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Sexton et al.

[11] **3,820,063**

[45] **June 25, 1974**

[54] **LOGGING-WHILE-DRILLING ENCODER**

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[73] Assignee: **Mobil Oil Corporation**, New York, N.Y.

[22] Filed: **Mar. 12, 1973**

[21] Appl. No.: **340,137**

[52] **U.S. Cl.**... **340/18 LD**, 340/18 NC, 340/18 FM, 175/50, 324/83 FE, 318/314

[51] **Int. Cl.**..... **G10v 1/40**

[58] **Field of Search**..... 340/18 P, 18 FM, 18 LD, 340/18 NC; 166/113; 175/40, 50, 298; 324/83 FE; 318/312, 314, 333–335, 227

[56] **References Cited**

UNITED STATES PATENTS

2,700,131	1/1955	Otis et al.	340/18 FM
3,015,801	1/1962	Kalbfell	340/18 FM
3,309,656	3/1967	Godbey	340/18 LD
3,553,555	1/1971	Morris et al.	318/314
3,668,492	6/1972	Kowishi et al.	318/314

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Assistant Examiner—N. Moskowitz
Attorney, Agent, or Firm—A. L. Gaboriault; William J. Scherback

[57] **ABSTRACT**

In a logging-while-drilling system motor speed is changed in order to change the phase of an acoustic signal between two phase states. In carrying out a change in phase state, a step voltage is initially applied to a motor control circuit. Added to the step voltage is a linearly increasing voltage. The amount of phase shift in the acoustic signal is detected, and upon the occurrence of a predetermined phase shift the voltage applied to the motor control circuit is reduced to a lesser value. The application of the voltage of lesser value is continued for a predetermined time at which the acoustic signal will have substantially attained the other phase state. The rotary valve driven by the motor imparts a high degree of phase coherence to the acoustic signal which it generates. Rotation of the motor is phase locked to a highly stable clock in near optimal manner by sampling the phase error between the clock and the motor angular position reference every half period of the acoustic signal.

15 Claims, 8 Drawing Figures

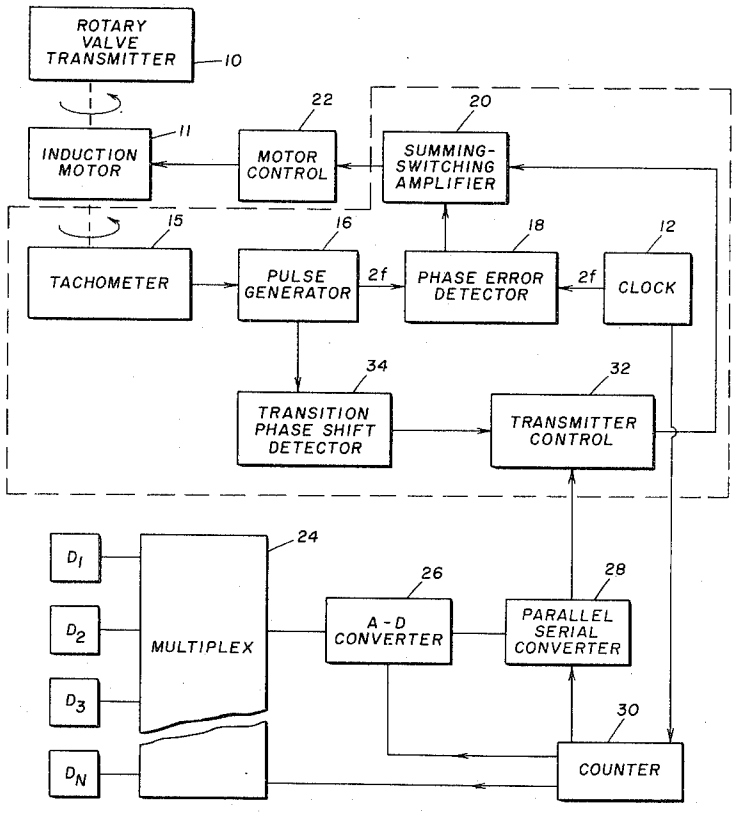


FIG. 1

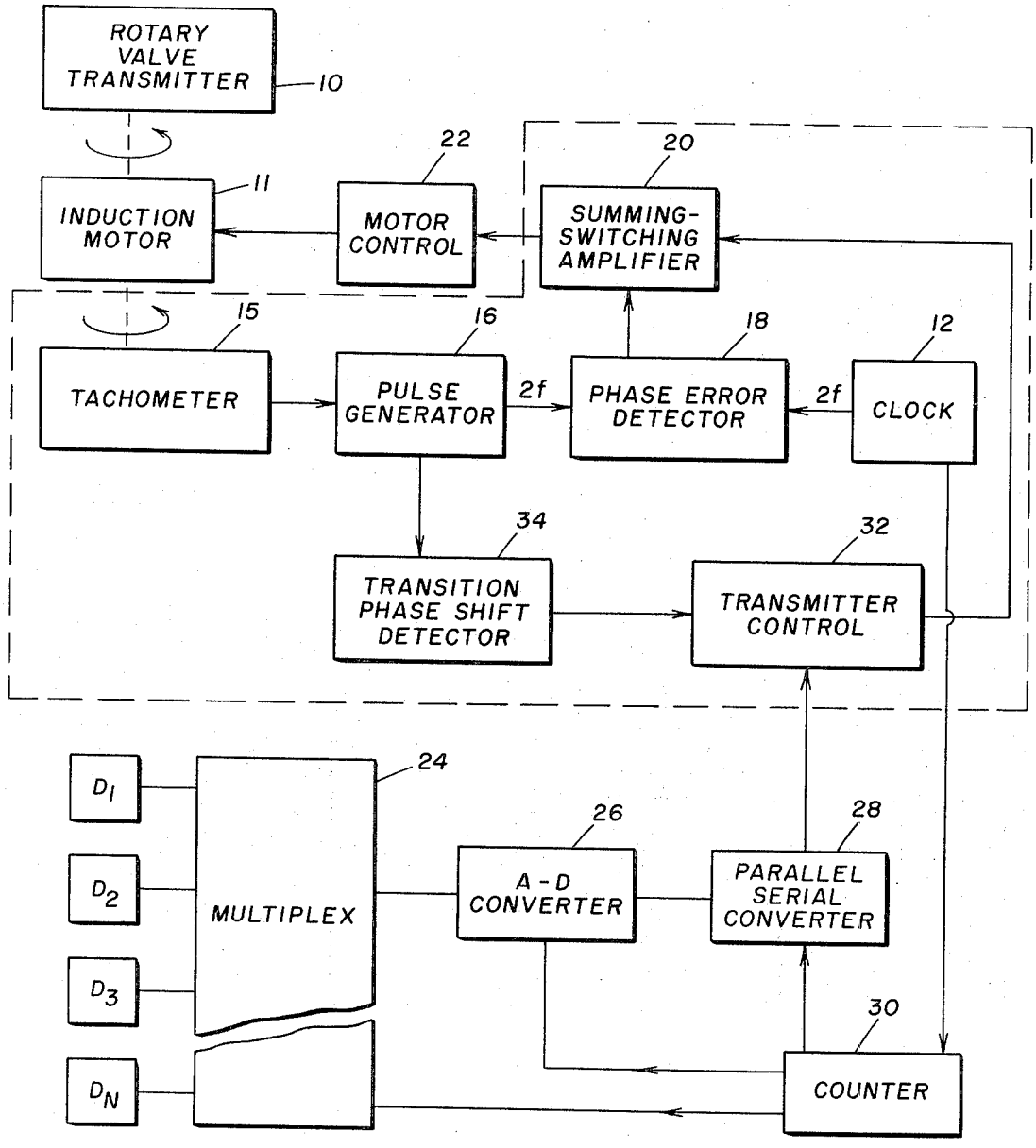
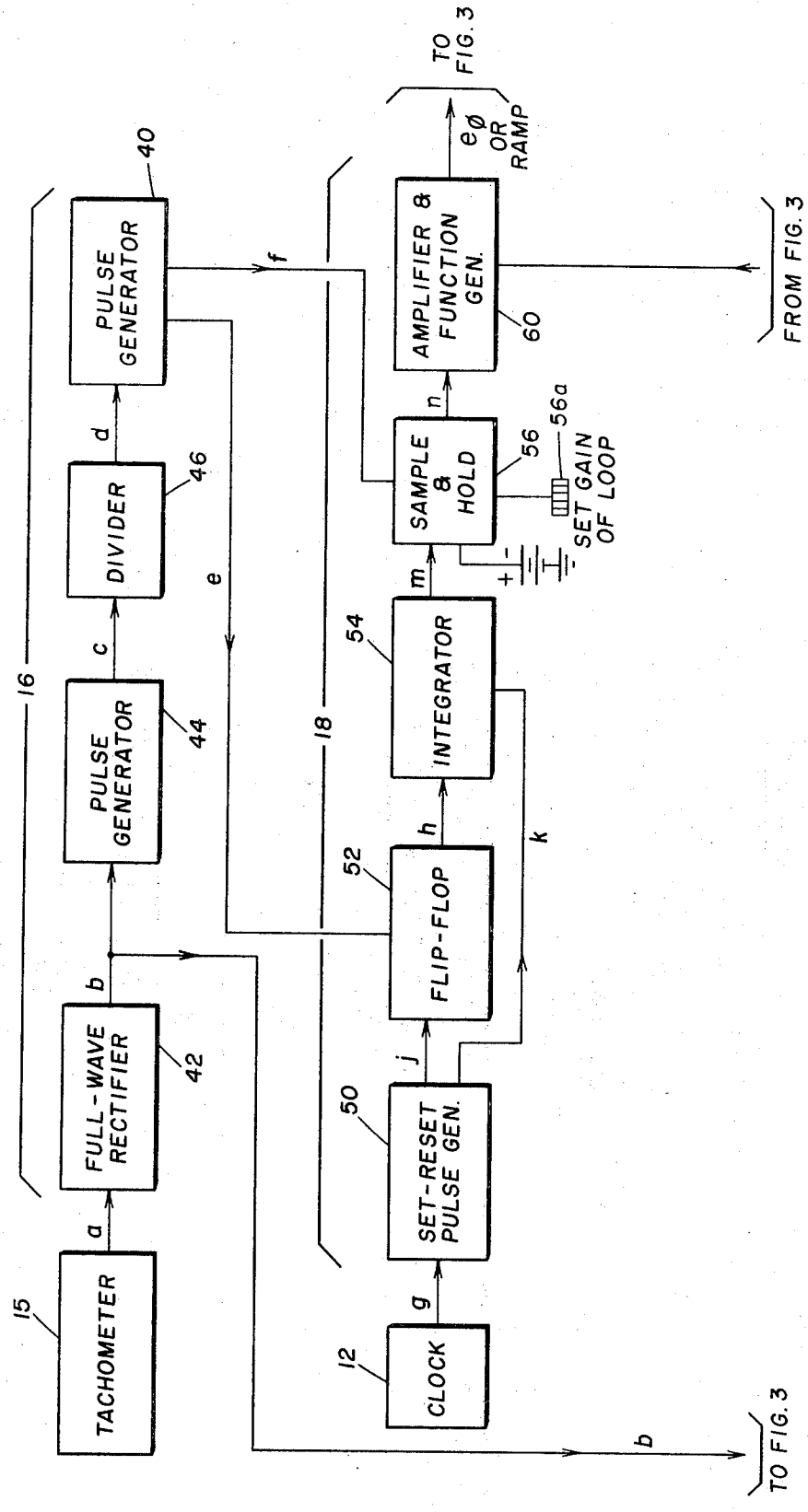

