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COMPLETE SPECIFICATION

Impulse Generator

5 We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organised according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, 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:—

10 The present invention relates to apparatus for generating a pressure impulse in a medium, and more particularly relates to an acoustical antenna for generating a directional impulse in either a solid, liquid or gas.

15 The antenna has particular application as a seismic source in seismic prospecting where it is important to know precisely the frequency and power characteristics of the source and the exact instant the impulse is initiated in the earth. Moreover, the frequency of the impulse generated by the apparatus can be varied to optimise the results achieved for the particular geographical location undergoing seismic prospecting. The nature and operation of the apparatus is such that the exact instant in which the seismic impulse is delivered to the earth is precisely known, and as a result, the related apparatus for recording the reflected waves detected by a geophone, or a geometrical array of geophones, is greatly simplified. That is to say, this feature of the invention greatly simplifies apparatus and circuitry required for synchronising and co-ordinating the time of initiating the seismic source and the recording of the seismic traces.

20 In addition to seismology, the antenna has application to a broad area of technology, such as an underwater acoustical source and a source for generating extremely high amplitude pressure waves in both fluids and solids for a variety of uses. As examples, the antenna can be used as a source for providing

high intensity shock waves in a wind tunnel, or can be used as a source for creating tremendous pressures within a confined fluid, such as is required for shaping metallic bodies within a die.

25 According to the present invention, an acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics comprises; a conductive means wound back and forth on itself to provide a parallel conductor configuration several layers in thickness, said parallel conductor configuration providing first and second portions each of which is elongated and substantially straight along its length, terminal means connected to each of the conductive means, said first portion and second portion carrying oppositely directed currents in response to a voltage applied across said terminal means, the current direction in any segment of any said first portion being opposite to the current direction in the opposing segment of said second portion, and resilient insulating means encapsulating said first and said second portions and having a surface for engaging said medium, said oppositely directed currents producing an opposing force and separation between said first and second portions causing said resilient insulating means to flex along a line perpendicular to and connecting opposing segments of said first portion and said second portion producing a pressure impulse along the length of said antenna and imparting said impulse to said medium through the surface of said insulating means.

30 The conductive means may include a first plurality of parallel, elongated and substantially straight conducting segments and a second plurality of parallel, elongated and substantially straight conducting segments disposed in opposing parallel relation to said first plurality of segments, the first and the second

conducting segments being connected electrically in series with one another forming a continuous winding.

The conductive means may be a flattened coil having elongated substantially straight first and second conducting portions disposed in parallel relation. A voltage applied across the coil terminals gives rise to oppositely directed currents in the first and second conducting portions producing an opposing force and separation between the two portions.

Alternatively, the conductive means may include a plurality of flattened conducting coils each having elongated, substantially straight first and second conducting portions disposed in parallel relation, each coil having a different length as defined by the length of its respective first and second portion. The coils are interconnected in electrical parallel and are disposed in concentric relation as defined by an axis passing between said first and second portions perpendicular thereto and symmetrical therewith, the coils of smaller lengths being surrounded by the coils of larger lengths. The first and second portions of the plurality of coils are encapsulated by resilient insulating means having a surface for engaging the medium. A voltage applied across the conductor means terminals give rise to oppositely directed currents in the first and second portions, producing an opposing force and separation between the first and second portions and causing the resilient insulating means to flex along a line connecting the first and second portions perpendicular to said axis whereby a non-uniform pressure impulse is generated in said medium at said surface along the lengths of said plurality of coils, the pressure at any point along said surface being related to the number of coils acting in cooperation at said point.

