

PATENT SPECIFICATION

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(54) TELEMETERING SYSTEM FOR BOREHOLES

(71) We, SUN OIL COMPANY of Pennsylvania, a corporation organised under the laws of the State of Pennsylvania, of 1608 Walnut Street, Philadelphia, Pennsylvania, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to a telemetering system for boreholes, and more particularly to a telemetering (signal transmission) system which operates without interfering with normal drilling procedures.

The value of a telemetering system for transmitting information from the bottom of a borehole to the surface has been recognised for a number of years, and proposed systems have been the subjects of numerous patents. At the present time, there is still no practical means for rapid data transmission from the bottom of a hole while drilling which does not use a wire line. The use of a line requires that the entire line be withdrawn for the addition of each length of pipe, thus interfering with the normal drilling procedures. This is costly, particularly in offshore drilling. Also, transmission when using a wire line is essentially limited to the use of pulses.

Attempts have been made to provide a telemetering system which operates without interference with normal drilling procedures and gives immediate information on the direction of the hole, the characteristics of the formation and the performance of the drill, as well as many other parameters of interest in the well, such as the gas content of the mud. Continually up-dated information has the advantage of giving warning of impending blowouts in time for preventive action.

Various telemetering systems (for providing communication without wires) have been proposed, using pressure pulses in the drilling mud, acoustic signals through

the mud, or electric signals utilizing conducting paths through the drill pipe and surrounding formation. However, because of excessive attenuation, large power requirements, high cost, slow speed of transmission, and so on, these prior proposals have not proved to be particularly practical.

According to our invention we provide an acoustic telemetering system for transmitting acoustic signals along a string of drill pipe comprising an acoustical transmitter/transducer for transmitting acoustically through the drill string a carrier signal having a nominal frequency f_1 ; a first repeater spaced from said transducer along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_1 and to retransmit such acoustic energy along said drill string in the form of a carrier signal having a nominal frequency f_2 ; and a second repeater spaced from said first repeater along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_2 and to retransmit acoustic energy along said pipe in the form of a carrier signal having a nominal frequency f_3 .

Acoustic signals are continuously transmitted through the drill pipe in a borehole by the insertion of repeaters as required, at intervals such as to restore the energy level before it drops too low to be recovered from the noise background. It is known that the impedance mismatch between steel and the surrounding mud essentially prevents the escape of acoustic energy into the mud. The principal loss of acoustic energy occurs at the screwed connections between pipe sections, and this loss increases as the frequency is raised. At a carrier frequency of 1000 Hz, the loss has been measured as 20 db per thousand feet

of pipe. For the purposes of illustration, the repeater separation may be 2000 feet.

Each repeater in the system: (i) restores the signal level lost due to attenuation in the pipe; and (ii) improves the signal-to-noise ratio.

The repeater units are normally more or less uniformly spaced. The distance between the top repeater and the surface varies with the hole depth, but does not exceed the inter-repeater spacing. Speaking generally, the function of each repeater in the system is to pick up (receive) an acoustic signal (signal-modulated carrier) from the string of drill pipe, amplify it, and retransmit it as an acoustic signal along the pipe.

According to this invention, as previously stated, information is carried by acoustic (sonic) waves travelling through the metal of the drill pipe wall. A system, to be practical, must provide solutions to three problems, namely: (i) the signal must be identified from background noise, e.g., noise created by the drill, by any mud motor used to drive the drill, by scraping of the pipe on the side of the hole and by machines at the surface; (ii) the system must compensate for the attenuation in the pipe and in crossing the air gap between threads at each tool joint; and (iii) the available bandwidth must be sufficient for the transmission of signals from several sensors with a high degree of accuracy, in a reasonable length of time.

The attenuation increases with the acoustic frequency. A carrier frequency of the order of 1000 Hz is sufficiently high to provide reasonable bandwidth, with acceptable attenuation. The strong harmonics of the background noise sources previously mentioned are generally below 500 Hz; most high frequency components are intermittent.

The acoustic telemetering system of the invention operates without interfering with normal drilling procedures, gives an improved transmission of acoustic signals through a drill pipe, and substantially completely eliminates the loss of signal information due to the mixing of signals.

