud, it acts as an acoustic mass or inertance. The chamber **56** fills with mud. The filled chamber presents a relatively large stiffness reactance as compared to the inertive reactance of the bore **54** and may be neglected in the acoustic circuit of the apparatus. The mud also fills the space inside of the cup shaped member **66** and also fills holes **72** and **92**. The mud also fills the tube **74**. The valve **82** is centered radially in the tube **74** by its thick disc portion **86**. The disc portion **86** has a diameter slightly less than the inner diameter of tube **74** to provide a clearance for axial motion of the valve **82**. This clearance is sufficiently small, however, to minimize acoustic losses in the annular gap between the cylindrical piston member defined by the thick disc portion **86** and tube **74**. The quiescent or static position of the valve, by which is meant the average position of the valve, considering that it normally oscillates reciprocatively along its longitudinal axis, is dictated by the static pressures in the chamber **56** and tube **74**. The static pressures in the cavity **56** and in the tube **74** are equalized, since the chamber **56** and the inside of the tube **74** communicate with each other through the channels **78** and **80**. The channels **78** and **80** are preferably small in cross sectional area to present a high acoustic impedance compared to the acoustic impedance seen looking into cavities defined by the chamber **56** and tube **74**. Thus, aside from equalizing the static pressures in the chamber **56** and tube **74**, these channels **78** and **80** do not affect the dynamic acoustic circuit to be described hereinafter. Forces are exerted on the valve **82** due to the pressures in the chamber **56** and tube **74** and also due to the momentum of the mud which flows through the valve orifice **68**. The areas of the upper or lower faces of the valve **82** may be slightly different so that the static forces tend to locate its thin disc portion immediately above the top of the stator member **66**. Reference may be had to J. V. Bouyoucos application Ser. No. 192,274, filed May 3, 1962, now Patent No. 3,143,999, for a further description of static valve location.

The body of drilling mud in the tube **74** is relatively large and therefore acts as an acoustic stiffness element. In other words, the mud in the tube is compressible and behaves as a liquid spring which is extended and compressed in response to the pressure on the valve **82** due to the circulating mud. The valve **82** oscillates in a self-sustaining manner, as may be understood from the acoustic circuit of the apparatus.

The simplified, equivalent acoustic circuit of the apparatus shown in FIG. 3 is illustrated in FIG. 4. A battery **100** represents a source of hydraulic pressure differential between the entrance to the cavity **52** and the bottom hole region **44**, and is due to the circulating mud. The acoustic compliance C_{52} presented by the cavity **52** is effectively across the pressure source **100**. An acoustic inertance M_{54} presented by the bore **54** is in series with the acoustical inertance M_{82} presented by the valve. The mud in the tube **74** is a stiffness element presenting a compliance C_{72} in series with the inertance of the valve **82**. Effectively in shunt with this circuit including the inertance M_{82} and the compliance C_{72} is an acoustic resistance R_{68} presented by the valve orifice **68**. In series with the valve orifice are successive acoustic inertances M_{92}, M_{94}, and M_{42} presented, respectively, by the mud in the holes **92**, **94**, and **42**. The mud in the bottom hole region **44** and the mud in the return channel also presents inertances M_{44} and M_r which are in series with R_{68}, M_{92}, M_{94}, and M_{42}. The acoustic circuit provided in the housing **36** exhibits resonance at a certain frequency depending primarily upon the values of M_{54}, M_{82}, and C_{72}. However, the other elements, eg. M_{92}, M_{94}, M_{42}, M_{44}, and M_r also are included in the circuit and also may have a slight effect on the determination of the resonant frequency of the circuit.

The resonant frequency is primarily determined by a tank circuit defined by the circuit branch including M_{54} and C_{52} in parallel with the circuit branch including M_{82} and C_{72}. At the desired resonant frequency of the tank circuit, the reactance of C_{72} is greater than the reactance of M_{82} and the reactance of M_{54} is greater than the reactance of C_{52}. The reactance looking into the branch including M_{82} is thus primarily a stiffness reactance, while the branch including M_{54} presents primarily in inertive reactance. The circulating mud is effectively introduced at the junction of the two branches and tends to sustain the oscillations of the valve **82** at the resonant frequency determined by the circuit so that the valve oscillation frequency and the circuit resonant frequency are about equal to each other. This frequency is desirably in the acoustic range, say 200 cycles per second. The flow through the valve orifice **68** is periodically varied in accordance with the valve oscillations. Acoustic pressure vibrations are thereby established in the circulating mud, which pressure vibrations are effective in the bottom hole region **44**. Reference may be had to Patent No. 3,004,512, issued to J. V. Buoyoucos et al. on Oct. 17, 1961, for more general description of acoustic vibration generators.

