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(54) Acoustic data transmission through a drill string.

(57) Acoustical signals are transmitted through a drill string by canceling upward moving acoustical noise and by preconditioning the data in recognition of the comb filter impedance characteristics of the drill string.

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BACKGROUND OF THE INVENTION

This invention relates generally to a system for transmitting data along a drill string, and more particularly to a system for transmitting data through a drill string by modulation of intermediate-frequency acoustic carrier waves.

Deep wells of the type commonly used for petroleum or geothermal exploration are typically less than 30 cm (12 inches) in diameter and on the order of 2 km (1.5 miles) long. These wells are drilled using drill strings assembled from relatively light sections (either 30 or 45 feet long) of drill pipe that are connected end-to-end by tool joints, additional sections being added to the uphole end as the hole deepens. The downhole end of the drill string typically includes a drill collar, a dead weight assembled from sections of relatively heavy lengths of uniform diameter collar pipe having an overall length on the order of 300 meters (1000 feet). A drill bit is attached to the downhole end of the drill collar, the weight of the collar causing the bit to bite into the earth as the drill string is rotated from the surface. Sometimes, downhole mud motors or turbines are used to turn the bit. Drilling mud or air is pumped from the surface to the drill bit through an axial hole in the drill string. This fluid removes the cuttings from the hole, provides a hydrostatic head which controls the formation gases, and sometimes provides cooling for the bit.

Communication between downhole sensors of parameters such as pressure or temperature and the surface has long been desirable. Various methods that have been tried for this communication include electromagnetic radiation through the ground formation, electrical transmission through an insulated conductor, pressure pulse propagation through the drilling mud, and acoustic wave propagation through the metal drill string. Each of these methods has disadvantages associated with signal attenuation, ambient noise, high temperatures, and compatibility with standard drilling procedures.

The most commercially successful of these methods has been the transmission of information by pressure pulse in the drilling mud. However, attenuation mechanisms in the mud limit the transmission rate to about 2 to 4 bits per second.

This invention is directed towards the acoustical transmission of data through the metal drill string. The history of such efforts is recorded in columns 2 - 4 of U.S. Patent No. 4,293,936, issued Oct. 6, 1981, of Cox and Chaney. As reported therein, the first efforts were in the late 1940's by Sun Oil Company, which organization concluded there was too much attenuation in the drill string for the technology at that time. Another company came to the same conclusion during this period.

U.S. Patent No. 3,252,225, issued May 24, 1966, of E. Hixon concluded that the length of the drill pipes and joints had an effect on the transmission of energy up the drill string. Hixon determined that the wavelength of the transmitted data should be at least twice the length of a section of pipe.

In 1968 Sun Oil tried again, using repeaters spaced along the drill string and transmitting in the best frequency range, one with attenuation of only 10 dB/1000 feet. A paper by Thomas Barnes et al., "Passbands for Acoustic Transmission in an Idealized Drill String", Journal of Acoustical Society of America, Vol. 51, No. 5, 1972, pages 1606-1608, was consulted for an explanation of the field-test results, which were not totally consistent with the theory. Eventually, Sun went back to random searching for the best frequencies for transmission, an unsuccessful procedure.

The aforementioned Cox and Chaney patent concluded from their interpretation of the measured data obtained from a field test in a petroleum well that the Barnes model must be in error, because the center of the passbands measured by Cox and Chaney did not agree with the predicted passbands of Barnes et al. The patent uses acoustic repeaters along the drill string to ensure transmission of a particular frequency for a particular length of drill pipe to the surface.

U. S. Patent No. 4,314,365, issued February 2, 1982, of C. Petersen et al. discloses a system similar to Hixon for transmitting acoustic frequencies between 290 Hz and 400 Hz down a drill string.

U. S. Patent No. 4,390,975, issue June 28, 1983, of E. Shawhan, noted that ringing in the drill string could cause a binary "zero" to be mistaken as a "one". This patent transmitted data, and then a delay, to allow the transients to ring down before transmitting subsequent data.

U. S. Patent No. 4,562,559, issued December 31, 1985, of H. E. Sharp et al., uncovered the existence of "fine structure" within the passbands; e.g., "such fine structure is in the nature of a comb with transmission voids or gaps occurring between teeth representing transmission bands, both within the overall passbands." Sharp attributed this structure to "differences in pipe length, conditions of tool joints, and the like." The patent proposed a complicated phase shifted wave with a broader frequency spectrum to bridge these gaps.

The present invention is based upon a more thorough consideration of the underlying theory of acoustical transmission through a drill string. For the first time, the work of Barnes et al. has been analyzed as a banded structure of the type discussed by L. Brillouin, *Wave Propagation in Periodic Structures*, McGraw-Hill Book Co., New York, 1946. The theoretical results have also been correlated to extensive laboratory experiments on scale models of the drill string, and the original data tape obtained from Cox and Chaney's field-test has been reanalyzed. This analysis shows that Cox and Chaney's measurements contain data which is in excellent agreement with the theoretical predictions; that Sharp misinterpreted the cause of the fine structure; and that the ringing and the frequency limitations cited by Shawhan and Hixon are easily overcome by signal processing.

Figure 1 shows some of the results of the new analysis of the data recorded by Cox and Chancy. This figure is a plot of the power amplitude versus frequency of the transmitted signal. The theoretical boundaries between the passbands and the stopbands are shown by the vertical dotted lines. If this figure is compared to Figure 1 in Cox and Chaney's patent, significant and obvious differences can be noted. These are attributable to error in Cox and Chaney's analysis.