A detailed description of the invention follows to be read in conjunction with the accompanying drawings, wherein;

Fig. 1 is a schematic view of a drill pipe string modified for the purposes of the present invention;

Fig. 2 is a schematic diagram illustrating typical circuitry which can be used in a downhole transmitter transducer;

Fig. 3 is a schematic diagram illustrating the circuitry used in a repeater unit;

Fig. 4 is a schematic diagram illustrating the circuitry used in a surface preamplifier unit;

Fig. 5 is a schematic diagram illustrating the circuitry used in a surface read-out unit and

Fig. 6 is a partial vertical cross-section of a sub-assembly for a repeater unit.

Fig. 1 shows a drill pipe string 1 which comprises a plurality of pipe sections (not separately delineated) coupled together end-to-end with a drill tool or bit 2 disposed at the bottom of the string, all more or less in a conventional manner.

For the purposes of the present invention, however, the drill pipe string is modified to include and to accommodate a transmitter transducer unit 3 which is disposed at or near the drill bit 2, and a plurality of repeater units 4, 5, 6 and 7 which are distributed along the length of the drill string for a purpose subsequently explained herein. At the surface, there is provided surface apparatus generally designated 8 for reading out (so as to display and/or record) signals received from downhole.

The system of Fig. 1 operates to provide continuous transmission in one direction only. In Fig. 1, this direction is indicated as being from downhole to the surface, which is the more useful of the two directions, since what is ordinarily desired is the transmission of downhole information to the surface. In the transmitter/transducer (downhole) unit 3, typical circuitry for which will be detailed hereinafter, signals from various transducers are conditioned, multiplexed by a clock-driven switch, then digitized by an analog-to-digital converter and transmitted in the form of frequency modulation (specifically, frequency shift keyed or FSK modulation) on an acoustic (sound carrier of approximately 1000 Hz. Data are transmitted, typically, at about ten bits per second. The FSK signal modulation ordinarily alternates between two fixed frequencies, separated by about 50 Hz on a 1000 Hz carrier.

The signal-modulated acoustic carrier (nominal or rest frequency f_1) developed in the transmitter transducer unit 3 is fed to an acoustic transmitter (sound source, later detailed) in this unit to apply the acoustic waves to the drill pipe wall, the transmitter being acoustically coupled to the wall of the drill pipe. These acoustic waves, of course, travel in both directions along the string of the pipe. The energy which travels downwardly towards the bit 2 is merely dissipated as heat. The acoustic waves travelling upwardly in the direction of the arrow 9 (which is the desired direction) reach the first repeater unit 4, where they are picked up by an acoustic receiver contained in this unit, are amplified, and are retransmitted along the pipe, both in the desired direction 10 and also

downwardly, towards the unit 3. To this extent, at least, the repeaters 4-7 all operate in similar fashion. Thus, the purpose of the repeater units is to provide a gain to compensate for the 40 db loss between the units 3 and 4 (it being assumed that these units are 2000 feet apart).

It is apparent from Fig. 1 that no repeater unit can simultaneously transmit and receive on the same frequency without severe loss of signal information due to mixing of the strong transmitted signal with the weaker incoming signal. Furthermore, if alternate units continuously transmit and receive on the same two frequencies, signals of the same level are received from two sources. For example, if the repeaters 4 and 6 both receive on frequency f_1 and transmit on frequency f_2 while the repeater 5 receives on frequency f_2 and transmits on frequency f_1 , the repeater 5 will receive f_2 signals of equal amplitude from the repeaters 4 and 6; because of the time displacement, there will be random cancellation and the modulating information will be lost.

Therefore, three different repeaters are used in sequence in the drill string, these three repeaters having different pairs of received and transmitted frequencies, as follows:

- (i) the repeater 4, receiving on f_1 and transmitting on f_2 ;
- (ii) the repeater 5, receiving on f_2 and transmitting on f_3 ; and
- (iii) the repeater 6, receiving on f_3 and transmitting on f_1 .

The sequence is reproduced by the repeater 7, which reproduces the repeater 4, and so on. Thus, each of the repeaters in the string includes a frequency converter between its input and its output, but these frequency converters are in general of three different types. As a result, interference between repeaters which transmit on the same frequency is prevented by the added attenuation resulting from the fact that one of the signals travels twice the distance along the string, as compared with the other. Thus, for example, both the repeater 7 and the repeater 4 transmit on frequency f_2 , while the repeater 5 receives on f_2 ; however, the f_2 signal which reaches the repeater 5 from the repeater 7 has had to travel twice as far along the string as the f_2 signal which reaches the repeater 5 from the repeater 4. Therefore, the f_2 signal from the repeater 7 to the repeater 5 is so much attenuated as to be insignificant when compared with the f_2 signal from the repeater 4 to the repeater 5.