It may be desirable to construct the housing **36** so that the length of the mud passage from the valve orifice **68** to the bottom hole region is approximately a quarter wavelength at the frequency of oscillation of the valve **82**. Then a standing wave of pressure is established, which wave may have a maximum point at the bottom hole region **44**.

It may be desirable in order to prevent appreciable transmission of vibratory energy along the mud return channel adjacent to side walls of the hole **36** to provide an acoustic termination approximately one-quarter wavelength at the oscillation frequency from the bottom of the hole. Such an acoustic termination may be any compliant member which retains its compliance in spite of the high hydrostatic pressures found in its vicinity. A suitable termination may, for example, be a hollow cylinder having a flexible outer wall and being filled with pressurized gas, such as nitrogen (see FIG. 10). Other forms of acoustic termination known in the art may be used.

A portion of another mud modulating element is shown in FIG. 5. This element is adapted to be connected between a drill collar and a drill bit assembly similarly with the mud modulating element shown in FIG. 3. Parts of the element shown in FIG. 5 which are similar to parts of the element shown in FIG. 3 are designated by light reference numerals with primes appended thereto. A massive, cylindrical valve member **102** is statically centered with its upper face immediately below the hole defining the valve orifice **68'**. The mass of the valve **102** is sufficiently great so that its inertive reactance at the frequency of resonance of the system is greater than the stiffness reactance of the mud in the tube **72'**. Accordingly, the valve **102** acts as an inertance or mass controlled element. While oscillating, the displacement of the valve is approximately one-hundred-eighty degrees out of phase with the force applied thereto. The top end face of the valve **102** is statically located below, rather than above, the lip of the hole in the stator member which, with the valve **102**, defines the valve orifice **68'**. The static location of the valve **102** may be accomplished by providing additional narrow channels through the body of the valve between its lower end face and its outer periphery. The pressure differentials across these channels tend to locate the valve by reference to a fixed point such as the upper rim of the tube **72'**. In all other respects, the operation of the mud modulator shown in FIG. 5 is similar to the operation of the mud modulator shown in FIG. 3.

FIG. 6 graphically represents the standing wave of pressure which may be generated in the system. Assuming the system is terminated approximately one-quarter wavelength from the bottom hole region **44** by means of a relatively soft compliant structure, a node and a maximum point of the standing wave are established at the termination and at the bottom hole region **44**, respectively. The acoustic path between the modulating element, the bottom hole region **44** and the termination includes both lumped and distributed acoustical elements. Accordingly, the physical length of the path may not equal exactly one-half wavelength. The valve orifice of the modulating element is desirably effectively one-quarter wavelength from the bottom hole region. The effective wavelengths are measured at the frequency of the generated acoustic vibrations in the fluid.

Referring to FIGS. 7 and 8, there is shown a drilling head **104** connected to a mud modulating element **106**, similar to the mud modulating element shown in either FIG. 3 or FIG. 5. The drilling head **104** includes a cylindrical sleeve **108** which extends upwardly from the head, over the region where the acoustic-vibration pressures are largest (say about one-quarter wavelength at the frequency of the generated acoustic vibrations). The sleeve **108** and the outer peripheries of the head **104** and of the mud modulating element housing **106** define a circular mud flow return channel **110** therebetween.

The sleeve **108** may be attached to the drilling head **104** by bolts or other suitable fastener means, or may be integral with the head as shown. The sleeve thus has the same diameter or gage as the borehole. Orifices **114** are drilled into the bottom face **116** of the drilling head **104**. These orifices have ports at the annular channel **112** defined in the head **104** at the bottom of the mud channel **110**. Other ports of the orifices **114** at the bottom face **116** are between the bits **118** (see FIG. 8).

Mud circulates through the passage **120** in the modulation element and in the head **104** into the bottom hole region adjacent to the bits **118**. This mud is acoustic-vibration modulated to assist in the drilling process. Modulated mud containing the chips and other debris enters the channel **110** through the orifices **114**. The outer periphery of the sleeve **108** is close to wall of the borehole. The mud in the channel **110** varies in pressure in accordance with the modulation thereof in the modulating element **106**. Since the sleeve **108** is interposed between the modulated flow of mud and the walls of the borehole, the sleeve **108** tends to reduce any damage to the walls of the hole due to the pressure variations in the mud which flows through the channel **110**. These pressure variations are substantially reduced in amplitude at the upper end of the channel **110**. Accordingly, the mud after passing through the channel **110** is not likely to do significant damage to the borehole walls. Depending upon the strength of the formation through which the borehole is drilled, the sleeve **108** may or may not be used. It is desirable for weak formations.