Furthermore, this Figure 1 also shows the "fine structure" of Sharp et al. From the new analysis we now know that this fine structure is caused by echos bouncing between opposite ends of the drill string, the number of peaks being correlated to the number of sections of drill pipe. A theoretical calculation of this field test was used to produce Figure 2. All of the phenomena important to the transmission of data in the drill string is represented in this calculation. These theoretical results accurately predict the location of the passbands and the fine structure produced by the echo phenomena.

The present invention relates to a method for transmitting data on a continuous data carrier signal through a drill string, comprising the steps of acoustically generating said signal at a first location near a first end of the drill string and detecting said acoustically generated signal at a second location near a second end of the drill string.

A first object of the present invention is to improve said method

This object is achieved by suppressing that part of said acoustically generated signal which travels in the direction of said first end of the drill string.

A second object of the present invention is to provide an apparatus for carrying out said improved method.

This object is achieved by the apparatus claimed in claim 16.

The apparatus and method for transmitting data along a drill string preferably use a modulated continuous acoustical carrier wave (waves) which is (are) centred within one (several) of the passbands of the drill string.

It is of advantage to use frequencies which are on the order of several hundreds to several thousands of Hertz in order to minimize the interference by the noise which is generated by the drilling process.

Preferred embodiments provide a system for suppressing the transmission of noise within the transmission band or bands.

It is also provided a system for suppressing echos from both ends of the drill string.

Additional advantages and features of the invention will become apparent to those skilled in the art upon examination of the following description or may be learned by practice of the invention.

The accompanying drawings, which we incorporated in and form part of the specification, illustrate an embodiment of the present invention and, together with the description, serve to explain the principles of the invention.

- Fig. 1 shows the measured frequency response within two passbands of the Cox-and-Chaney drill string.
- Fig. 2 shows the calculated frequency response within two passbands of the Cox-and-Chaney drill string.
- Fig. 3 shows a drill string.
- Fig. 4 shows dispersion curves for a uniform string (dashed line) and a typical drill string (solid line).
- Fig. 5 shows the transmission arrangement at a first end of a drill string.

DETAILED DESCRIPTION

As shown in Figure **3**, this invention involves the transmission of acoustical data along a drill string **10** which consists of a plurality of lengths of constant diameter drill pipe **15** fastened end-to-end at thicker diameter joint portions **18** by means of screw threads as is well known in this art. Lower end **12** of drill string **10** may include a length of constant diameter drill collar to provide downward force to drill bit **22**. A constant diameter mud channel **24** extends axially through each component of drill string **10** to provide a path for drilling mud to be pumped from the surface at upper end **14** through holes in drill bit **22** as is well known in this art. The upper end **14** of drill string **10** is terminated in conventional structure such as a derrick, rotary pinion, and kelly, represented by box **25**, to permit additional lengths of drill pipe to be added to the string, and the string to be rotated for drilling. Details of this conventional string structure may be found in the aforementioned patent of E. Hixon.

Although the disclosure is directed towards transmitting data from the lower end to the upper end, it is to be understood that the teachings of this invention apply to data transmission in either direction.

The theory upon which this invention is based begins with the derivation of the following Equation 1, which equation is in the form of a classical wave equation:

$$\frac{\partial^2 F}{\partial t^2} = z^2 \frac{\partial^2 F}{\partial m^2}. \qquad (1)$$

where impedance $z = \rho ac$, and total axial force

$$F(x,t) = -cz\frac{\partial u}{\partial x}$$

where ρ is density, a is area, and c is speed of sound over a cross-section of a slender, elastic, rod, u is the displacement, x is the position , m is the Lagrangian mass coordinate, and t is the time.

The existence of frequency bands which block propagation of acoustic energy is demonstrated for an idealized drill string where each piece of drill pipe consists of a tube of length d_1, mass density ρ_1, cross-sectional area a_1, speed of sound c_1, and mass r_1; and a tool joint of length d_2, mass density ρ_2, cross-sectional area a_2, speed of sound c_2, and mass r_2. A procedure demonstrated at page 180 of Brillouin has been used with the Floquet theorem to generate the following eigenvalue problem:

$$\begin{pmatrix} z_1 & z_1 & z_2 & z_2 \\ 1 & -1 & 1 & -1 \\ z_1 e^{\alpha_1 r_1} & z_1 e^{\beta_1 r_1} & z_2 e^{-\alpha_2 r_2} & z_2 e^{-\beta_2 r_2} \\ e^{\alpha_1 r_1} & -e^{\beta_1 r_1} & e^{-\alpha_2 r_2} & -e^{-\beta_2 r_2} \end{pmatrix} \begin{pmatrix} A_l/z_1 \\ B_l/z_1 \\ -A_{l-1}/z_2 \\ -B_{l-1}/z_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad (2)$$

where

$z_\xi = \rho_\xi a_\xi c_\xi$ (3)

$\alpha_\xi = i(kd/r - K_\xi)$ (4)

$\beta_\xi = i(kd/r + K_\xi)$. (5)

Here k is the wave number, $i = \sqrt{-1}$, $r = r_1 + r_2$, $d = d_1 + d_2$, $\omega = 2\pi f$, $K_\xi = \omega/z_\xi$, and f is the frequency being transmitted. This equation is seen to be similar to Equation 18 of Barnes et al., except the present examination shows Barnes' "W" to be kd.

Brillouin shows that frequencies which yield real solutions for k are banded and separated by frequency bands which yield complex solutions for k. He calls these two types of regions passbands and stopbands. The attenuation in the stopbands is generally quite large. Within each of the passbands the value of the phase velocity ω/k depends upon the value of ω. The drill string functions as an acoustic comb filter, and frequencies which propagate in the passbands are dispersed. Thus, signals which have broad frequency spectra are severely distorted by passage through a drill string. However, signal processing techniques can be used to remove this distortion.