As previously stated, the repeater 7, like the repeater 4, receives at the nominal frequency f_1 and transmits at the nominal frequency f_2 . If the repeater 7 is that nearest

the surface, the preamplifier portion 11 of the surface unit 8, which portion includes an acoustic receiver acoustically coupled to the drill pipe, receives the signal-modulated (FSK) carrier at the nominal frequency f_2 . This surface unit 8 is described in greater detail below.

The operation of the Fig. 1 system can be summarized as follows. Various parameters of interest in the well are sensed by transducers in the downhole unit 3 and are converted to electrical signals which are multiplexed and used to frequency modulate (FSK) a sonic (acoustic) carrier of nominal or rest frequency f_1 (approximately 1000 Hz). The f_1 acoustic signal is then fed to the drill string 1 by means of an acoustic transmitter (sound source). The f_1 acoustic signal is picked up by an acoustic receiver in the first repeater 4, is converted to a different nominal frequency f_2 , is amplified, and is then retransmitted as an f_2 acoustic signal in the drill string by means of a transmitter in the repeater unit 4. The f_2 acoustic signal is picked up by an acoustic receiver in the second repeater 5, is converted to a different nominal frequency f_3 , is amplified, and is then retransmitted as an f_3 acoustic signal in the drill string by means of a transmitter in the repeater unit 5. The f_3 acoustic signal is picked up by an acoustic receiver in the third repeater 6 is converted to the original nominal frequency f_1 , is amplified, and is then retransmitted as an f_1 acoustic signal in the drill string by means of a transmitter in the repeater unit 6. Further repetition of the acoustic signal travelling along the drill string may take place in the same manner as previously described, depending, obviously, on the number of additional repeater units present in the string. One additional repeater unit 7 is illustrated in Fig. 1, the unit 7 being of the same type, and operating in the same manner, as the repeater unit 4. As previously indicated, the repeater unit next above the unit 7 (if there were one) would be of the same type as the unit 5 and would operate similarly, while the second repeater unit above the unit 7 (if there were one) would be of the same type as the unit 6 and would operate similarly, and so on.

It should be made clear that the acoustic signal transmitted by each acoustic transmitter (sound source) does, of course, travel in both directions along the pipe; thus, for example, the f_1 signal transmitted from the repeater 6 travels downwardly, as well as upwardly (which latter is the desired direction). However, the staggered-frequency arrangement described (wherein there are three different types of repeaters, with different pairs of received and transmitted frequencies, and wherein these

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types are disposed in a regular sequence in the drill string) discriminates in favour of the upward direction of travel of the acoustic signal, as previously described.

5 At the surface, the preamplifier portion 11 of the surface unit 8, which portion includes an acoustic receiver, picks up the acoustic signal of say f_2 nominal frequency and feeds it by means of a link 12, schematically illustrated, to a read-out circuit 13 for display and/or recording. If the acoustic receiver in the preamplifier 11 is clamped to the drill pipe, and if the drill pipe is rotated the link 12 is a radio link; if the drill is driven by a mud motor (in which case the drill string does not rotate), or if the acoustic receiver is clamped above the swivel, the link 12 is a wire.

20 One form of borehole information transmission system (borehole telemetry system) is illustrated in block diagram form in Fig. 2 of the accompanying drawings. The arrangement now to be described can be used in the transmitter transducer (downhole unit) 3. Two sensors, for measuring information downhole, are indicated at 14 and 15, respectively. The signals developed by the sensors 14 and 15 (as well as by other sensors, not specifically illustrated) are selected in sequence by a multiplex switch 16 controlled by a clock drive 17. The downhole multiplexing arrangement 16, 17 includes means for providing identifying signals, so that synchronism can be maintained between this downhole multiplexing arrangement and a similar multiplexing arrangement at the surface.

35 The output side of the multiplex switch is fed to an analog-to-digital or pulse width converter 18, for converting the sensor outputs to digital coding, or to pulse width coding. The output of the converter 18, which would be in the form of constant amplitude pulses (digital or pulse-width coded), appears on the output lead 19.

40 The output lead 19 is coupled through a resistor 20 to a frequency modulator circuit (specifically, a frequency shift keying circuit) 24, to provide the keying signal for the circuit.