ROTARY VALVE TRANSMITTER
10
INDUCTION MOTOR
11
MOTOR CONTROL
22
SUMMING-SWITCHING AMPLIFIER
20
TACHOMETER
15
PULSE GENERATOR
16
2f
PHASE ERROR DETECTOR
18
2f
CLOCK
12
TRANSITION PHASE SHIFT DETECTOR
34
TRANSMITTER CONTROL
32
D1
D2
D3
DN
MULTIPLEX
24
A-D CONVERTER
26
PARALLEL SERIAL CONVERTER
28
COUNTER
30

FIG. 2


TACHOMETER
15
a
FULL-WAVE RECTIFIER
42
b
PULSE GENERATOR
44
c
DIVIDER
46
d
PULSE GENERATOR
40
16
e
f
18
CLOCK
12
g
SET-RESET PULSE GEN.
50
j
FLIP-FLOP
52
h
INTEGRATOR
54
m
SAMPLE & HOLD
56
56a
SET GAIN OF LOOP
n
AMPLIFIER & FUNCTION GEN.
60
eø OR RAMP
TO FIG. 3
FROM FIG. 3
TO FIG. 3
k
b

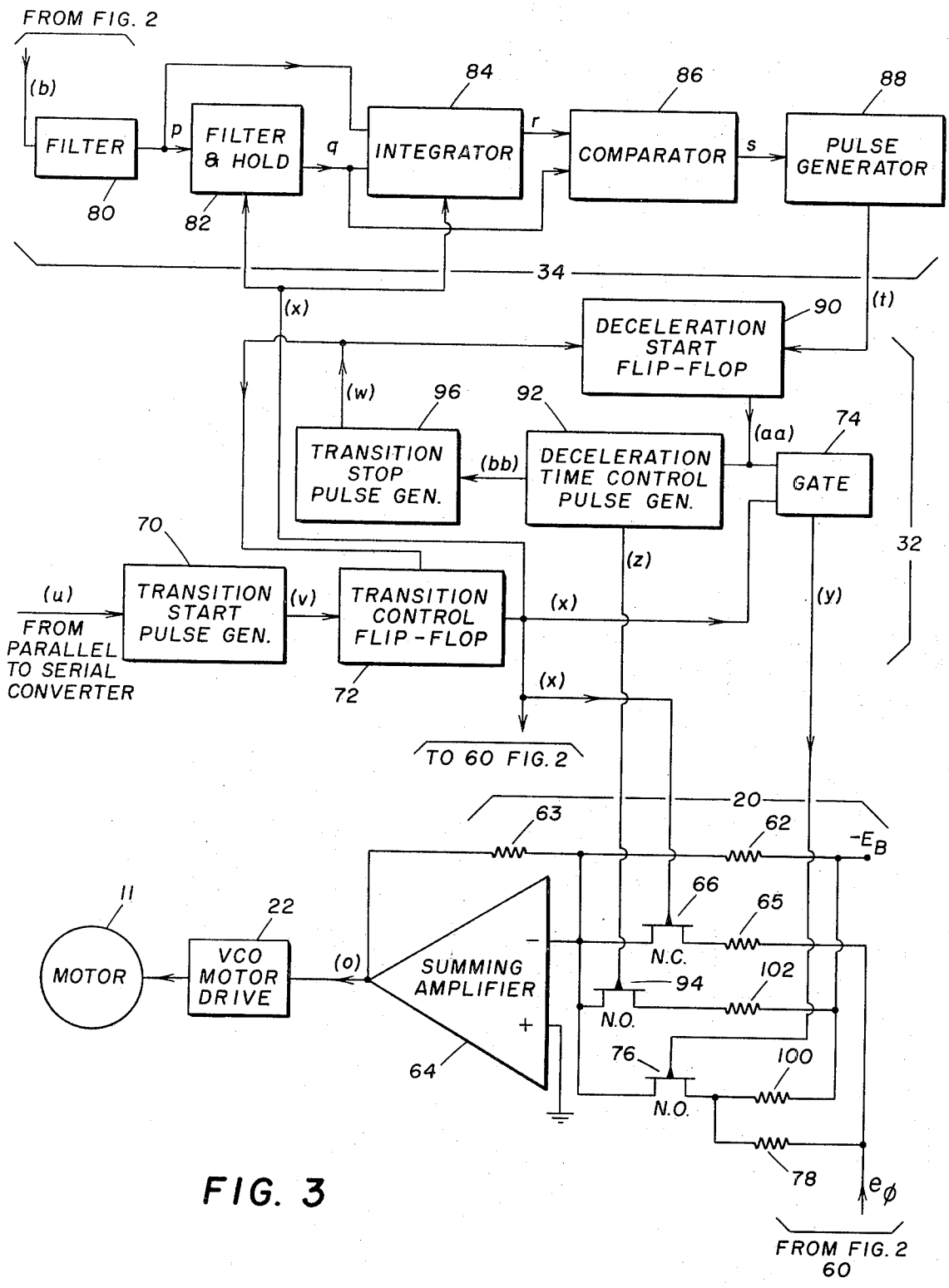

FROM FIG. 2
(b)
FILTER
80
p
FILTER & HOLD
82
q
84
INTEGRATOR
r
86
COMPARATOR
s
88
PULSE GENERATOR
34
(x)
90
DECELERATION START FLIP-FLOP
(t)
(w)
96
TRANSITION STOP PULSE GEN.
92
(bb)
DECELERATION TIME CONTROL PULSE GEN.
(aa)
74
GATE
32
70
(u)
FROM PARALLEL TO SERIAL CONVERTER
TRANSITION START PULSE GEN.
(v)
TRANSITION CONTROL FLIP-FLOP
72
(z)
(y)
TO 60 FIG. 2
20
63
62
$-E_B$
66
65
N.C.
94
102
N.O.
76
100
N.O.
78
e_ϕ
FROM FIG. 2
60
11
MOTOR
22
VCO MOTOR DRIVE
(o)
SUMMING AMPLIFIER
64

FIG. 3

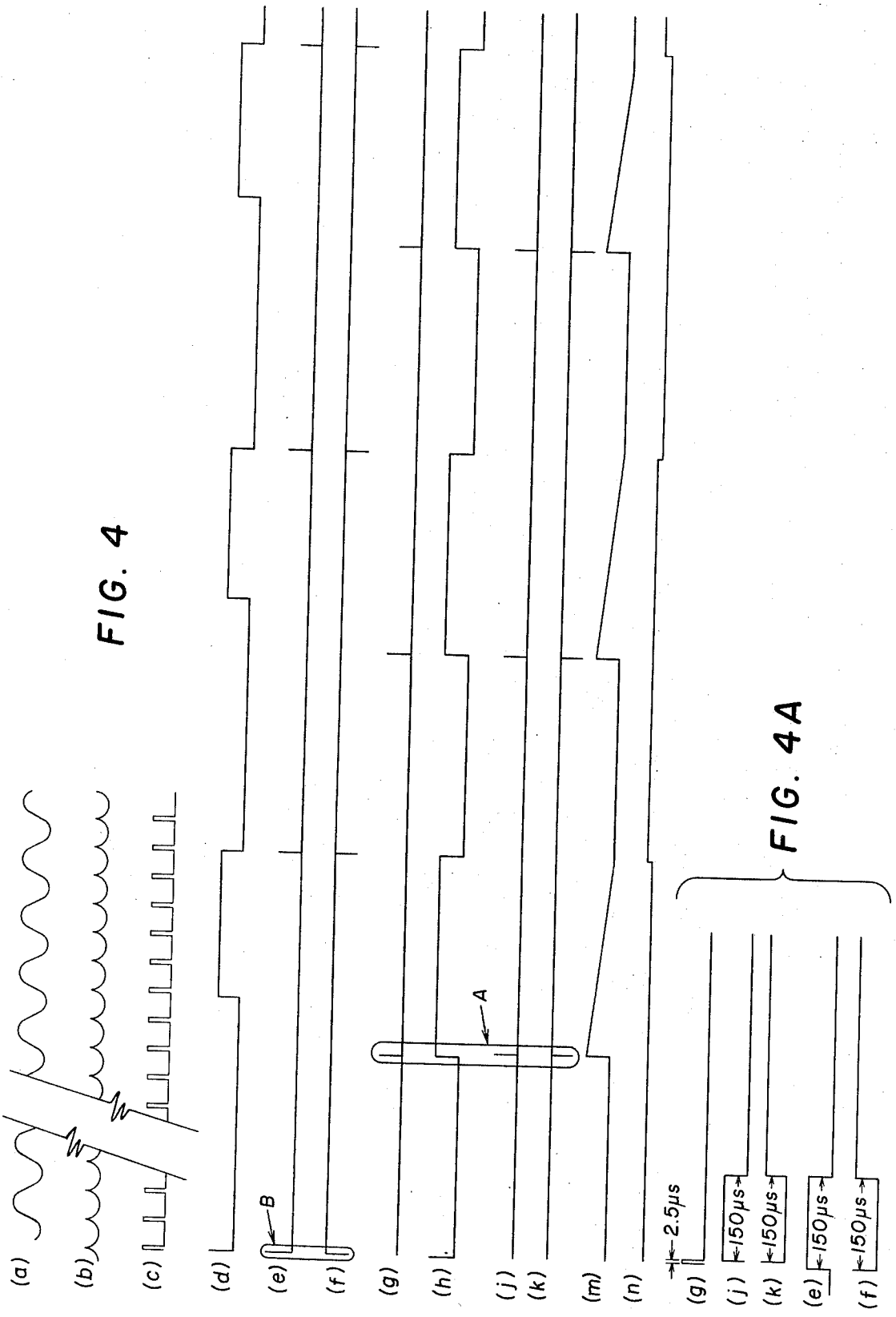
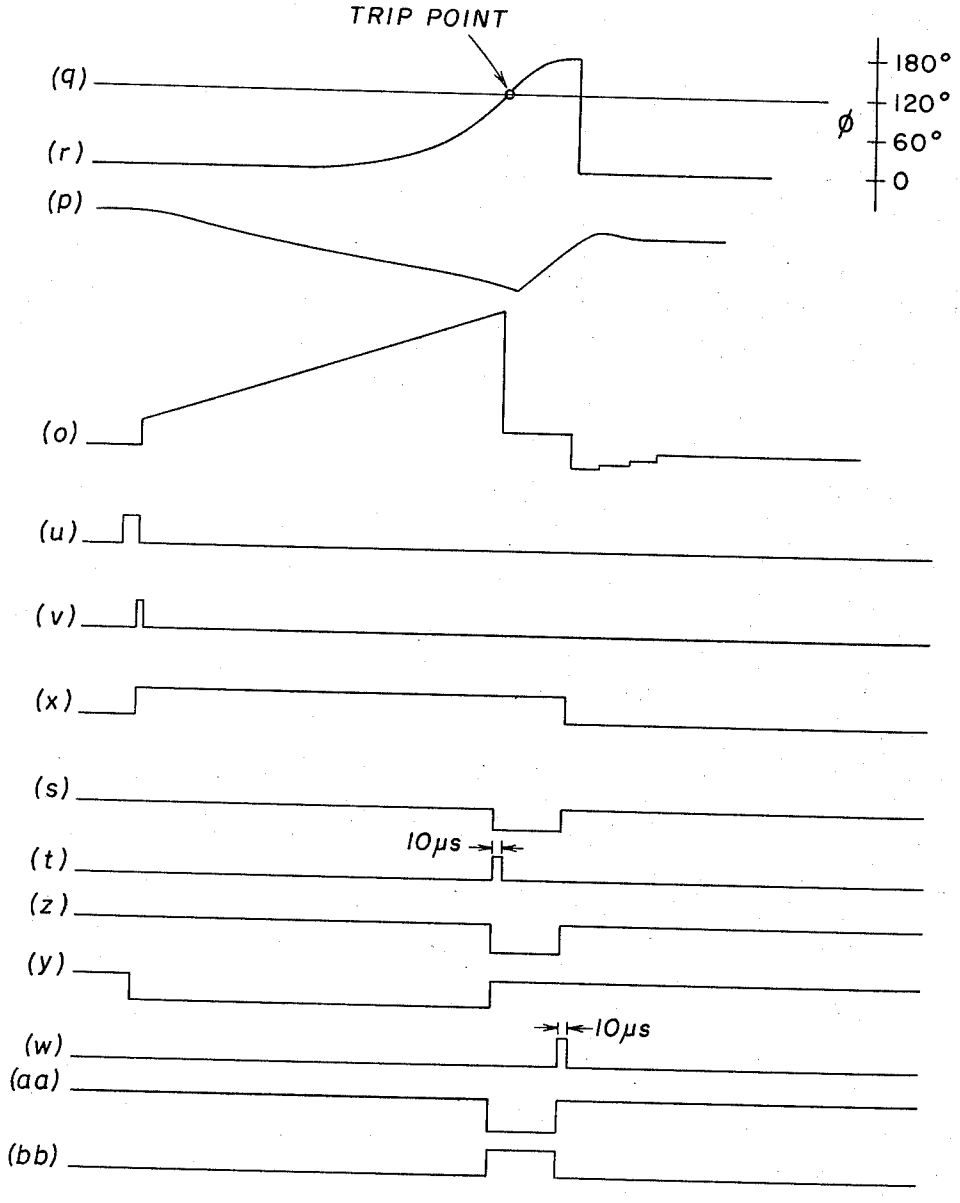