It is to be understood that the "comb filter" referenced above refers to the gross structure in the frequency spectrum which is produced by the stopbands and the passbands, where each tooth of the comb is an individual passband. In contrast, Sharp's reference to a comb refers to a fine structure which exists within each passband.

Figure 4 shows a plot of the characteristic determinate of Equation 2 using values for ρ_ξ, a_ξ, c_ξ, and d_ξ representative of actual drill pipe parameters. The straight dotted line represents the solution for a uniform drill string, e.g., one where the diameter of the joints is equal to the diameter of the pipe. The velocity of propagation for a given frequency is represented by the phase velocity. For the uniform drill string, this ratio is constant and equal to the bar velocity of steel. When waves containing multiple frequency components travel through a uniform drill string (or drill collar **20**), they do not distort as all frequency components remain in the same relative position.

A different result occurs when the plot of Fig. 4 is curved, as each frequency then travels at a different speed. The solid lines of Fig. 4 represent the solution to Equation 2 for a realistic drill string where the area of the drill pipe is 2450 mm^2 (4 in^2) and the area of a tool joint is 12,900 mm^2 (20 in^2). In this situation, the phase velocity within each passband is curved, meaning that distortion exists.

Furthermore, the gaps represent stopbands. This analysis predicts the same values for the boundaries between the stopbands and the passbands as that of Barnes et al.; however, it also shows the characteristics of wave propagation within each of the passbands. Barnes et al. did not predict the distortion resulting from the effects of the passbands .

Calculations using a smaller diameter tool joint, representative of the reduction in diameter that occurs from wear, shows the stopbands to be narrower. This change is to be expected, because the worn joints bring the string geometry closer to the uniform geometry that produced the straight, dotted, line of Fig. 4.

Further calculations show that strings comprised of random length pipes will have significantly narrowed passbands. This result corresponds with, and for the first time explains, observations made by others.

Since the transmission of acoustical data through the drill string involves sending waves with complex transient shapes through strings of finite length, transient wave analysis has been used to predict the performance of the drill string. Fig. 2 shows the third and fourth passbands of a fast Fourier transform of the waveform which results from a signal which represents, to a rough approximation, the hammer blow used in the Cox and Chaney field test. This signal has a relatively narrow frequency content which only stimulates the third and fourth passband of the drill string. Ten sections of drill pipe were used in this field test, and the ends of the drill string produced nearly perfect reflection of the acoustic waves which resulted from the hammer blows.

This figure shows the "fine structure" of Sharp et al. to be caused by standing wave resonances within the drill string. The number of spikes in each passband correlates with the number of sections of pipe in the drill string, as explained in greater detail in the Appendix.

The analysis suggests the following technique for processing data signals and compensating for the effects of the stopbands and dispersion. First, transmit information continuously (as opposed to a broadband pulse mode) and only within the passbands and away from the edges of the stopbands. Second, compensate for dispersion by multiplying each frequency component by $\exp(-ikL)$, where L is the transmission length in the drill pipe section **18** of the drill string. Where a large amount of acoustical noise is present, such as would be caused by a drill bit or drill mud, it is preferable to transform the data signal before transmission, resulting in an undispersed signal at the receiver position.

The foregoing analysis is based on the assumption that echos are suppressed at each end of the drill string. This is necessary to eliminate the spikes or fine structure within each of the passbands. It is common knowledge that signal processing is effective when echo strength is 20 dB below the the signal level. Each time the acoustic wave interacts with the intersection of the drill pipe and the drill collar **80**, the signal weakens by 6 dB. Also, from the analysis of Cox and Chaney's field test, the signal attenuates about (2 dB/1000 feet). Therefore, an echo which is generated by a reflection of the data signal 2 dB/300 m at the top of the drill string **14** will lose 6 + 4 (L/300) dB (if L in meters) or 6 + 4 (L/1000) dB (if L in feets) as it travels back down the drill string to **80** and then returns to the receiver. Thus, if the drill pipe section has a length of 1065 m (3500 feet) or more, the echos from the receiving end of the string will be naturally attenuated to an acceptable level.

For shorter drill strings, additional echo suppression will be required. This can be accomplished with a device called a terminating transducer. This device has an acoustical impedance which matches the acoustical impedance of the drill string and an acoustical loss factor which is sufficient to make up the required 20 dB of echo suppression.

Because attenuation in the drill string is low, the energy velocity and group velocity are approximately equal. Therefore, the characteristic impedance of the drill string is the force F divided by velocity

$$\frac{\partial u}{\partial t}.$$

This value is the eigenvalue part of Equation 2, a complex number with a real part called the viscous component and an imaginary part called the elastic component. Ideally, the terminating transducers must have a stiffness equal to the elastic component and a damping coefficient equal to the viscous component. Practically, the response need only make up the difference between 20 dB and the natural attenuation of the drill string.

The characteristic impedance is a function of frequency and position, the position dependence being periodic in accordance with the period of the drill string. Calculations show that tool joints are not a good location for a termination because the impedance is a sensitive function of position. For the fourth passband, a location 1/3 or 2/3 along the pipe is better.

The design of termination transducers is a conventional problem to those of ordinary skill in that art provided with the impedance data from Equation 2. This device, for example, could consist of a ring of polarized PZT ceramic elements and an electronic circuit whose reactive and resistive components are adjusted to tune the transducer to the characteristic impedance of the drill string and provide the necessary acoustic loss factor.

Echo suppression is a more critical problem at the downhole end of the drill string where echos travel freely up and down the drill collar section and confuse the transmission of data. At this location, it is useful to use noise cancellation techniques both to suppress echos and to prevent the noise of the drill bit or drilling mud from interfering with the desired data signal uphole. A noise cancellation technique is disclosed hereinafter.