45 In the circuit 24, an acoustic (sonic) carrier with a frequency of approximately 1000 HZ is generated, and the frequency of this (continues) carrier is switched between two frequencies by the digital or pulse-width signal output of the converter 18 (on the lead 19).

60 In the circuit 24, the solid-state operational amplifier 25, which has its output terminal 26 connected back to its inverting input 27 through the illustrated resistance-capacitance network, is used as an active filter tuned to the carrier frequency. Another solid-state operational

amplifier 28 has its inverting input 29 coupled to the amplifier output terminal 26 and its output 30 coupled back to the input terminal 27 of the amplifier 25 by way of a resistor 21.

70 A number of resistors are connected essentially across the two inputs of the amplifier 25 to form a frequency determining circuit; among these are a fixed resistor 31, an adjustable resistor 32, and an FET 33 in series with a resistor 34.

75 A pulse originating in the filter 25 (for example, when this filter is energized) drives the amplifier 28 to saturation and generates a square wave of constant amplitude at carrier frequency. The fundamental of the square wave is passed by the filter 25 to sustain oscillation and to develop a sine wave at the output 26 of the device 25. Since the amplitude of the square wave and the gain of amplifier 25 are fixed, no gain control circuit is required to maintain a constant sine-wave output at 26.

80 The carrier frequency may be varied by means of the adjustable resistor 32. The effective resistance afforded by the FET 33 is in series with the resistor 34, this combination being in parallel with the resistor 32.

90 The modulating or keying voltage which appears on the lead 19 is applied to the gate of the FET 33, here operating as a switch which is opened or closed by the signal output of the converter 18. The carrier (of nominal or rest frequency f_1) is switched between two frequencies as the FET switch is opened or closed (that is, made non-conducting or conducting) by the digital or pulse-width signal output of the converter 18, applied to the gate of the FET switch.

100 The power demand of the frequency modulator is 6 milliamperes from ± 12 volts, and a 100 millivolt (rms) signal produces a maximum frequency deviation. Distortion and amplitude modulation are negligible.

105 The frequency modulated (FSK) carrier of sonic or acoustic frequency (nominal or rest frequency f_1 , say 1000 Hz) appearing at the output 26 is amplified by means of a power amplifier 35, and is then fed to the input transformer 36 of a transformer-coupled, push-pull power output stage 37. The secondary of the output transformer 38 of the stage 37 is connected to the acoustic transmitter (sound source) schematically illustrated at 39. This sound source is acoustically coupled to the drill string 1, and feeds the frequency modulated (FSK) carrier thereto, for transmission of the acoustic signal therealong from the downhole location adjacent to the drill bit 2. By way of example, approximately one watt of electrical power may be supplied to the source 39.

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Fig. 3 diagrammatically illustrates reentry which can be employed for any of — repeater units 4—7, etc. In each repeater unit, an acoustic receiver or pickup 40 is acoustically coupled to the drill string to receive acoustic signals being transmitted therealong. The pickup 40 is preferably an accelerometer of conventional type, employing a piezoelectric crystal as a transducing element. The acoustic signal picked up by the receiver 40 (which, in the repeater 4, may be an FSK signal of 1000—1050 Hz) is amplified by means of an amplifier 41, and is then fed to the first of a pair of solid-state operational amplifiers 42 and 43 which together act as a high pass filter (two-stage active filter) for the incoming (received) signal at f_1 . The filter 42—43 passes signals above 800 Hz, by way of example, and thus eliminates low frequency noises such as those due to the drill and those due to the scraping of the pipe on this side of the hole, etc.

From the last stage 43 of the two-stage, high pass filter, the signal is fed to the first of a pair of solid-state operational amplifiers 44 and 45 which together serve as a two-stage band pass filter having a very narrow pass band, centered between 1000 Hz and 1050 Hz, for example (if f_1 nominal frequency is 1000 Hz). One of the band pass filters (44 or 45) is peaked at the lower FSK frequency and the other at the higher frequency, e.g. 1000 Hz and 1050 Hz.

From the output 46 of the band pass filter, the signal passed goes to a point 47, which is one of two paired diagonally-opposite input terminals of a ring modulator 48 which comprises four diodes connected more or less conventionally. The required anti-phasing or push-pull feed for the opposite terminal 49 is obtained by passing the signal at 46 through a signal inverting stage 50, the output of which is connected to the terminal 49.