By way of example, the invention will be described in greater detail with reference to the accompanying drawings, in which:—

Figs. 1a—1c are electrical conductor configurations illustrating the principle upon which the operation of the invention is based,

Figs. 2a and 2b are, respectively, series and parallel schematic circuit arrangements for obtaining the force effect using the principle embodied and shown in Figs. 1a—1c,

Fig. 2c is an equivalent circuit of either of the arrangements of Figs. 2a and 2b,

Fig. 3 illustrates graphically as a function of time (a) the current through the equivalent inductor of the circuit shown in Fig. 2c, and (b) the total opposing force between the two coils caused by the current there-through,

Fig. 4 illustrates graphically the frequency spectrum of the opposing force between the coils of an arrangement such as that shown in Fig. 1c, and there is also shown the relative magnitude of the force as a function of frequency for a series and parallel arrange-

ment of the coils as shown in Figs. 2a and 2b, respectively,

Figs. 5 and 6 are two schematic embodiments of the apparatus of the invention,

Fig. 7 is one embodiment of the antenna of the invention that is primarily useful as a seismic source,

Fig. 8 is a block diagram of the electrical apparatus used to energise the antenna of the invention,

Fig. 9 is a view, partly in section, of a preferred embodiment of the conductor configuration of the antenna of this invention,

Fig. 10 is a cut-away view of a preferred form of an insulated conductor to be used in the antenna,

Fig. 11 is a view, partly in section, of a preferred embodiment of the antenna showing the conductor configuration of Fig. 5 encapsulated in a flexible insulator,

Fig. 12 illustrates the use of the antenna for off-shore exploration, and

Fig. 13 is a side elevational view of a modification of the antenna constructed so as to cause an attenuation of pressure along its length.

The invention utilises the well known principle that electrical charge flowing in opposite directions in parallel conductors produces an opposing force between the conductors that is proportional to the product of the currents therein and inversely proportional to the distance of separation therebetween. The opposing force effect will be produced so long as there is a component of the current vector in one of the conductors that is opposite a component of the current vector in the other conductor, and the greatest force is realised when the net current vectors in the conductors are oppositely directed, this being the case of parallel conductors. The amount of force produced by this effect is easily controlled by regulating the current magnitudes in the conductor, whereas in contra-distinction to this effect, a force produced between a current carrying conductor, such as a coil, and a metallic body in which eddy currents are generated due to the field of the coil is not easy to predict or regulate. Moreover, the opposite current effect utilised by this invention can produce a much greater force than by the eddy current effect.

To take advantage of this effect to provide a large energy, pressure impulse source, the current must be large and/or the distance of separation must be small. The antenna of the invention, in order to generate a very large force by means of this effect, utilises many parallel conductors in addition to a high magnitude current, thus taking advantage of each of the separate forces generated between the individual conductors. This, in effect, produces a large net force that is equivalent to utilising a very large current. However, it is to be noted that the antenna also is capable

of handling large currents, thus further increasing the net force.

In order to utilise and take advantage of this large force, the antenna incorporates suitable means for coupling the energy represented by the force to the medium to which it is to be imparted. For use as a seismic source, it is preferable that a large amount of energy be coupled to the earth over a sufficiently large area so that the elastic limit of the medium (earth) is not exceeded when the force is generated. Another reason for distributing the energy over a large area is to create in the medium, to a close approximation, a plane acoustical wave as distinguished from a point source of acoustical energy. Thus one embodiment of the invention that has primary application to seismic prospecting has the conductors between which the force is generated embedded in a pair of structural members each having a large surface area, where the force is generated between the conductors in the respective members. Provision is made to allow the members to separate by a small amount upon the generation of the force so that a pressure wave can be generated in the medium immediately adjacent either of the surfaces of the members. If the conductors are not permitted to separate at least an incremental amount during the generation of the force, all of the energy will be dissipated as heat within the conductors.

Because of the utility of the invention as a seismic source, a detailed description of the preferred embodiment for this application will be presently given with a discussion of the manner in which it is used.

The antenna provides advantages for seismic prospecting heretofore unrealised, and one of the major features of this apparatus, in addition to the large force that can be generated, is the exact time synchronisation achieved between the imparting of the seismic signal to the earth and the start of the recording of the reflected signals received by a geophone array. Since a complete seismic pattern usually comprises the sending of a seismic signal into the earth at a plurality of spaced points on the surface of the earth and recording each, it is important that the recording of the trace of each reflected seismic signal start when the signal is initially imparted to the earth for correspondence in the time domain between the several traces. Alternatively, the recordation of each individual seismic trace should start after a constant, known time has elapsed between the imparting of the signal to the earth. Here, the force is generated virtually instantaneous with the sending of a current through the conductors, and thus the exact instant the force is coupled to the earth is known.