Fig. 5 shows a section **30** of drill collar **20** located relatively close to downhole end **12** of drill string **10** and containing apparatus for transmitting a data signal towards the other end of the drill string while suppressing the transmission of acoustical noise up the drill string. In particular, this apparatus includes a transmitter **40** for transmitting data uphole, but not downhole, a sensor **50** for detecting acoustical noise from downhole and applying it to transmitter **40** to cancel the uphole transmission of the noise, and a sensor **60** for providing adaptive control to transmitter **40** and sensor **50** to minimize uphole transmission of noise.

Transmitter **40** includes a pair of spaced transducers **42**, **44** for converting an electrical input signal into acoustical energy in drill collar **30**. Each transducer may be a magnetostrictive ring element with a winding of insulated conducting wire. These transducers are spaced apart a distance b equal to one quarter wavelength of the center frequency of the passband selected for transmission. A data signal from source **28** is applied directly to uphole transducer **44**, preferably through a summing circuit **46**. The data signal is also applied to transducer **42** through a delay circuit **47** and an inverting circuit **48**. Delay circuit **47** has a delay value equal to distance b divided by the speed of sound in drill collar **30** at transmitter **40**.

The operation of this transmitter may be understood from the following explanation. Each of transducers **42, 44** provide an acoustical signal F_2, F_4 that travels both uphole and downhole. Accordingly the resulting upward and downward waves from both transducers are:

$$\phi_u(t,x) = F_2(t-x/c)+F_4(t-(x-b)/c)) \text{ where } x>b$$
$$\phi_d(t,x) = F_2(t+x/c)+F_4(t+(x-b)/c)) \text{ where } x<0 \qquad (6)$$

where x is the uphole distance from transducer **42** and c is the speed of sound. For no downward wave, $\phi_d(t,x) = 0$, or

$$F_2(t) = -F_4(t-b/c) \qquad (7)$$

and

$$\phi_u(t,x) = -F_2(t-(x+b)/c)+F_2(t-(x-b)/c) \qquad (8)$$

If the acoustical signal F_2 has the form $A\cos(\omega t)$, then Equation 8 solves to

$$\phi_u(\tau) = -2A\sin(\omega b/c)\sin(\omega\tau) \qquad (9)$$

where $\tau = (t - x/c)$.

Accordingly, with a quarter wavelength spacing for waves at the center of the transmission passband, transmitter **40** transmits an uphole signal having approximately twice the amplitude A of the applied signal, and no downhole signal.

Noise sensor **50** includes a pair of spaced sensors **52, 54** which operate in a similar manner to provide an indication of acoustic energy moving uphole, and no indication of energy moving downhole. The output of sensor **52**, which sensor may be an accelerometer or strain gauge, is an electrical signal that is summed in summing circuit **56** with the output of similar sensor **54**, which output is delayed by delay circuit **57** and and inverted by inverting circuit **58**. If the delay of circuit **57** is equal to the spacing b divided by the speed of sound c, downward moving energy is first detected by sensor **54** and delayed, and later detected by downhole sensor **52**. The inverted electrical signal from **54** arrives at summing circuit **56** at the same time as the output of sensor **52**, providing a net output of zero for downward moving noise. Upward moving noise of the form $A\sin\omega(t - x/c)$ yields an output from summing circuit **56** of:

$$\phi(t) = 2A\sin(\pi f/2f_0)\cos\omega(t-b/c) \quad (10)$$

where f_0 is the center frequency of the passband.

In the description which follows it is to be understood that all electrical signals are filtered so that the frequency content is limited to the passband or bands which are used for data transmission. Sensor **50** is spaced from transmitter **40** by distance a. Accordingly, noise that is sensed at sensor **50** arrives at transmitter **40** a time a/c later. If the output of sensors **50** is delayed by delay circuit **59** for an interval of a/c and applied to transmitter **40** through summing circuit **46**, the output of transmitter **40** can be shown to cancel the upward moving noise to within an error $\epsilon = -(\sin(\omega b/c))^2 + 1$. For a bandwidth-to-center frequency ratio of 150 Hz/650 Hz, the error is zero at the center of the transmission band and is only .03 at the band edges, a result showing 30 db noise cancellation.

Further control of upward moving noise is provided by adaptive control **70**, a conventional control circuit that has an input from a second pair of sensors **62, 64**. These sensors, identical to sensors **52, 54,** also have corresponding delay circuit **67** and inverter **68** to provide an output indicative of an upward moving wave and no output in response to a downward moving wave. The upward moving wave at control sensors **60** is a mixture of the noise and data that passed transmitter **40**. Accordingly, by delaying the data signal in delay circuit **72** and adding the result to the output of sensors **60** with summing circuit **74**, an error signal is produced which indicates the effectiveness of noise cancelation. This signal is fed into an adaptive control circuit **70** which controls conventional circuitry **75** to adjust voltage amplitudes or phases of the signals being applied to any of sensors **52** and **62** or transmitters **42, 44** to minimize the amount of noise being transmitted upward towards the surface.

For a conventional steel drill collar, the spacing b between sensors or transmitters in the third passband would be about 30 cm (78 inches) or about 21 cm (53 inches) in the fourth passband.