FIG. 4

FIG. 4A

FIG. 5



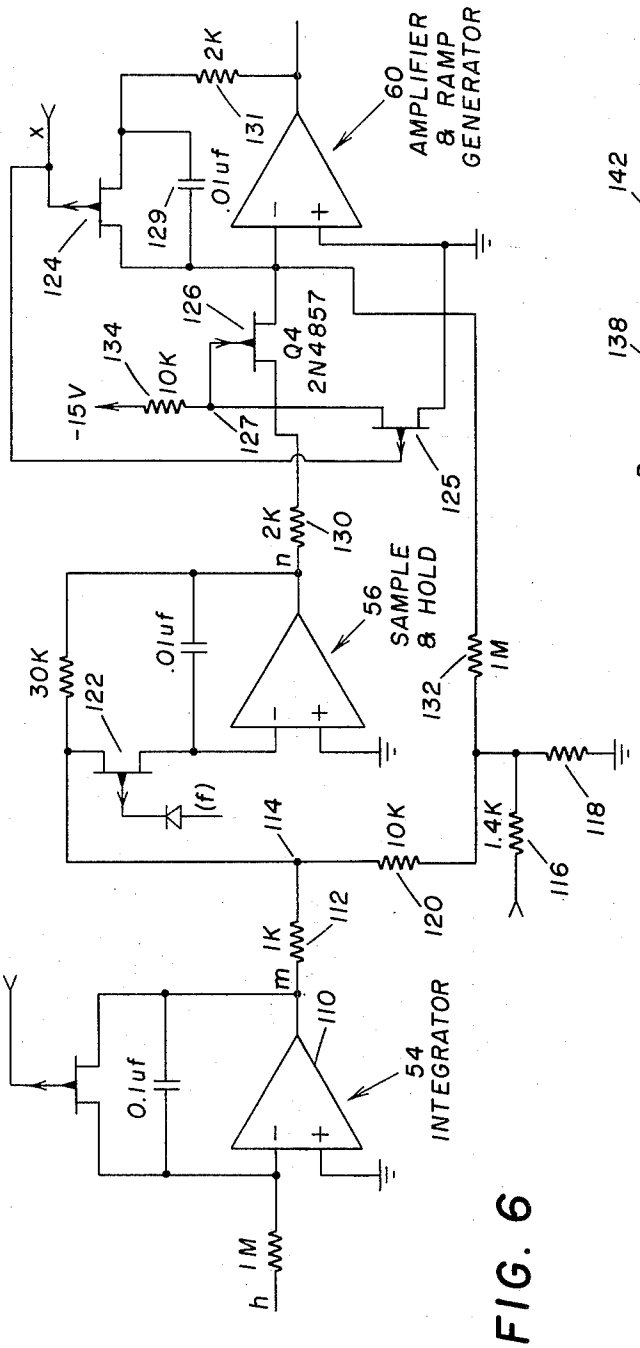

60
AMPLIFIER
& RAMP
GENERATOR
2K
131
.01uf
129
124
x
126
Q4
2N4857
134
10K
-15V
127
125
2K
130
n
56
SAMPLE
& HOLD
30K
122
.01uf
132
1M
(f)
114
10K
120
1.4K
116
118
1K
112
m
110
54
INTEGRATOR
0.1uf
h
1M

FIG. 6

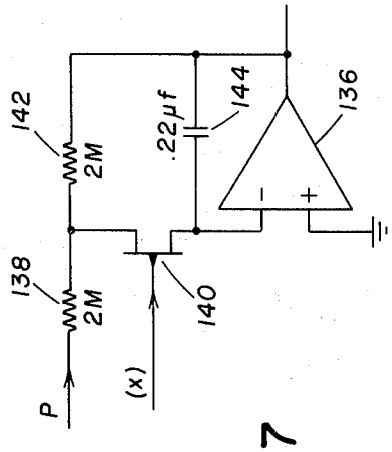

142
2M
.22μf
144
136
138
2M
140
P
(x)

FIG. 7

LOGGING-WHILE-DRILLING ENCODER

BACKGROUND OF THE INVENTION

This invention relates to the logging of wells during drilling and more particularly to the telemetry of data relating to downhole conditions by means of an acoustic signal transmitted through drilling liquid within a well while concomitantly drilling the well.

Various telemetering methods have been suggested for use in logging-while-drilling procedures. Examples are shown in U.S. Pat. Nos. 3,015,801 and 3,205,477 to Kalbfell. In the Kalbfell systems, an acoustic energy signal is imparted to the drill pipe and the signal is frequency modulated in accordance with a sensed downhole condition. Frequency shift keying is employed to transmit the acquired data in a digital mode. Yet other telemetering procedures proposed for use in logging-while-drilling systems employ the drilling liquid within the well as the transmission medium. One such technique is described in U.S. Pat. No. 3,309,656 to Godbey. In the Godbey procedure, an acoustic wave signal is generated in the drilling liquid as it is circulated through the well. This signal is modulated in order to transmit the desired information to the surface of the well. At the surface the acoustic wave signal is detected and demodulated in order to provide the desired readout information.

In U.S. Pat. No. 3,789,355 to Bobby J. Patton, there is disclosed a technique utilizing a modulator similar to that disclosed in the Godbey patent for the purpose of encoding pressure signals in a phase shift keying mode. In the foregoing an electric motor is utilized to control the operation of the modulator.

SUMMARY OF THE INVENTION

In accordance with the present invention the operating characteristics of an electrical motor are controlled to drive a mud stream interrupter or modulator at a predetermined speed.

The invention relates to a method of and apparatus for imparting a high degree of phase coherence to an acoustic signal generated by a rotary valve driven by the motor. The phase of the acoustic signal is changed by 180° thereby encoding a binary bit into the signal. In carrying out a change in phase, the speed of a motor is changed by initially applying a step voltage to a voltage controlled motor speed control circuit. Added to the step voltage is a linearly increasing voltage.

The step and ramp voltage cause the motor to accelerate thus changing the phase of the acoustic signal. The amount of phase shift in the acoustic signal is measured. Upon the occurrence of a predetermined phase shift, the voltage applied to the voltage controlled motor speed control circuit is immediately reduced to a lesser value. The application of the voltage of lesser value is continued for a predetermined time at which the acoustic signal will have substantially attained a 180° phase shift. At the end of this predetermined time, the speed of the motor is phase-locked to the local clock.