FIG. 9 shows a simplified acoustic circuit of the apparatus shown in FIGS. 7 and 8. The source **122** represents the oscillating pressure of the mud established by the mud modulating element at its output. M_{120} represents the inertance of the passage **120** and the passages through the modulating element adjacent thereto (e.g. FIG. 3, passages **94**, **92**, and **70**). C_{hb} represents the acoustic compliance of the fluid in the bottom hole region. The compliance of the bottom hole region may dictate the acoustic characteristics of the circuit, since the volume of the fluid in the bottom hole region may be large as compared to the volume of the fluid in the channels **120** and the channel **110**. M_{110} represents the inertance of the fluid in the orifices **114** and channels **110** and **112**. R_{rn} represents a resistive load provided by the fluid return channel above the sleeve **108**. Since the bottom hole cavity may be effectively large and thereby presents a stiffness reactance rather than an inertive reactance in the acoustic circuit, the acoustic pressure may be maximized in the bottom hole region. Also, a little acoustic energy is transmitted into the fluid return channel by suitably proportioning the channel **110** and passage **120** to effectively provide a low pass filter having a cutoff frequency below the frequency of vibration of the mud.

Referring to FIG. 10, another drilling tool is shown having a mud modulating element **124** and a drilling head assembly **126**. The mud modulating element itself includes a cylindrical housing **130** connected at its upper end to a drill collar **128**. An upper hole **132**, an intermediate hole **133** and a lower hole **134** are bored through the housing **130**. All the holes may be circular and coaxial. The upper hole **132** provides an inlet channel for the circulating mud. The intermediate hole is much larger in diameter than the upper hole and communicates therewith through a conical section **136**. The hole **133** defines a cavity which isolates the upper portion of the mud circulating channel acoustically from the modulating element. A plurality of webs **138**, two of which are shown in FIG. 10 support an elongated tube **140** closed at its upper end **142**. A cylindrical valve **144** is located in the hole **133** with its upper portion centered within the tube **140**. The bottom of the hole **133** defines a shoulder **146**. The rim of this shoulder and the portion of the wall of the lower hole **134** which extends immediately below the shoulder **146**, with the circular edge of the end face of the valve **144**, define a valve orifice **148**. A plurality (for example, three) L-shaped feet **150** tend to center the lower portion of the valve coaxially within the hole **134**.

A pinion gear **152** is disposed within the hole **134** below the valve orifice **148** and journalled to the housing **130**. A rack gear **154** engages the pinion gear **152**. The upper end of the rack gear is attached by means of a spring **156** to the bottom of the valve **144**. Aside from mechanically coupling the rack gear **154** to the valve **144**, the spring also may aid in locating the valve with respect to the valve orifice defining shoulder **146** and as a stop to limit the travel of the valve **144**. Other hydraulic valve locating circuits are mentioned hereinafter.

The drilling head assembly **126** includes a neck portion **158** which extends into the lower hole **134**. The lower hole **134** is cut away to receive the neck **158** of the bit assembly **126**. A shoulder **160** of the cut away portion limits the axial movement of the assembly **126** in the upward direction. A rack gear **162** extends from the upper end of the neck **158** and engages the pinion **152**. Cooperating splines **164**, **166** in the inner periphery of the cylindrical housing **130** and in the outer periphery of the neck **158** permit non-rotative translation of the housing **130** and neck **158**.

The assembly **126** also includes an end portion **168** to which three rotatable, conical bits **170** are journalled. The neck **158** and end portion **168** may be integral, if desired. A flanged end **172** of the neck portion is interposed between the end portion **168** and the bottom of the housing **130**. A plurality of channels **174**, two of which are shown, extend through the housing **130**, the flanged end **172** of the neck portion **158** and the end portion **168** in a direction along the common longitudinal axis thereof. The channels terminate at the end face of the end portion between the drilling bits **170** (FIG. 8) so that they communicate the bottom hole region with the intermediate hole **133** in the housing **130**.

In operation the drilling mud flows through the upper hole **132** and fills the intermediate hole **133** which functions as a cavity having relatively large compliance when filled with the drilling mud. The tube **140** also fills with the drilling mud. A liquid spring is provided by the drilling mud contained in the tube **140**. The mud flows through the valve orifice **148** and fills the lower hole **134**. The drilling mud circulates through axial holes **176** and **178**, respectively, in the neck and end portions **158** and **168** of the drill assembly **126**. The mud then flows into the bottom hole region (similar to region **44**, FIG. 3). The return channel for the mud is provided between the wall of the borehole and the outer periphery of the drill assembly **126**, mud modulating element **124** and the remaining drill collars and portions of the drill string (see FIG. 1). Mud passed through the channels **174** is expelled in jets against the bottom of the borehole to assist in removal of chips and the like.