The operation of the invention is as follows: The circuitry of Fig. 5 is mounted on a drill collar, including suitable circuitry **28** for generating data representative of a downhole parameter. Power supplies, such as batteries or mud-driven electrical generators, and other supportive circuitry known to those of ordinary skill in the art, would also be incorporated into drill collar **30**. The drill bit and mud create acoustic noise that travels in both directions through drill string **10**. Downward noise is not sensed by the sensors; however, upward noise, including echos from the bottom of the drill collar, are sensed by sensor circuit **50** and applied to transmitter circuit **40**, yielding a greatly reduced upward noise component. Primarily the data travels to the connection **80** (Fig. 3) between drill collar **30** and the lowest drill joint **18**, where a significant reflection of the data occurs because of the mismatch in acoustic impedance between these elements. Further echos occur at the tool joints **18** between each section of drill pipe **15**. These echos move downward through drill collar **30** where they pass the circuitry of Fig. 5 undetected, and become noise that is canceled out when they echo off the bottom of the drill collar. The signal that reaches the top is detected by a receiver such as an accelerometer. If necessary because of low attenuation within the drill string, an acoustically impedance matched transducer **80** may be used to terminate the signal and provide an accurate representation of the data transmitted from below.

As stated above, the data from circuit **28** may be precompensated by multiplying each frequency component of the signal by $\exp(-ikL)$ to adjust for the distortion caused by the passbands of the drill string. Such compensation may be accomplished by any manner known to those of ordinary skill in the art with a device such as an analog-to-digital signal processing circuit.

This invention recognizes and solves the problems noted by many previous workers in the field of transmitting data along a drill string. As a result, quality transmission on continuous acoustic carrier waves without extensive downhole circuitry, and without the use of impractical repeater circuits and transducers along the drill string, is possible at frequencies on the order of several hundred to several thousand Hertz. These frequencies are high in relation to the ambient drilling noise (about 1 to 10 Hz), and therefore allow transmission relatively free of this noise. Also the bandwidths of the passbands allow data rates far in excess of present mud pulse systems. Also it is recognized that this method will work in drilling situations where air is used instead of mud.

The particular sizes and equipment discussed above are cited merely to illustrate a particular embodiment of this invention. It is contemplated that the use of the invention may involve components having different sizes and shapes, as long as the principle set forth in the claims is followed. It is intended that the scope of the invention be defined by the claims appended hereto.

Claims

1. Method for transmitting data on a continuous data carrier signal through a drill string (10) comprising

acoustically generating said signal at a first location near a first end (12) of the drill string (10),

detecting said acoustically generated signal at a second location near a second end (14) of the drill string (10) characterized by

suppressing that part of said acoustically generated signal which travels in the direction of said first end (12) of the drill string (10).

2. Method as claimed in claim 1, characterized in that the drill string (10) has low attenuation passbands and high attenuation stopbands of acoustical signals, and in that the frequency components of said acoustic signal are located in said passbands.

3. Method as claimed in claim 1 or 2, characterized in that the data carrier signal is an electrical signal that is converted in an acoustical signal at said first location near the first end (12) of the drill string, and in that said detected acoustical signal is converted to an electrical signal at said second location near the second end (14) of the drill string.

4. Method as claimed in any one of the claims 1 to 3, characterized by suppressing acoustical echoes from each end (12, 14) of said drill string.

5. Method as claimed in any one of the claims 1 to 4, characterized in that the drill string (10) has a plurality of drill pipe sections (15) connected end-to-end by joints (18), the length and the cross-sectional area of the drill pipe sections (15) being different from the length and cross-sectional area of the joints (18), and in that said first end (12) of the drill string (10) is located below the surface of the earth and said second end (14) of the drill string (10) is located above the surface of the earth.

6. Method as claimed in any one of the claims 1 to 5 characterized by generating two acoustical signals in the drill string (10) in an acoustical passband of the latter, at two locations spaced apart axially along the drill string by a distance of approximately an odd multiple of a quarter wave-length of the centre frequency of said passband.

7. Method as claimed in claim 6, characterized in that the acoustical signal generated at the location that is the farthest away from said second end (14) is delayed by a time equal to b/c, where b is an add multiple of a quarter wave-length of the centre frequency of said passband and c is the speed of sound in the drill string (10) in the vicinity of said two locations.

8. Method as claimed in claim 7 characterized by sensing between said first end (12) of the drill string and the location where the delayed acoustical signal is generated, the acoustical noise moving from said first end (12) to said second end (14) of the drill string.

9. Method as claimed in claim 8, characterized in that the sensing of said acoustical noise includes

sensing the outputs of two acoustical sensors (52, 54) spaced apart axially along the drill string (10) by a distance of approximately an add multiple of a quarter wave length of the centre frequency of said passband, and

delaying and inverting one of said outputs relative to the other by a time equal to b/c, where b is an add multiple of a quarter wave length of the centre frequency of said passband, and c is the speed of sound in the drill string (10).

10. Method as claimed in claim 9, characterized by summing said outputs and applying the summed outputs to generate a signal which cancels acoustical noise travelling from said first end (12) to said second end (14) of the drill string.

11. Method as claimed in claim 10, characterized by sensing between the location where the non-delayed acoustical signal is generated and said second end (14) of the drill string, acoustical energy moving towards said second end (14) of the drill string.

12. Method as claimed in claim 11, characterized in that the sensing of the acoustical energy moving towards said second end of the drill string includes

sensing the outputs of two acoustical sensors (62, 64) spaced apart axially along the drill string (10) by a distance of approximately an add multiple of a quarter wave length of the centre frequency of said passband, and

delaying and inverting one of said outputs relative to the other by a time equal to b/c, where b is an add multiple of a quarter wave length of the centre frequency of said passband, and c is the speed of sound in the drill string (10).

13. Method as claimed in claim 12 characterized by summing the non-delayed with the delayed output of the acoustical sensors (62, 64) and applying them to generate an adaptive control signal for data transmission.

14. Method as claimed in any one of the claims 1 to 13, characterized by suppressing acoustical echoes at said second end (14) of the drill by matching the acoustical impedance of said drill string (10) and providing a sufficient loss factor to keep echo strength about 20 dB below signal level to terminate the signal.