The feature of the seismic source permitting synchronisation of the seismic apparatus as above described is important in another

respect, in that it is now possible to take the record of all of the recorded seismic traces for a given seismic pattern and add them directly in the field where the operation is being carried out. This follows from the fact that each seismic signal is in exact time correspondence with every other seismic trace, and that the recordation of each trace is initiated simultaneous with the seismic signal. When the adding of the traces can be done in the field, it is obviously possible to observe the result of the seismic pattern and determine to a large measure, the value of the shots, such as whether they should be repeated because of a faulty seismic pattern or the like. In essence, the apparatus of this invention makes possible extremely rapid seismic exploration and a timely return of the information gained from the explorations, so that within minutes after the seismic pattern has been run it can be determined whether another pattern is necessary.

The simplicity and portability of the seismic source is such as to reduce purchase, operating and maintenance costs over systems presently available. These features will become apparent from the following detailed description.

A feature of equal importance is that the frequency characteristics of the seismic signal generated by the antenna can be controlled within wide limits. A force can be generated by the antenna that is comprised of a frequency spectrum, practically all of which is in the usable frequency band for seismic exploration. The frequency components of the force and their relative magnitudes can be virtually controlled at will, thus providing a source whose frequency characteristics may be altered to achieve optimum results in practically any terrain. More precisely, the subsurface strata in some geographical locations transmit some frequencies better than others and it is obviously desirable that the seismic source be adaptable for adjustment to achieve these optimum results, of which the seismic antenna of this invention is capable.

It should be noted in connection with the frequency control that may be had over the seismic signal produced by the antenna, that whenever the antenna is adjusted to produce a given seismic signal, this signal may be reproduced exactly every time without change of its characteristics. This follows from the precise control that can be exercised over the electrical current used to generate the force, as will be seen more clearly hereinafter. This is extremely important when shooting a seismic pattern, because each trace, ideally is a recording of the reflection of seismic signals of exactly the same characteristics. Thus errors in calculation in depth of given substrata of the earth are reduced or eliminated.

All of the above advantages and features will become apparent from the following described embodiments of the invention used

primarily in seismology. Specifically, there is shown in Fig. 1a a pair of parallel conductors with oppositely directed currents i_1 and i_2 therein. The currents produce an opposing force F between the conductors that is proportional to the products of the currents and inversely proportional to the distance of separation therebetween, or mathematically:

$$F \propto \frac{i_1 i_2}{d}, \quad (1)$$

where d =distance of separation.

In Fig. 1b there is shown a conductor arrangement that can be utilised to effect this result, where the conductor is doubled back on itself, and where the current in the upper half is the same current in the lower half but is directed oppositely thereto. Another arrangement, Fig. 1c, utilises a pair of coils each having as many turns as desired, and the same current can be used in both where the electrical connection therebetween is such as to produce opposite current polarities. Alternately, different currents may be used. In Fig. 1c, the coils are positioned close enough together so that the configurations of either Fig. 1a or Fig. 1b is approximated, that is, any increment dl_1 of one coil acts as a parallel conductor to the corresponding increment dl_2 of the other conductor. This condition is satisfied when the diameter of the coil is large as compared to the distance of separation of the coils. However, even if this condition is not satisfied, the force of separation between the coils approximates that given by Equation (1).

The foregoing illustrates the principle upon which the operation of the antenna is based. Referring now to Fig. 2a there is shown a schematic circuit arrangement illustrating one embodiment of the antenna. A pair of coils L_1 and L_2 are serially connected for opposite polarities and form part of a series circuit including a switch S_2 and capacitor C . The series resistance of the coils L_1 and L_2 are designated as R_1 and R_2 , respectively. A power supply V connected in series with a limiting resistance R and switch S_1 are connected to charge the capacitor C when the switch S_2 is opened. To achieve a large force of separation between the coils, a large capacitor bank is charged to a high voltage. Once, charged, the switch S_1 is opened and switch S_2 is closed, sending a current pulse through the two coils and producing the opposing force therebetween.