The frequency and phase of the acoustic signal is determined by the rotation of an induction motor which drives the rotary valve through a positive, nonslip drive train. The rotation of the motor is phase-locked to a highly stable clock. Phase locking is accomplished in a near optimal manner by sampling the phase error between the clock and a motor angular position reference every half period of the acoustic signal and immediately correcting the frequency of the motor supply in proportion to the phase error.

DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates in block schematic form a transmitting system embodying the present invention utilized in controlling the operation of a rotary valve for the generation of an acoustic signal within a liquid path in a well;

FIG. 2 illustrates in block schematic form further details of the pulse generator and the phase error detector of FIG. 1;

FIG. 3 illustrates in block schematic form further details of the transmitter control and transition phase shift detector of FIG. 1;

FIGS. 4 and 4A depict the waveforms associated with the operation of the equipment illustrated in FIG. 2;

FIG. 5 depicts waveforms associated with the operation of the equipment of FIG. 3; and

FIG. 6 illustrates in circuit schematic form details of the sample-and-hold and amplifier and ramp generator of FIG. 2.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The Overall Logging-While-Drilling System, FIG. 1

In accordance with the preferred embodiments of the invention as described in more detail hereinafter, an acoustic signal is transmitted through the drilling liquid employed in normal drilling operations. As the well is drilled, at least one downhole condition within the well is sensed and a signal, in most cases analog, is generated which is representative of the sensed condition. An analog signal is converted to a serial digital signal. The acoustic signal generated within the drilling liquid is modulated in response to the digital signal by correlating the phase of the acoustic signal during sequential time periods corresponding to the digit intervals of the digital signal with a plurality of phase conditions representative of the respective digit values of the digital signal. The acoustic signal is received at an uphole station and demodulated as described in the aforesaid Patton application in order to produce appropriate readout functions corresponding with the respective phase conditions. These readout functions then may be applied to appropriate utilization means, such as recording and/or data processing systems such as computers, from which desired information may be derived.

Turning now to FIG. 1, there is disclosed a system for controlling the operation of a rotary valve transmitter 10 driven by induction motor 11 to continuously interrupt the flow of drilling liquid within the drill pipe in order to produce an acoustic signal of substantially fixed frequency and phase.

Phase coherency is maintainted in the acoustic signal by phase-locking the rotation of induction motor 11 to a stable clock 12. Phase-lock is accomplished by a control loop comprised of clock 12, a tachometer 15, pulse generator 16, phase error detector 18, summing amplifier 20, and voltage controlled motor speed control circuit 22. The tachometer 15 together with pulse generator 16 produce pulses at a rate which is twice the sonic frequency produced by the rotary transmitter 10. The output from the clock 12 is a series of pulses whose rate

is twice the desired output frequency from the rotary transmitter **10.** Pulses from the pulse generator **16** and from the clock **12** are applied to the phase error detector **18** which measures the relative time occurrences of the pulses. Should these pulses from the pulse generator **16** have a time occurrence or phase relationship other than definitive of the desired sonic phase, an error signal is applied by way of the summing-switching amplifier **20** to the motor speed control **22** to change the speed of the induction motor **11,** thus, to bring the system into what is referred to as a "phase-lock mode."

Sensible information concerning measured downhole conditions can be transmitted by the drilling liquid to the surface by changing the phase of the signal generated by the rotary transmitter **10** employing an encoding or telemetry mode known as phase-shift keying.

In employing such a mode, data, usually in analog format, is received from a plurality of downhole detectors, D_1, D_2, D_3 . . . D_N, and applied by way of a multiplexer **24** to an A/D converter **26.** The output of the A/D converter **26** is applied to parallel to serial converter **28** which arranges the data in a serial binary format.

As more fully explained in the aforesaid Patton application, the multiplexer **24,** the A/D converter **26,** and the encoder **28** are synchronized and otherwise under control of the clock **12** and a counter **30,** the latter being essentially a divider which establishes outputs having different pulse rates to enable proper operation of the aforesaid components. One such train of pulses is applied to the converter **28** to establish data bit intervals, or, otherwise stated, intervals during which a data bit is to occur. The data bits are serially applied to a transmitter control **32.** The transmitter control **32** is effective by way of the switching amplifier **20** to disable the phase-lock control and to apply a programmed function to the motor speed control **22** to change the speed of the motor. The change in speed may be either by way of deceleration or acceleration. In the embodiment being described, we choose to accelerate the speed of the motor with the programmed function.

Upon the occurrence of a predetermined amount of phase shift in the acoustic signal generated by the rotary transmitter **10,** transition phase-shift detector **34** generates a control pulse applied to the transmitter control **32.** This terminates the application of the first programmed function and effects the application of a second programmed function which preferably is of a fixed time duration to again change the speed of the motor to return it to the predetermined value but with 180° shift in the phase of the acoustic signal. If the first program is utilized to accelerate the motor, then the second program obviously will be utilized to decelerate the motor. And of course the converse is true.

In the system described, the mode of telemetry is phase shift keying nonreturn to zero. In such a mode, the phase of the signal produced by the rotary transmitter will be changed only upon the occurrence of a "1" bit; therefore, the transmitter control **32** will initiate the above-described operation only upon the occurrence of a "1" bit from the converter **28.** Nonreturn to zero may also be implemented in response to the occurrence only of a "0" bit. However, it is more conventional to employ the "1" bit for effecting the phase change.

The Pulse Generator **16** and The Phase Error Detector **18,** FIG. **2**

Referring now to FIG. **2** there is shown further details concerning the pulse gnerator **16** and the phase error detector **18.** The pulse generator **16** receives the output of tachometer **15,** a sine wave shown in FIG. **4** as the wave train *a*, and treats it to produce at the output of pulse generator **40** two series of complementary pulses *e* and *f* whose rate is equal to twice the frequency of the sonic signal produced by the rotary transmitter **10.** The pulses *e* and *f* are produced in the following manner. The output *a* from the tachometer **15** is applied to a full-wave rectifier **42** whose output, the wave train *b*, is negative going. The type of full-wave rectifier utilized is commonly referred to as an absolute rectifier which will utilize an operational amplifier such that the rectification is essentially absent of distortion. The wave train *b* is converted by way of pulse generator **44** to a series of pulses *c* whose repetition rate is twice the frequency of the tachometer output. The pulse generator utilized in the practice of the present invention can be described as a comparator or level detector which produces an output only when the input is between zero and some predetermined negative value of the wave train *b*. In the system employed, the tachometer output had a frequency of exactly **15** times the frequency of the sonic signal generated by the rotary transmitter **10.** Accordingly, in order to produce the desired pulse repetition rate for the pulses *e*, that is, twice the actual sonic frequency, it is necessary to divide, as by utilizing the divider **46,** the pulses *c* by a quotient of **15** to produce a train of square waves *d*. The pulse generator **40** responds to the trailing edge of the square wave *d* to produce the pulses *e*.

Using a pulse generator and a clock which produce pulses at twice the frequency of the acoustic signal has many advantages. The phase lock is necessarily automatically in one of two phase states. A phase state change is implemented by adding one tachometer pulse to produce a 180° phase change. Also a phase state change need only be targeted to 180° ± 90°, then phase-lock is automatic at 180°.

As a practical matter, it may be possible to design a tachometer whose output frequency will be twice the sonic frequency of the rotary transmitter. In such an event, it is obvious that there would be no need for the divider **46** or for the pulse generator **44** and that other means could be devised and utilized in conjunction with the pulse generator **40** to produce the desired pulse train *e*. The pulse generator **40** responds to pulses *d* to produce a second train of pulses *f* having the same repetition rate as the pulses *e*.

The pulses *e*, *f*, together with the pulses *g* from the clock **12,** are utilized by phase error detector **18** to maintain the phase of the acoustic signal, generated by the transmitter **10,** substantially constant with respect to the pulses *g*. If any two pulses *e*, *f* occur at a point in time which is precisely at the midpoint between the occurrence of two consecutive pulses *g*, then the pulses *e*, *f* will be exactly 180° out of phase with the pulses *g*. For this condition the error signal e_{ϕ}, applied to the motor speed control **22** (FIG. **3**) by summing switching amplifier **20** will be zero. For any other phase difference ϕ besides 180°, an error signal will be generated proportional to $180° - \phi$. A correction frequency proportional to the error signal described above is applied by motor speed control **22** to induction motor **11** to

change its speed in a direction (increase or decrease) which reduces the phase error.