15. Method as claimed in any one of the claims 1 to 14, characterized by

multiplying each frequency component of said signal by exp(-ikL), where L is the transmission length of said drill string, k is the wave number in said drill string at the frequency of the respective frequency component, and i is the imaginary unit ($i^2 = -1$), in order to counteract comb filter like distortions caused by the drill string.

16. Apparatus for transmitting data on a continuous data carrier signal through a drill string (10), comprising

an acoustical transmitter (40) near a first end (12) of said drill string (10) for acoustical transmission of said data carrier signal,

an acoustical receiver near a second end (14) of said drill string (10) for receiving said acoustically transmitted data carrier signal,

characterized by

a first and a second acoustical transmitter (42, 44) spaced along said drill string (10) a distance approximately equal to an odd multiple of quarter wave length of said data carrier signal, said first transmitter (42) being closer to said first end (12) than said second transmitter (44), and said first and second transmitter (42, 44) making up said acoustical transmitter (40) near the first end (12) of said drill string (10),

a first delay and invert circuit (47, 48) connected to said first transmitter (42) for delaying and inverting said data carrier signal, and

adjusting means connected to said first delay and invert circuit (47, 48) for adjusting said delay to the transmission time of an acoustical signal from said first transmitter (42) to said second transmitter (44).

17. Apparatus as claimed in claim 16 characterized by

a first and second acoustical receiver (52, 54) spaced along said drill string (10) a distance equal to an odd multiple of a quarter wave-length of the carrier wave, said first receiver (52) being between said first end (12) and said second receiver (54), said second receiver (54) being between said first receiver (52) and the transmitter (40),

a second delay and invert circuit (57, 58) connected to said second receiver (54) for delaying and inverting the received noise signal of said second receiver (54),

adjusting means connected to said delay and invert circuit (57, 58) for adjusting the delay to the transmission time of the acoustical noise signal from said first receiver (52) to said second receiver

(54),

first summing means (56) for summing the delayed, inverted noise signal of the second receiver (54) and the received noise signal of the first receiver (52),

a third delay circuit connected to said first summing means (56) for delaying the output signal of said first summing means (56),

adjusting means connected to said third delay circuit (59) for adjusting the delay to the transmission time of the acoustical noise signal from said second receiver (54) to said transmitter (40),

second summing means (46) for summing the output signal of said third delay circuit (59) and said data carrier signal, the output signal of said second summing means (46) being the input signal for said first delay and invert circuit (47, 48) connected to said first transmitter (42) and for said second transmitter (44).

18. Apparatus as claimed in claim 17, characterized by

a third and fourth acoustical receiver (62, 64) spaced along said drill string (10) a distance equal to an odd multiple of a quarter wavelength of said carrier wave, said fourth receiver (64) being between said transmitter (40) and said second end (14), said third receiver (62) being between said fourth receiver (64) and said transmitter (40),

a fourth delay and invert circuit (67, 68) connected to said fourth receiver (64) for delaying and inverting the received signal of the fourth receiver (64),

adjusting means connected to said fourth delay and invert circuit (67, 68) for adjusting the delay to the transmission time of the acoustical signal from said third receiver (62) to said fourth receiver (64),

third summing means for summing the delayed, inverted signal of the fourth receiver (64) and the received signal of the third receiver (62),

a fifth delay circuit (72) for delaying the data carrier signal,

adjusting means connected to said fifth delay circuit (72), for adjusting the delay to the transmission time of an acoustical signal from said second transmitter (44) to said third receiver (62), and

fourth summing means (74) for summing the delayed data carrier signal and the output signal of said third summing means, the output signal of said fourth summing means (74) being an input signal of an adaptive control circuit (70).

19. Apparatus as claimed in any one of the claims 16 to 18 characterized in that said first end (12) of said drill string (10) comprises a drill collar, and in that said transmitter (40) and said anti-noise means are affixed to said drill collar.

20. Apparatus as claimed in any one of the claims 16 to 19 characterized in that the acoustical impedance of said receiver near the second end (14) of the drill string is matched to the acoustical impedance of said drill string (10) at said second end (14), thereby preventing the generation of echos from said second end (14) towards said first end (12) of said drill string.

21. Apparatus as claimed in any one of the claims 16 to 20 characterized by a signal processing circuit capable of multiplying each

frequency component of said date carrier signal by exp(-ikL), where L is the transmission length of said drill string (10), k is the wave number in said drill string at the frequency of the respective frequency component, and i is the imaginary unit ($i^2 = -1$), said signal processing circuit counteracting comb filter like distortions caused by the drill string (10).