Each repeater includes frequency converting means for changing the carrier frequency received to the next frequency in the sequence before retransmission; this frequency scheme or sequence has been described previously, in connection with Fig. 1. The frequency converting means includes a frequency shift oscillator enclosed by the dotted-line rectangle numbered 51. The frequency shift oscillator is quite similar to the oscillator of the frequency modulator 24 (Fig. 2) previously described, but without the FET modulating device, since no frequency modulation of the oscillator 51 is desired. Hence, the description will not be repeated; suffice it to say here that the output of the oscillator 51 appears on a lead 52 and is fed to the ungrounded terminal 53 of the other two

paired, diagonally opposite input terminals of the modulator 48.

The frequency shift oscillator 51 has a frequency of $(f_2 - f_1)$. If the frequency f_1 is 1000 Hz, as previously stated, f_2 may be 1200 Hz, so that the frequency of the oscillator 51 may be 200 Hz. When the nominal received frequency of 1000 Hz is mixed or modulated (in the modulator 48) with a local oscillator frequency of 200 Hz, upper and lower sidebands centered at 1200 Hz and 800 Hz, respectively, are produced.

Output from the ring modulator 48 is taken from a terminal 53 and fed to the input of a solid-state operational amplifier 54 serving as a band pass filter (having a relatively broad pass band), which selects for use one sideband from the output of the modulator 48. The filter 54 selects and passes the nominal frequency f_2 , the upper sideband (centered at 1200 Hz), from the output of the modulator 48.

Output from the filter 54 is fed through a full-wave limiter comprising a pair of Zener diodes 55 and 56, the purpose of which is to cut out noise spikes and to provide a square wave on the output lead 57, which provides one of the inputs for a phase comparator 58 contained in a phase-locked loop 59. The purpose of the phase-locked loop 59 is to distinguish between received noise bursts and a persistent signal. The other input for the phase comparator 58 is taken from the square-wave output of a voltage-controlled oscillator 60 whose free-running frequency is set by means of a capacitor 61 and a resistor 62 connected to certain terminals of this solid-state oscillator circuit.

The phase comparator 58 operates to generate a d.c. control voltage which adjusts the voltage-controlled oscillator 60 to keep its frequency equal to that of the incoming signal (at 57). This control voltage is fed back to the oscillator 60 by way of a resistance-capacitance filter including a series resistor 63 and a shunt capacitor 64, the voltage across the capacitor 64 being fed to the oscillator 60 by way of a lead 65. The aforesaid d.c. voltage is representative of the keying (frequency shift), and it is supplied to the oscillator 60 to maintain it locked with the frequency-changed (and frequency-shift-keyed) received signal.

Rejection of noise within the pass-band of the filter 54 depends on the phase-locked loop circuit 57. The selectivity is determined by the time constant of the low-pass filter formed by the resistor 63 and the condenser 64. The phase-locked loop follows the most persistent (i.e., the strongest) signal frequency within its capture range, and thus effects substantial reduction of random noise. It also eliminates the weaker of two signals of approximately the same frequency. Thus,

referring back to Fig. 1, the f_2 signal reaching the repeater 5 from the repeater 7 (in the undesired direction) is weaker than the f_2 signal reaching the repeater 5 from the repeater 4 (in the desired direction); this has been explained above. The phase-locked loop in the repeater 5 locks on to the stronger of these two f_2 signals, and thus entirely eliminates the weaker f_2 signal (from the repeater 7, in the undesired direction).

The frequency modulated (FSK) carrier output of the phase-locked oscillator 60 (nominal or rest frequency f_2 , 1200 Hz, in the sonic or acoustic range) is fed by means of a lead 66 to the input of a power amplifier 67, in which it is amplified; it is then fed to the input transformer 68 of a transformer-coupled, push-pull power output stage 69. The secondary of the output transformer 70 of the stage 69 is connected to the acoustic transmitter (sound source) 71, which is acoustically coupled to the drill string 1, and feeds the modulated carrier (rest frequency f_2 , for example 1200 Hz, frequency modulated 1200—1250 Hz) thereto. If we assume, as before, that Fig. 3 illustrates the circuitry of the repeater unit 4, the acoustic signal is transmitted at the frequency f_2 in the desired direction 10 (Fig. 1), as well as in the downward or undesired direction.