The simplified equivalent acoustic circuit of the mud modulating element **124** is shown in FIG. 11. A battery **180** represents the hydraulic pressure differential between the entrance to the cavity presented by the hole **133** and the bottom hole region. C_{133} represents the acoustic compliance of the fluid in that hole **133** and is effectively across the pressure source **180**. Since the mud flows through the valve orifice **148**, the resistance R_{148} of that orifice is in series with a branch circuit **191** including an inertance M_{144} which represents the mass of the valve **144** and an acoustic compliance C_{140} presented by the fluid in the tube **140**. Another branch circuit **193** in series with the valve orifice resistance R_{148} includes a number of inertance elements due to the mud in the successive holes and passages indicated as M_{134}, M_{176}, M_{178}, M_{bh}, and M_{rn}. The mud in the holes **134**, **176**, and **178** and in the bottom hole and return channel regions may effectively be inertance elements looking toward the bottom hole from the valve orifice because of the shape of these holes and the acoustic characteristics of the drilling mud.

The two branch circuits **191** and **193** define a parallel resonant circuit which is resonant at a frequency where the branch **191** presents an effective stiffness reactance which is equal to the effective inertive reactance in the other branch **193**. This resonant frequency is suitably arranged to be in the acoustic range, say two hundred c.p.s. by configuring the holes in the mud modulating element, the mass of the valve, and the acoustic compliance of tube **140**.

The oscillation frequency of the valve is approximately equal to the resonant frequency of the circuit. The valve periodically derives energy from the circulating mud which flows through the valve orifice **148** as the valve oscillates, so that the valve oscillation is sustained at the oscillation frequency.

The mud channel including the holes **134**, **176**, and **178** as well as the bottom hole region, are all in the resonant circuit of the mud modulating element. The mud pressure accordingly varies at the oscillation frequency in the mud channel and in the bottom hole region. The pressure variations are larger in the bottom hole region since that region presents an acoustic compliance, C_{bh} (FIG. 11). M_{rn}, M_{bh}, and C_{bh} define a pressure maximizing circuit that enables the acoustic pressures in the branch **193** to be high in the bottom hole region. The elements in the branch **193** nevertheless present an inertive reactance which resonate with the stiffness reactance of the branch **191** including the valve inertance.

An acoustic termination is provided which may be in the form of an annular groove **182** in the housing **130**. The groove is sealed by a resilient ring **184** and is filled with a gas, such as nitrogen. This termination may effectively return M_{rn} to the point of acoustic reference pressure.

In order to prevent any chips or aggregate material from clogging the valve orifice **148**, the drill string may be lifted slightly. The bit assembly **126** being in engagement with the bottom hole region tends to remain in engagement therewith. Thus, the cylindrical housing **130** moves upwardly while the neck portion **158** of the bit assembly **126** remains stationary. This relative movement of the housing **130** with respect to the neck portion **158** causes counterclockwise rotation of the pinion gear **152**. The counterclockwise rotation of the pinion **152** raises the valve **144** to the position indicated by the dashed lines **145** and clears the valve orifice **148** so that debris can flow through the orifice. When the orifice is cleared, the mud modulating element is dropped back in place and drilling may then resume.

A narrow U-shaped channel **180** which presents only a resistive acoustic impedance connects the tube **140** and the lower hole **134** in the housing **130** and equalizes the static pressure therein. The hydrostatic pressure of the mud in the lower hole **134** and in the tube **140** is balanced so as to aid in locating the valve **144** so that its average position is with its bottom end face just above the valve orifice **148**. The relative areas of the end faces of the valve **144** may be different or channels through the valve may be provided also to aid in locating the valve **144** statically, as was mentioned above.

From the foregoing description, it will be apparent that there has been provided improved methods and apparatus for earth boring and drilling which are especially adapted for drilling deep boreholes in earth formations for sinking oil and gas wells. While several embodiments of the invention have been described, various modifications in the method and in the elements of the apparatus will, no doubt, become apparent to those skilled in the art. Accordingly, the foregoing description should be taken as illustrative and not in any limiting sense.