FIG. 1

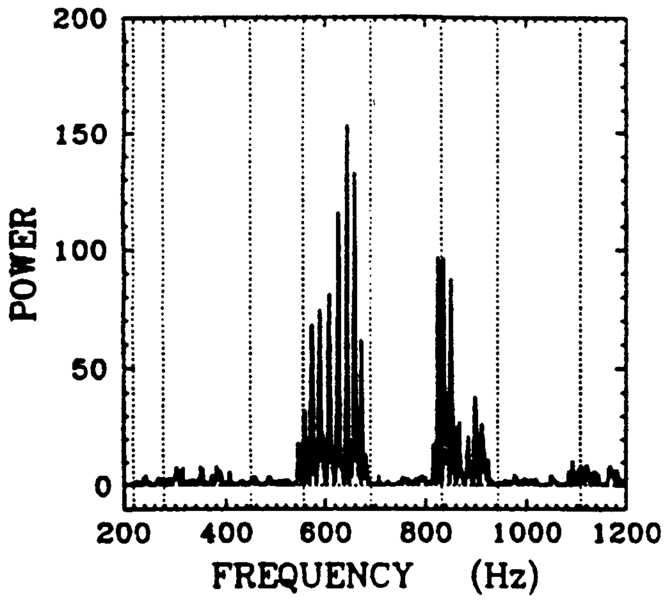


FIG. 2

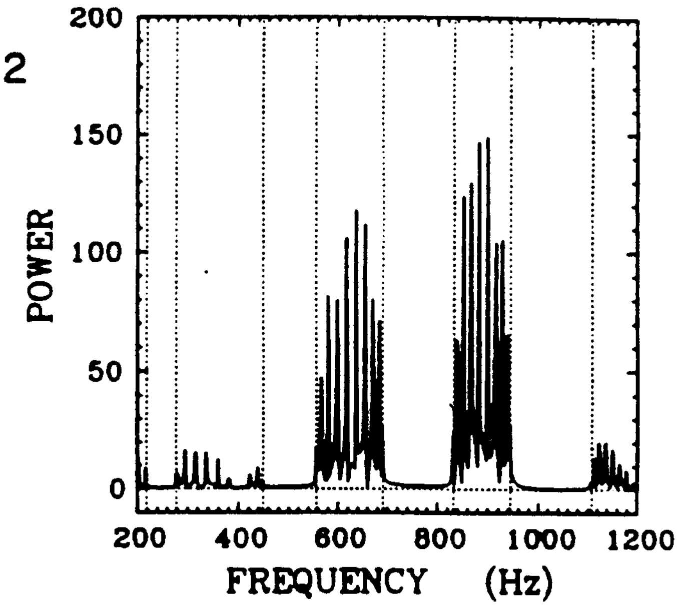
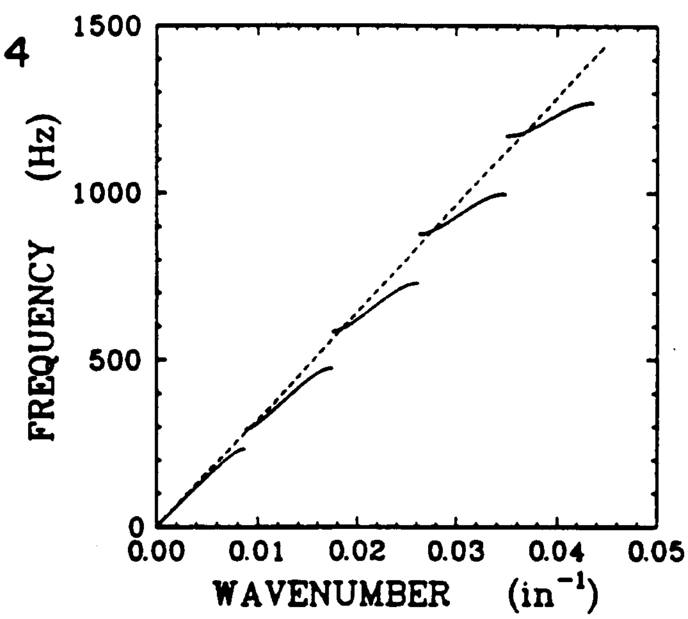