Fig. 3 shows the differences between the three repeater units of the system, i.e.: (i) the repeater unit 4 receives on f_1 , 1000 Hz nominal, transmits on f_2 , 1200 Hz nominal, frequency shift oscillator 200 Hz, select upper sideband from modulator for transmission; (ii) repeater unit 5 receives on f_2 , 1200 Hz nominal, transmits on f_3 , 800 Hz nominal frequency shift oscillator 400 Hz, select lower sideband from modulator for transmission; and (iii) the repeater unit 6 receives on f_3 , 800 Hz nominal, transmits on f_1 , 1000 Hz nominal, frequency shift oscillator 200 Hz, select upper sideband from modulator for transmission.

Fig. 4 is a schematic of typical circuitry which may be utilized at the surface, in the pre-amplifier portion 11 of the surface unit 8. An acoustic signal receiver or pickup 40', which is preferably exactly similar to the receiver 40 previously described, is clamped to the outside of the drill string 1 at the surface, so as to be acoustically coupled to the drill pipe. The FSK acoustic or sonic carrier reaching the surface from the uppermost repeater unit (such as the unit 7, Fig. 1) is picked up by the receiver 40' and fed to the input of a solid-state amplifier 72 which provides a gain of about 40 db.

From the output of the amplifier 72, the amplified signal is fed into an operational

amplifier 73 which is connected to operate as a high pass filter (single stage active filter), which passes all signals above 800 Hz. The amplifier 73 is preferably similarly connected and operates similarly to one of the stages 42 and 43 in Fig. 3. The high pass filter 73 functions to remove or to eliminate low frequency noise, such as noise due to machines at the surface.

The output signal from the high pass filter 73 is applied to the link coupling 12 previously described, which conveys the signal to the surface read-out portion 13 of the surface unit 8.

Fig. 5 is a schematic of typical circuitry which may be utilized at the surface, in the read-out portion 13 of the surface unit 8.

The signal received from the preamplifier unit 11 via the link coupling 12 is fed into an operational amplifier 73' which operates as a high pass filter (single stage active filter), passing all signals above say 800 Hz and eliminating low frequency noises. The amplifier 73' is connected similarly and operates similarly to the amplifier 73 (Fig. 4), or to one of the stages 42 and 43 in Fig. 3.

In Fig. 5, components which are identical to those of Fig. 3 are denoted by the same reference numerals, but carry prime designations.

From the high pass filter 73', the signal is fed to the first of a pair of solid-state operational amplifiers 44' and 45' which together serve as a two-stage band pass filter having a very narrow pass band (50 Hz, for example), centered between 1200 Hz and 1250 Hz (if f_2 nominal frequency is 1200 Hz; see Fig. 1). The narrow band pass filter arrangement 44', 45' is preferably quite similar to the arrangement 44, 45 in Fig. 3.

From the output 46' of the band pass filter 44', 45', the signal passed goes through a full-wave limiter comprising a pair of Zener diodes 55' and 56', the purpose of which is to cut out noise spikes and to provide a square wave on the output lead 57', which provides one of the inputs for a phase comparator 58' contained in phase-locked loop 59'. The phase-locked loop 59' is used as a demodulator and noise discriminator (which distinguishes between received noise bursts and a persistent signal). The other input for the phase comparator 58' is taken from the square-wave output of a voltage-controlled oscillator 60' whose free-running frequency is set by means of a capacitor 61' and a resistor 62' connected to certain terminals of this solid-state oscillator circuit.

The phase-locked loop 59' (including the components 58' and 60'—65') is very similar to the correspondingly-numbered phase-locked loop in Fig. 3, and operates

similarly. The d.c. voltage developed on the lead 65' is representative of the keying (frequency shift), and it is supplied to the oscillator 60' to maintain it locked with the FSK signal received at the surface (nominal frequency f_2 received from the repeater unit 7 of Fig. 1).

This d.c. control voltage is fed through a transistor 74 connected as an emitter follower to provide a low impedance signal at its output. It should be realized that the signal developed on the lead 65' is the demodulated carrier, which is to say that it is the modulating signal originally applied to the carrier.