Phase error detector 18 consists of set-reset pulse generator 50, flip-flop 52, integrator 54, sample and hold 56, and amplifier and function generator 60. The clock pulses *g* are applied to set-reset pulse generator 50 which produces two trains of complementary pulses *j* and *k*. At the onset of pulse *j*, flip-flop 52 is set to a logic "1" (10 volts). For the duration of pulse *k*, integrator 54 is reset. Pulse *e* produced by pulse generator 40 resets flip-flop 52 to a logic "0" (zero volts). In this manner pulses *j* and *e* determine the time flip-flop 52 remains in the logic "1" state. The output of flip-flop 52, *h*, is a constant amplitude pulse whose width is directly proportional to the phase difference between pulses *j* and *e*. Pulses *j* have a frequency of exactly twice the desired acoustic signal frequency. Pulses *e* have a frequency exactly twice the actual acoustic signal frequency. The output of flip-flop 52, *h*, is applied to integrator 54 which is reset by pulse *k* and begins integrating signal *h* at the termination of pulse *k*. At the onset of pulse *k*, *h* is set to 10 volts by pulse *j* which is coincident with pulse *k*. The output of integrator 54 is a negative-going ramp, *m*, until *h* is reset to zero by pulse *e*. Upon the occurrence of pulse *e*, the integrator output, *m*, remains at the attained negative voltage since its input has been reset to zero.

The value of the negative voltage at the integrator output is directly proportional to the time *h* remained at 10 volts and therefore is proportional to the phase difference between *j* and *e*. Pulse *f* is coincident with pulse *e* and is applied to sample-and-hold 56. For the duration of *f*, sample-and-hold 56 samples the sum of *m* and a reference voltage provided as shown by a source of d-c (illustrated as a battery). The reference voltage is selected to be equal and opposite in sign to the integrator output for the condition where pulses *j* and *e* are exactly 180° out of phase. Sample-and-hold 56 inverts the sign of the sampled sum of its two inputs producing error signal *n*. Signal *n* will be zero when pulses *j* and *e* are 180° out of phase; however, for any departure from this desired phase relationship, *n* will be a positive or negative voltage proportional to the phase error. The output of sample-and-hold 56, *n*, is applied to amplifier and ramp generator 60. In the phase-lock mode, 60 is a unity gain inverting amplifier whose output is denoted by $e\ \phi$. Signal $e\ \phi$, in the phase-lock mode, is applied to summing switching amplifier 64 (FIG. 3) which inverts $e\ \phi$ producing output *o* which is applied to motor speed control 22. In this manner phase error detector 18 produces a bipolar error voltage $e\ \phi$ which is effective in changing the motor speed in such a manner as to substantially establish and maintain the desired phase relationship between pulses *j* and *e*.

Note that phase error voltage $e\ \phi$ is constant during the interval between two consecutive pulses *f* producing a constant frequency signal which is applied to the motor. Error voltage $e\ \phi$ is updated every half cycle of the acoustic signal during the occurrence of pulse *f*. Sample-and-hold circuit 56 samples the phase error for the duration of *f* and upon the termination of *f* holds the sampled value until the occurrence of the next consecutive sample pulse *f*. Each updated sample of the phase error is immediately (no filtering) effective in changing the frequency of the motor drive power.

High gain is incorporated into this control loop to provide rapid phase lock of the acoustic signal — a few sample periods. The gain of the phase error detector 18 (volts/degree) can be adjusted by changing the RC time constant of integrator 54 or by changing the gain of sample and hold 56. The proper gain depends on the gain of motor speed control 22 (Hz/volts), characteristics of induction motor 11, and other system properties. The optimum gain is best determined empirically.

Summing Amplifier 20, FIG. 3

By the means previously described, the phase of the acoustic signal is maintained substantially constant when the system is in the phase-lock mode. Referring to FIG. 3, further details of the summing switching amplifier 20 are shown. When the system is in the phase-lock mode, the motor is under control of two functions. One of them is a constant voltage designated as $-E_B$ which is applied by way of resistor 62 to the input of summing amplifier 64. The other is the phase error voltage $\pm e\ \phi$ which is applied from the output of amplifier 60 (FIG. 2) by way of resistor 65 and normally closed switch 66 also to the input of the summing amplifier. The sum of these two signals is inverted and positive signal, $+E_B \pm e\ \phi$, is applied to motor speed control to maintain the phase-lock condition. The motor speed control is effective in changing the speed of the induction motor 11 by changing the frequency which is applied to the motor. The frequency applied to the motor is linearly related to the voltage produced at the input to motor speed control 22 by summing amplifier 64, increasing with increasing voltage and vice-versa. The voltage E_B is selected to provide approximately the correct frequency.

Upon the occurrence of a data pulse, and in this instance a serial binary "1" bit, the phase of the acoustic signal will be changed to a second phase state by the initiation of the generation of a programmed function which will change the speed of the motor. Where a binary mode of transmission is being utilized, the second phase state will differ from the first phase state by 180°. To change the phase state, the motor may either be accelerated or decelerated. With this understanding of the options available, the following description will concern itself with the mode wherein the speed of the motor is first accelerated and then decelerated to change the phase. In this operation, having accelerated the motor there will be generated thereafter and upon occurrence of a predetermined phase shift in the acoustic signal a control pulse which will be effective to initiate operations which will be effective to decelerate the motor and return it to the predetermined constant speed but with the phase of the acoustic signal changed by 180°. Thereafter and until the occurrence of another binary "1" bit, the motor will be under control of the phase-lock loop.

Implementation of the 180° phase shift is accomplished in the following way, described with reference to FIG. 3 which shows further details of the transmitter control 32 and transition phase shift detector 34 with associated waveforms shown in FIG. 5. A binary "1" bit represented by the waveform *u* is applied to a transition start pulse generator 70. This generator, which may be a monostable multivibrator, produces a pulse *v* initiated by the trailing edge of the waveform *u*. The leading edge of the pulse *v* triggers a transition control flip-flop 72 which produces a square wave *x* having a time duration in which the phase change or shift is to

occur in the acoustic signal. The onset of the square wave *x* initiates several functions. One of them is immediately to disable the phase-lock loop as by disconnecting the circuits of block **60** and, in the specific embodiment described, to convert the amplifier function of block **60** to a function generator. At the same time, the switch **66** is opened. The onset of the square wave *x* is also applied to a gate **74** whose output *y* changes to a logic "0". Upon the occurrence of this change in y to a logic "0", normally open switch **76** is closed. The output from the block **60** (FIG. **2**), now a function generator, is applied by way of resistor **78** and switch **76** to the input of the summing amplifier **64** to begin the acceleration of motor **11** by way of motor control **22.**

The motor will continue to accelerate until a predetermined shift in the phase of the acoustic signal occurs. At this predetermined shift in phase, preferably at about 90° or greater, the control function applied to the summing amplifier **64** will be changed so as to decelerate the motor and return it to its phase-locked speed and phase. The determination of the attainment of the predetermined shift in phase at which time the character of the control function is changed is accomplished in the following manner.

Transition Phase - Shift Detector **34**, FIG. **3**

We have found that there is a relationship between the phase-lock speed of the tachometer **15** and the instantaneous speed of the tachometer which can be detected and is a direct measure of phase shift. More particularly, it can be shown that a measure of phase shift can be obtained by comparing a voltage representative of the speed of the tachometer in the phase-lock mode with the integral of the difference between that voltage and a voltage representative of the instantaneous speed of the tachometer. When the integral voltage together with the voltage representative of phase-lock speed attain equality, (or some fraction thereof), a specific phase shift has been attained. The amount of phase shift required to produce the equality can be shown to be determined by the RC characteristics of the integrator being employed. Therefore, by establishing the amount of phase shift desired, it is necessary only to establish the appropriate constant for the integrator.