What is claimed is:

1. Apparatus for drilling a borehole in the earth comprising

(a) a drill string adapted to be lowered into the hole and having a channel therethrough,

(b) a drill bit for excavating the bottom of said bore hole,

(c) a mud flow modulating element for generating periodic pressure pulses including a fluid actuated valve means adapted to generate acoustic vibrations in fluid passing therethrough, said mud flow modulating element being disposed between said bit and said drill string,

(d) means for circulating a drilling fluid through said drill string channel, said modulating element, and said bit for discharge into said hole bottom, said mud returning to the surface of the earth along a path adjacent the walls of said borehole, said element establishing periodic variations in the fluid pressure at said hole bottom in response to the fluid vibrations generated in said element, and

(e) isolation means formed in said drill string and acting upon said return path for confining the pressure modulations within said bore hole adjacent to said bit.

2. Apparatus for drilling boreholes in earth formations with the aid of a drilling head engageable with the bottom of said borehole into which drilling mud is adapted to be introduced, said apparatus comprising

(a) a housing having a passage along the longitudinal axis thereof for the flow of said mud therethrough,

(b) said passage being contoured to define regions of different cross sectional areas and having at least a first and a second region therein respectively disposed successively in the direction of flow of the drilling mud, said first region having a relatively large volume and defining a stiffness reactance at a certain frequency of acoustic-vibration in said mud, and said second cavity defining an inertance at said certain frequency,

(c) means providing a valve orifice on said housing and disposed in said passage in one of said regions,

(d) a free floating valve member disposed in said housing and being reciprocatively movable along a path into and out of said orifice for modulating the flow of said mud, said valve presenting an inertive reactance at said frequency,

(e) means disposed within one of said regions for providing a cavity into which at least a portion of said valve member is movable, said cavity presenting a stiffness reactance at said frequency which with the inertive reactance of said valve member, the inertive reactance of said second region, and the acoustic reactances of the regions communicating therewith defining an acoustic circuit resonant at said certain frequency,

(f) means in said housing for coupling said drilling head to said housing and communicating said housing passage and said borehole bottom, and

(g) isolation means formed in said housing and acting upon said return channel for confining the pressure modulations within said bore hole region adjacent to said bit.

3. The invention as set forth in claim 2 including means providing an acoustic termination in said housing, said termination being diposed about one-quarter wavelength from said borehole bottom and one-quarter wavelength from said valve orifice, the wavelength being defined at said certain frequency.

4. The invention as set forth in claim 2 including means coupled to said valve member and said bit head for moving said valve member clear of orifice when said housing is translated in a direction away from said borehole bottom.

5. The invention as set forth in claim 2 including a plurality of channels extending longitudinally through said housing and communicating with said bit head for supply jets of said mud to said bottom of said borehole.

6. The invention as set forth in claim 2 including a sleeve around said housing and the outer periphery of said drilling head, said sleeve being spaced from said housing and head outer periphery to define an annular channel therewith, said drilling head having orifices communicating the bottom of said borehole and said channel.

7. Apparatus for drilling a bore hole in an earth formation with the aid of a source of pressurized fluid and a

drill bit disposed in a bit cavity at the bottom of said hole, said apparatus comprising

(a) an acoustic vibration generator coupled to said source for delivering fluid to and substantially modulating the pressure of the fluid at said bit cavity, said generator including

(i) a housing having passage means for conducting the flow of fluid from said source through said generator to said bit cavity and from said bit cavity through a return channel formed between said housing and said earth formation,

(ii) a valve mechanism supported in said housing and including a valve member disposed adjacent a stator port and adapted to move in relation to said stator port between an open first position and a fluid flow throttling second position,

(b) said passage means comprising a transmission line between said bit cavity and said stator port and communicating said stator port with said bit cavity for modulating the pressure in said bit cavity,

(c) isolating means in said housing communicating with said return channel for confining the pressure modulation within said bit cavity, and

(d) said passage means, said valve mechanism, and said isolation means being configured to define an acoustic circuit for supporting self-excited oscillatory movement of said valve between said positions.

8. The invention as set forth in claim 7 wherein said housing includes first and second chambers disposed successively in the direction of flow of said fluid, said first chamber having a relatively large volume and defining a stiffness reactance at the frequency of acoustic-vibration in said fluid produced by said generator, and said second chambers defines an inertance at said frequency.

9. The invention as set forth in claim 8 including liquid spring means disposed in said passage means for acting upon said valve mechanism in said second position urging it toward said first position.

10. The invention a set forth in claim 9 wherein said isolating means is comprised of a compliant member disposed in said housing.

11. The invention as set forth in claim 10 wherein said valve member includes a portion which cooperates with said stator port and a piston portion, said housing defining an elongated tube adapted to be filled with said fluid and upon which said piston portion acts to produce a spring force upon said piston portion aiding the oscillatory movement of said valve.

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