The signal from the transistor 74 output (emitter) is fed into a multiplex switch 75 controlled by a clock drive 76. The switch 75 is similar to the switch 16 (Fig. 2), but is multiplexed at its output, rather than at its input (as is the switch 16). The received (demodulated) signal may be fed in sequences (as controlled by the switch 75) to respective display apparatus 77, 78 or 79. The apparatus 77 may be a digital-to-analog converter display correlated to sensor No. 1 of Fig. 2; the apparatus 78 may be a display correlated to sensor No. 2 of Fig. 2; the apparatus 79 may be a pulse-switch demodulator (used when a pulse-width converter is employed at 18 in Fig. 2).

Fig. 6 shows certain details of the mechanical construction of a repeater unit (such as the units 4, 5, 6 or 7 in Fig. 1). Fig. 6 is a partial vertical cross-section of a sub-assembly in which the repeater unit is mounted, so that it can be withdrawn at any time from the surface by means of a fishing tool. The sub-assembly 93 is coupled by threads 94 at its upper end to the lower end of a length of drill pipe which forms a portion of the drill string 1.

The body of the sub-assembly 93 has welded fins 95 and 96, welded at one end to the inner wall of the subassembly body and welded at their other ends to a concentric inner tube 97. During drilling, the drilling mud flows down the annular space 98, and past the fins 95 and 96, as indicated by the arrows 99.

Inside the tube 97, and slidably fitted therein, is an instrument housing 100. The housing 100 comprises an upper ball retainer portion 101, a disc-like upper mounting plate 102 secured within the housing, an intermediate shell portion 103, a disc-like bottom end mounting plate 104 secured within the housing, and a bottom (lower) tubular continuation 110.

The upper ball retainer portion 101 has a number of balls 105 sitting in radial holes in this portion. A latch 106 slides in an upper end portion 101 and is urged downwardly by a spring 107, so that its conical surface

108 urges the balls 105 into a semi-circular internal groove in the tube 97. In this condition, the balls 105 lock the instrument housing 100 in the tube 97.

If it is desired to remove the instrument housing 100, a standard grappling hook (fishing tool) can be lowered until it hooks onto the latch 106. As the latch (spear or fish bolt) 106 is raised, it releases the balls from the groove in the tube 97, and they then fall into a circumferential groove 109 provided at the lower end of the latch 106. The housing 100 can then be withdrawn up the drill string.

The space inside the shell 103, between the plates 102 and 104 provides an instrument chamber 111. Within the chamber 111 are mounted the various circuit components illustrated in Fig. 3, and described above.

The crystal-type accelerometer 40 (pickup or sound receiver) is securely fastened to the inner face of the plate 104 (within the chamber 111), e.g., by means of a bolt 112 threadably coupled to the outer casing of the accelerometer. As previously mentioned, the accelerometer 40 is a standard item of manufacture, which is readily available. Compressional waves (that is, sonic or acoustic signals) travelling along the drill string 1 reach the subassembly body 93 through a threaded coupling such as the coupling 94, and, from the sub-assembly body, the signals travel through the fins 95 and/or 96, the tube 97, the balls 105, the housing 100 and the plate 104 to the pickup 40.

The acoustic transmitter (sound source) 71 is a modified "outdoor" type dynamic loudspeaker having a domed housing 113 within which is a coil (to which the electrical energy of acoustic frequency is supplied) movably mounted in the usual air gap in a magnetic field contained within the housing 113; this coil is attached to, and drives the diaphragm 114. The diaphragm 114 is attached to, and drives, a resonant member 115 which in turn is attached by means of a plurality of rods 116 (four in number) to a plate 117 to which is centrally secured a solid cylindrical plug 118. The plug 118 is secured to a mounting collar 119 which in turn is fastened to the inner face of the plate 102 (within the chamber 111). Vibratory energy (compressional wave energy) from the diaphragm 114 is conveyed by parts 115—119 to the plate 102, from whence it travels through the housing 100, the balls 105, the tube 97 and the fins 95 and/or 96 to the sub-assembly body 93 and the drill string 1.

From a consideration of Figs. 3 and 6, it should now be apparent that, in a repeater such as 4, 5, 6 or 7 (Fig. 1), acoustic signals travelling along the drill string (drill pipe)

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are picked up by the pick-up or receiver 40 and are converted by this pick-up to electrical signals which are amplified, filtered, shifted in frequency, again amplified, and then applied to the sound source 71, which converts them to acoustic signals for re-transmission along the drill pipe (drill string).

In the system of this invention, the signal transmitted from the downhole may be of any form suitable to frequency modulate the acoustic (sonic) carrier. It may be an analog amplitude, a phase shift, a binary word, or a time interval signal. The rate of data transmission is limited by the maximum modulation frequency.