In carrying out the foregoing in the system of the present invention the waveform *b* from the output of the fullwave rectifier **42** is applied to the input of a first filter **80.** The amplitude of waveform *b* is linearly proportional to the motor speed. This filter has a relatively short time constant and is provided primarily to remove ripple present in the waveform *b*. The output of the filter waveform *p* representative of the instantaneous speed of the tachometer, is applied to a filter-and-hold circuit **82** and to one input of the differential integrator **84.** The integrator **84** is normally disabled or in a reset mode. The filter **82** has a long time constant ($T = RC \approx 0.2$ sec, ideally a time like **1** baud) or otherwise is a low-pass filter which essentially ignores rapid fluctuations that may occur at its input. Therefore its output *q* is essentially a constant value representative of the average speed of the motor during the time filter and hold **82** functions as a filter. As will be seen below, filter and hold **82** functions as a filter only while the motor is in the phase-locked carrier mode; consequently, its output is, at all times, representative of the phase-locked speed of the motor.

Upon the onset of the square wave *x*, the integrator **84** is enabled. The filter **82** is disconnected from the input waveform *p* and placed in a hold position such that its output *q* will remain constant and will be unaffected by the expected change in the value of *p* occasioned by the acceleration to take place in the speed of the tachometer.

The output from the integrator **84** is the integral of the difference between the voltages *q* and *p*. The integrator output waveform *r* is shown in FIG. **5** to rise to a value identified as the trip point. At this moment the value of the voltage *r* has equaled the value of the voltage q and the output of comparator **86**, *s*, changes from a logic "1" to a logic "0". This triggers pulse generator **88** producing a control pulse *t*. The occurrence of the pulse *t*, is always at the time when the measured phase shift is the predetermined desired value. This measured phase shift is independent of changes in the operating characteristics of the tachometer due to wear, pressure, temperature, or any other condition. This is by reason of the fact that any changes in voltage output from the tachometer will apply equally to both voltages being compared for the establishment of the trip point.

Transmitter Control **32**, FIG. **3**

At the time occurrence of the trip point, the function applied to the summing amplifier is changed to begin decleration of the motor. This is accomplished by application of the pulse *t* to a deceleration start flip-flop **90** whose output *aa* changes from a logic "1" to a logic "0". Output *aa* is applied to the input of the gate **74.** The gate **74** is a NAND gate. With a logic zero, waveform *aa* at one input and a logic "**1**", input *x*, at the other input, its output immediately goes to a logic "1". The output, square wave *y* opens the switch **76** and disconnects the input of the summing amplifier **64** from the function generator **60** (FIG. **2**).

The onset of the negative-going square wave *aa* is applied to a decleration time control pulse generator **92** whose output, a negative-going square wave *z*, is applied to switch **94** to initiate the second part of the programmed function necessary to bring the acoustic signal back into phase lock at a phase shift of 180°. The pulse generator **92** is a monostable multivibrator having a predetermined astable time. It also produces a second pulse *bb* which is applied to a transition stop pulse generator **96.** At the end of the astable period of the pulse generator **92,** the square wave *bb* changes to a logic "0" and the transition stop pulse generator **96** responds to produce the pulse *w*. The pulse *w* is effective to change *x* back to a logic "0" and *aa* to a logic "1", whereupon the gate **74** will cause its output to remain at a logic "1", maintaining the switch **76** open. The pulse *w*, in carrying out these functions, is applied to the deceleration start flip-flop **90** to change its output *aa* from a logic "0" to a logic "1". Pulse *w* is also applied to the transition control flip-flop **72** to effect the change in the logic state of the waveform *x*. With the return of the waveform *x* to a logic "0", the switch **66** is closed and the circuits in block **60** are reconnected to the output of the sample-and-hold block **56** (FIG. **2**). Additionally the function of the block **60** is returned to that of an amplifier. In addition the integrator **84** is reset and the filter-and-hold circuit **82** returns to a simple filter status.

While the present invention is useful with many control functions for accelerating or decelerating the motor **11** to change the phase of the sonic signal, we have found a function which is particularly useful in effecting a 180° phase change in the sonic signal in a min-

imum of time. The characteristic of this function is represented by the waveform 0. It comprises an initial step function followed by a linear ramp. The step and ramp are chosen to increase the applied frequency in such a manner that "slip" between the applied frequency and motor speed is near optimum to give maximum acceleration. The ramp continues until the trip point is reached whereupon the voltage is immediately dropped to another predetermined step value and held for a predetermined time period as is represented by the astable period of the deceleration time control pulse generator 92.

The Generations of the Linear Ramp Function o, FIG. 3

The generation of the function *o* is accomplished in the following manner. Function *o* is the output of summing switching amplifier 20. Summing switching amplifier 20 is basically an inverting adder with switchable inputs which can be weighted by proper selection of the feedback resistor and input resistor ratios. Appropriate inputs are selected by means of FET analog switches 66, 94 and 76 which are controlled by transmitter control 32. It will be recalled that at the beginning of the transition period the switch 76 was closed. At this time voltage of approximately +2 volts at the output of operational amplifier 64 is derived by way of the voltage source, $-E_B$, and resistors 100 and 63. This represents the onset or the initial step portion of the waveform *o*. To this is added the linearly rising ramp function generated by the circuits of block 60. At the occurrence of the trip point, the switch 76 is immediately opened and switch 94 closed whereupon the voltage applied to the input of the summing amplifier immediately drops to a new value determined by the $-E_B$ input and the values of resistors 102 and 63. This voltage is maintained over the astable period of the pulse generator 92, at the end of which the control of the motor is returned to the phase-lock loop wherein switches 76 and 94 are opened and switch 66 closed. The variations in the value of the voltage *o* represents the presence of an error voltage from the phase-lock loop and the rapid return to phase lock by the system.

The Circuitry of Integrator 54 Sample-and-Hold 56 and Function Generator 60, FIG. 6

The circuit which performs the function of transforming the block 60 (FIG. 2) from amplifier to ramp generator and back again is illustrated in FIG. 6. The circuit includes integrator 54, sample-and-hold circuit 56, and the amplifier and ramp generator 60. The integrator 54 includes an operatonal amplifier 110. The waveform *h* is applied to its input. The output *m* is applied by way of resistor 112 to a summing point 114 of the sample-and-hold circuit 56. A voltage derived by a voltage dividing network comprised of resistors 116 and 118 is applied to the summing point by way of resistor 120. This voltage is of opposite polarity from the output of the integrator and has a value equal to that which the integrator should have if the clock pulses and the tach pulses are exactly 180° out of phase. With the switch 122 closed, the circuit 56 is in a sample mode and samples the difference in the voltages applied to the summing point 114. With the switch 122 under control of the waveform *f* open, the circuit 56 is in a hold mode and its output, waveform *n*, is applied to the circuit 60.

With operation in the phase-lock mode, the circuit 60 is an amplifier. At this time the waveform *x* is a logic "0" and is applied to the switches 124 and 125 which are closed. Switch 126 is also closed by reason of the fact that the closed switch 125 connects its control point to ground. With the capacitor 129 being shorted by closed switch 124, it can immediately be seen that the circuit is a unity-gain inverting amplifier operating upon the input voltage *n* which is applied by way of resistor 130. Unity gain is achieved by having the feedback resistor 131 equal in value to the resistor 130. While in this configuration, a voltage is being applied from the 15-volt source, by way of a resistor 132 which is very much larger than the feedback resistor 131. Hence any input that might be applied by way of resistor 132 can be ignored because the gain of the amplifier is essentially zero due to the relation in the sizes of the resistors.