FIG. 4



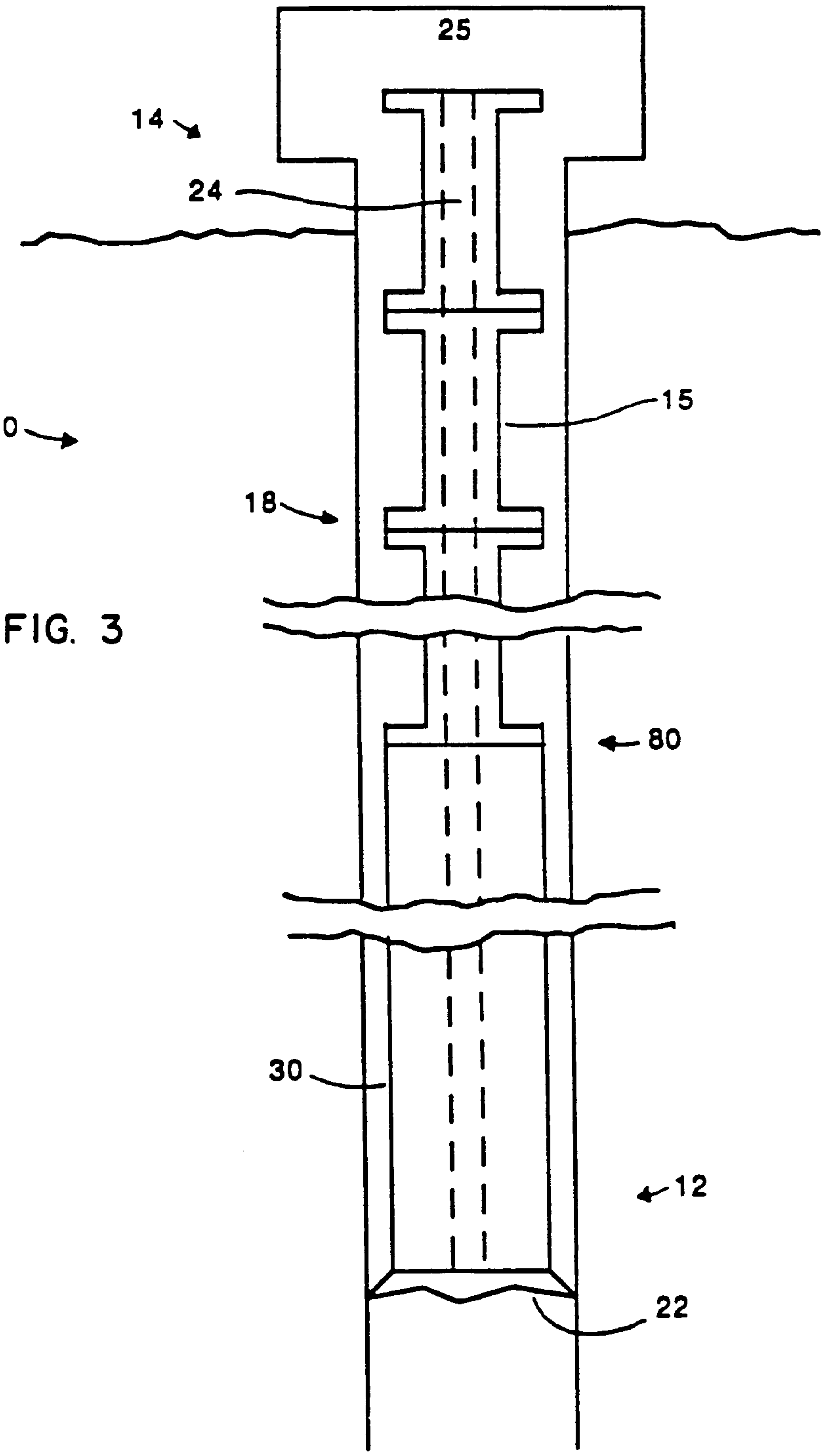


FIG. 3

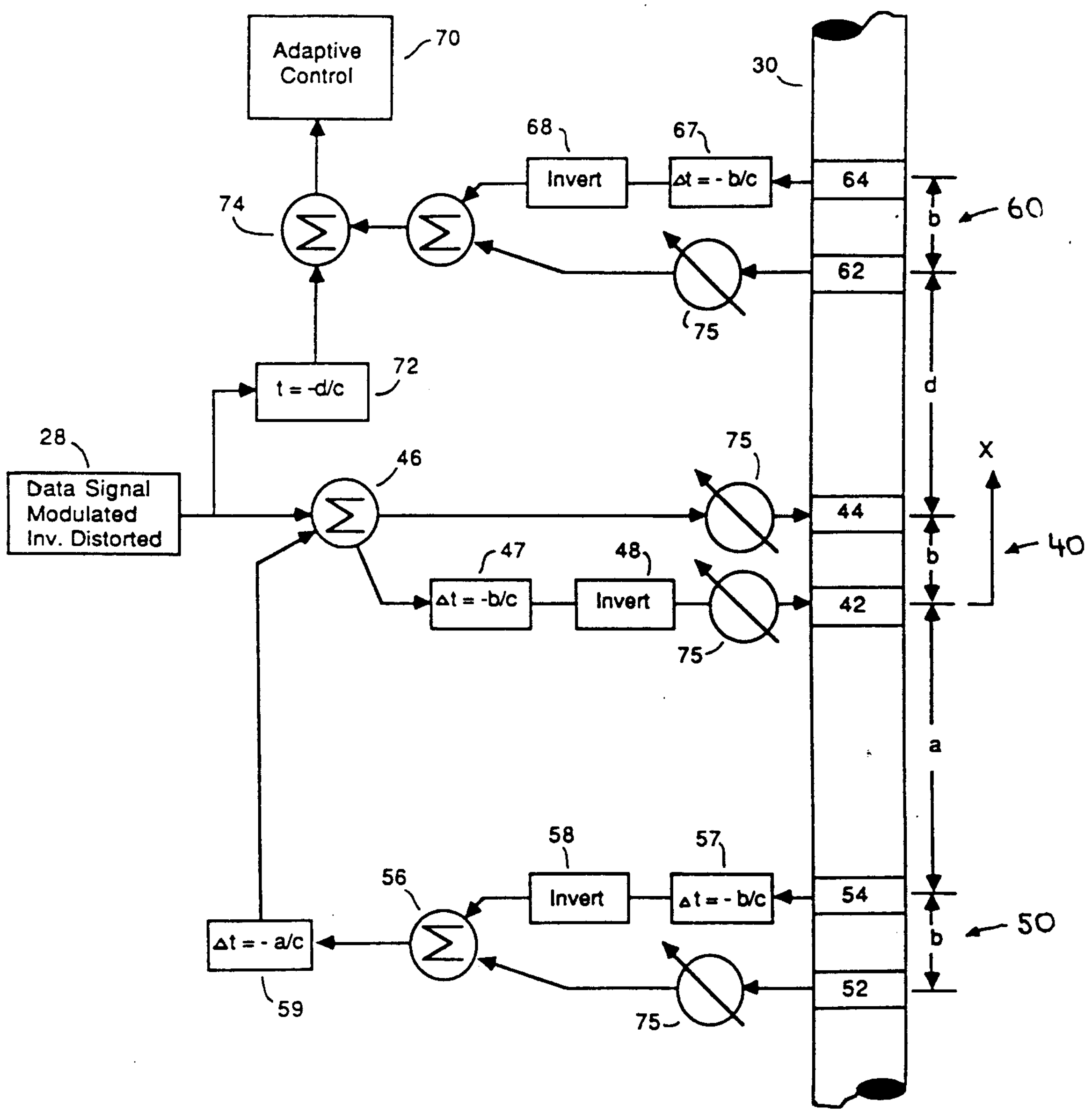

Adaptive Control
70
30
68
67
Invert
Δt = - b/c
64
60
74
b
62
75
72
t = -d/c
d
28
Data Signal Modulated Inv. Distorted
46
75
X
44
47
48
b
40
Δt = -b/c
Invert
42
75
a
58
57
56
Invert
Δt = - b/c
54
Δt = - a/c
b
50
52
59
75

Fig. 5