WHAT WE CLAIM IS:—

1. An acoustic telemetering system for transmitting acoustic signals along a string of drill pipe comprising an acoustical transmitter/transducer for transmitting acoustically through the drill string, a carrier signal having a nominal frequency f_1 ; a first repeater spaced from said transducer along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_1 and to retransmit such acoustic energy along said drill string in the form of a carrier signal having a nominal frequency f_2 ; and a second repeater spaced from said first repeater along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_2 and to retransmit acoustic energy along said pipe in the form of a carrier signal having a nominal frequency f_3 .

2. A system as claimed in claim 1, and further comprising a third repeater spaced from said second repeater along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_3 , and to retransmit

such acoustic energy along said drill string in the form of a carrier signal having nominal frequency f_1 .

3. A system as claimed in claim 1 or claim 2, wherein each of said repeaters also comprises an amplifier having its input connected to the corresponding receiver and having its output connected to the corresponding transmitter.

4. A system as claimed in claim 1, wherein said first repeater includes frequency converter means for changing the acoustic energy picked up at frequency f_1 to energy at frequency f_2 , and wherein said second repeater includes frequency converter means for changing the acoustic energy picked up at frequency f_2 to energy at frequency f_3 .

5. A system as claimed in any of the preceding claims, and further comprising means associated with said transmitter/transducer for modulating the first-named carrier signal with signals representative of measured parameters of interest in the well containing said string.

6. A system according to any of the preceding claims, wherein each transmitter includes means for modulating its carrier signal by frequency shift keying.

7. A system according to any of the preceding claims, wherein a first transmitter/transducer near the bottom of the drill string includes means for modulating its carrier signal in accordance with various parameters detected at the bottom of the drill string.

8. An acoustic telemetering system for transmitting acoustic signals along a string of drill pipe substantially as herein described with reference to the accompanying drawings.

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are picked up by the pick-up or receiver 40 and are converted by this pick-up to electrical signals which are amplified, filtered, shifted in frequency, again amplified, and then applied to the sound source 71, which converts them to acoustic signals for re-transmission along the drill pipe (drill string).

In the system of this invention, the signal transmitted from the downhole may be of any form suitable to frequency modulate the acoustic (sonic) carrier. It may be an analog amplitude, a phase shift, a binary word, or a time interval signal. The rate of data transmission is limited by the maximum modulation frequency.

WHAT WE CLAIM IS:—

1. An acoustic telemetering system for transmitting acoustic signals along a string of drill pipe comprising an acoustical transmitter/transducer for transmitting acoustically through the drill string, a carrier signal having a nominal frequency f_1 ; a first repeater spaced from said transducer along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_1 and to retransmit such acoustic energy along said drill string in the form of a carrier signal having a nominal frequency f_2 ; and a second repeater spaced from said first repeater along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_2 and to retransmit acoustic energy along said pipe in the form of a carrier signal having a nominal frequency f_3 .

2. A system as claimed in claim 1, and further comprising a third repeater spaced from said second repeater along said drill string and including a receiver and a transmitter acoustically coupled to said drill string to pick up acoustic energy therefrom at frequency f_3 , and to retransmit

such acoustic energy along said drill string in the form of a carrier signal having nominal frequency f_1 .

3. A system as claimed in claim 1 or claim 2, wherein each of said repeaters also comprises an amplifier having its input connected to the corresponding receiver and having its output connected to the corresponding transmitter.

4. A system as claimed in claim 1, wherein said first repeater includes frequency converter means for changing the acoustic energy picked up at frequency f_1 to energy at frequency f_2 , and wherein said second repeater includes frequency converter means for changing the acoustic energy picked up at frequency f_2 to energy at frequency f_3 .

5. A system as claimed in any of the preceding claims, and further comprising means associated with said transmitter/transducer for modulating the first-named carrier signal with signals representative of measured parameters of interest in the well containing said string.

6. A system according to any of the preceding claims, wherein each transmitter includes means for modulating its carrier signal by frequency shift keying.

7. A system according to any of the preceding claims, wherein a first transmitter/transducer near the bottom of the drill string includes means for modulating its carrier signal in accordance with various parameters detected at the bottom of the drill string.

8. An acoustic telemetering system for transmitting acoustic signals along a string of drill pipe substantially as herein described with reference to the accompanying drawings.

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