Upon the initiation of the transition interval, that is, the time at which we desire to change the phase of the sonic signal, the waveform x changes from a logic "0" to a logic "1." Upon the occurrence of a logic "1", switch 124 as well as switch 125 are open. The opening of switch 125 disconnects the control point 127 from ground and a negative voltage is applied by way of resistor 134 to open the switch 126. Accordingly, the input of the circuit 60 is disconnected from the output of the sample-and-hold circuit 56. With the switch 124 open, the circuit 60 now becomes an integrator having applied to its input a voltage from the 15-volt source by way of the resistor 132. Accordingly, there is produced at the output of the circuit 60 a negative-going ramp function which is applied to summing switching amplifier 20 producing the ramp portion of function 0 in FIG. 5.

At the end of the transistion interval the waveform *x* returns to a logic "0" and the function of the circuit 60 is returned to that of an amplifier.

Filter-and-Hold Circuit 82, FIG. 7

Details of the filter-and-hold block 82 are illustrated in FIG. 7. Circuit 82 includes an operational amplifier 136 having waveform *p* applied to its negative input by way of resistor 138 and normally closed switch 140. The switch 140 is closed during the phase-lock mode by reason of having applied thereto the waveform *x* which is in a logic "0." With resistor 142 and capacitor 144 in its feedback loop, the operational amplifier represents a low-pass filter whose output is the waveform *q*. Upon the initiation of the transition mode, the waveform *x* changes to a logic "1" which opens switch 140. This immediately disconnects the input of the operational amplifier 136 from the waveform *p*, and with only the capacitor 144 in its feedback loop the operational amplifier assumes the function of a hold circuit and maintains the last value of waveform *q* at its output.

The various switches 122, 125, 124 and 140 referred to in the foregoing description are provided by FET P-Channel Transistors which are the 2N3993 type. Switch 126 is a 2N4857 N-Channel FET.

What is claimed is:

1. In a logging-while-drilling system including a motor which drives an acoustic generator at a predetermined speed for imparting to well liquid an acoustic signal having phase states representative of data derived from measured downhole conditions, a data encoder, the improvement comprising:

means responsive to the occurrence of a data pulse for generating a programmed function applied to said motor to change the speed of the motor,

means for generating a control pulse upon the occurrence of a predetermined phase shift in the acoustic signal caused by a shift in motor speed relative to said predetermined speed to terminate the application of said first programmed function, and

means responsive to said control pulse for generating a second programmed function of fixed time duration applied to said motor to again change the speed of the motor to return it to said predetermined speed but with a shift in the phase of the acoustic signal.

2. The system recited in claim **1** further comprising:

a motor control circuit including means for maintaining the speed of said motor constant at said predetermined speed and in a constant predetermined phase relation to local clock pulses.

3. The system recited in claim **2** wherein said motor control circuit includes:

a tachometer producing tachometer pulses representing the speed of rotation of said motor, and

means for producing an error voltage representing the difference in phase between said tachometer pulses and said local clock pulses.

4. The system recited in claim **3** further comprising:

means for sampling said error voltage each tachometer period, and

means for applying the sampled error voltage directly to said motor to change the speed thereof.

5. The system recited in claim **3** further comprising a pulse generator responsive to said tachometer pulses, said pusle generator producing pulses at a rate which is twice the frequency of said acoustic signal produced by said acoustic generator, the output of said pulse generator being compared to said local clock pulses to produce said error voltage.

6. The system recited in claim **1** further comprising:

means for generating a phase lock signal representative of said predetermined speed of the motor,

speed changing means responsive to the occurrence of a data pulse for changing the speed of said motor to change the phrase state of the acoustic signal,

means for generating an instantaneous signal representative of the instantaneous speed of the motor,

a differential integrator, said phase lock and said instantaneous signals being applied to said differential integrator to produce an integral signal representing the integral of the difference between said predetermined speed and said instantaneous speed, and

means for comparing said phase lock signal with said integral signal to produce a control signal when a specific phase shift in said motor speed has been attained.

7. The system recited in claim **1** wherein said means for generating a programmed function comprises:

means for initially applying a step voltage to said motor control circuit, and

means for adding a linearly increasing voltage to the step voltage.

8. The system recited in claim **7** wherein said means for generating a second programmed function comprises:

means for, upon the occurrence of said predetermined phase shift, immediately reducing the voltage applied to the motor control circuit to a lesser value, and

means for continuing the application of said voltage of lesser value for a predetermined time whereupon the acoustic signal will have attained another predetermined phase state.

9. In a logging-while-drilling system including an acoustic generator for imparting to a well liquid an acoustic signal having a constant frequency, the method of momentarily changing the speed of said motor to effect a change in the phase state of the signal comprising:

accelerating said motor,

measuring the change in phase of said acoustic signal caused by the changing motor speed, and

stopping said acceleration when the measured change of phase is a predetermined phase shift which is less than the desired change in phase.

10. The method recited in claim **9** wherein the step of accelerating comprises:

initially applying a step voltage to a motor control circuit, and

adding a linearly increasing voltage to the step voltage.

11. The method recited in claim **10** wherein the step of stopping the acceleration upon the occurrence of said predetermined phase shift comprises:

immediately reducing the voltage applied to the motor control circuit to a lesser value, and

continuing the application of said voltage of lesser value for a predetermined time whereupon the acoustic signal will have attained another predetermined phase state.

12. The method recited in claim **9** wherein the desired change in phase is 180° and the predetermined change of phase is more than 90°.

13. The method recited in claim **12** wherein said predetermined change in phase is approximately 90°.

14. In a logging-while-drilling system for use in a wellbore filled with liquid and having an acoustic generator for imparting to the liquid an acoustic signal whose frequency is proportional to the speed of a motor driving the acoustic generator, the improvement comprising:

a motor control circuit,

means for maintaining through said motor control circuit the speed of the motor constant at a predetermined value and in a constant predetermined phase relation to local clock pulses,

means responsive to the occurrence of a data pulse to disable the aforesaid means and to apply to said motor control circuit a programmed function to change the speed of the motor in a first direction to change the phase state of the acoustic signal,

means responsive to a predetermined change in the phase state caused by change in the speed of said motor to terminate said first programmed function and to apply a second programmed function to change the speed in a second direction, and

means for enabling said maintaining means following a predetermined phase change to again obtain said

constant speed with the acoustic signal having undertaken a phase change of 180°.

15. In a logging-while-drilling system wherein the drilling mud stream is continuously interrupted to generate acoustic signals having multiple phase states representative of a measured downhole condition and wherein the frequency of interruption is determined by the rotation of an electrical motor, a system responsive to a measured data condition for rapidly changing the speed of the motor to in turn change the phase of the acoustic signal comprising:

means for initially applying a step voltage to a motor control circuit,

means for adding a linearly increasing voltage to the step voltage,

means for detecting the amount of phase shift in the acoustic signal caused by a shift in motor speed relative to said predetermined speed,

means for, upon the occurrence of a predetermined phase shift, immediately reducing the voltage applied to the motor control circuit to a lesser value, and

means for continuing the application of said voltage of lesser value for a predetermined time whereupon the acoustic signal will have attained another predetermined phase state.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,820,063 Dated June 25, 1974

Inventor(s) James H. Sexton, Bobbie J. Patton, and John W. Harrell

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, lines 45 and 46, and Column 3, lines 25 and 26, "Patton application" should read -- United States Patent No. 3,789,355--. Column 4, line 61, Column 5, lines 47, 49, 52, 56, and 59, and Column 6, lines 20 and 24, "e Ø", each occurrence, should read -- $e_{\emptyset}$ --. Column 8, lines 25 and 36, "decleration", each occurrence, should read --deceleration--. Column 9, line 2, "waveform 0" should read --waveform o--. Column 10, line 33, "function 0" should read --function o--. Column 11, lines 10 and 11 (Claim 1), delete "of fixed time duration"; line 13 (Claim 1), after "phase" insert --state--; and line 48 (Claim 6), "phrase" should read --phase--.

Signed and sealed this 29th day of October 1974.

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