Another schematic circuit arrangement is shown in Fig. 2b, where the two coils L_1 and L_2 are connected in parallel but again in opposite polarities to produce the force arrangement shown in Fig. 1c. If the inductances and series resistances of the coils are equal, the respective currents i_1 and i_2 will be equal.

The equivalent of either of the circuits of

Figs. 2a and 2b is shown in the circuit of Fig. 2c, where L_{eq} denotes the equivalent inductance of the two coils in series or in parallel, whichever is the case, and R_{eq} denotes the equivalent resistance of the coils. The capacitor C is shown to be charged to some arbitrary voltage V .

The current in the equivalent circuit of Fig. 2c can be expressed by an equation governing a free oscillating circuit comprised of an inductor, a resistor and a charged capacitor connected in series, namely:—

$$V = \frac{1}{C} \int i dt + i R_{eq} + L_{eq} \frac{di}{dt}, \quad (2)$$

where V is the voltage across the charged capacitor C , and i is the current in the circuit.

Because of the equivalent series resistance of the circuit, the oscillations will be damped. The current in the circuit as a function of time can then be shown to be expressed by the relation:—

$$i(t) = \frac{V}{L_{eq}} \frac{1}{\beta} e^{-\alpha t} \sin \beta t, \quad (3)$$

where

$$\alpha = \frac{R_{eq}}{2L_{eq}},$$

$$\beta = \left(\frac{1}{L_{eq}C} - \frac{R_{eq}^2}{4L_{eq}^2} \right)^{1/2}, \text{ and}$$

$$t = \text{time.}$$

The above equation can be easily derived by taking the Laplace transform of the current function and then taking the inverse transform. Reference is had to Garner and Barnes, *Transients in Linear Systems*, John Wiley and Sons, page 342, equation 1. 301, for the inverse transform function. Physically, the expression for the current in the circuit as a function of time states that the current is governed by the sinusoidal function $\sin \beta t$, whose amplitude decreases exponentially, being governed by the function $e^{-\alpha t}$, and the period of which is constant. The current as a function of time is shown graphically in Fig. 3 and denoted by $i(t)$. The constant period of this function will be noted, whereas the amplitude decreases exponentially with time.

To determine the force between the two opposing coils of the antenna, reference is again had to Fig. 1c, where the coils are close enough together so that it can be assumed that magnetic flux acting at a given location on one of the coils is primarily the result of a current in the other coil at a location just opposite the location on the first coil. In other words, the force between the two coils can be considered that which results between two parallel, current-carrying wires, where the length of each wire is equal to the circumference of its corresponding coil times the number of turns N in the coil.

It can then be shown that the force F between the coils of equal radii can be expressed by the equation:—

$$F = \frac{R\mu_0 N_1 N_2 i_1 i_2}{d} \quad (4)$$

- 5 where R is the radius of either coil,
 μ_0 is the permeability of free space,
 N_1 and N_2 are the number of turns
 of wires in the coils L_1 and L_2 ,
 respectively,
 10 i_1 and i_2 are the currents in the coils
 L_1 and L_2 , respectively, and
 d is the distance between the coils.

The force F between the coils is attractive if the currents are in the same direction, whereas it is opposing if the currents are in opposite directions, the latter being the case of interest. If the coils are connected in series, the currents are equal, and if the effective series impedance of each are equal when they are connected in parallel, the currents will also be equal. Then the expression for force takes the form of:—

$$F(t) = \frac{k i(t)^2}{d}, \quad (5)$$

- 25 where $F(t)$ is the instantaneous force as a function of time,
 $i(t)$ is the instantaneous current as a function of time, and
 k is a constant.

- 30 This equation is derived and shown in Seeley, *Introduction to Electromagnetic Fields*, McGraw-Hill, 1958, p. 250. The curve $F(t)$ shown in Fig. 3 illustrates the relative magni-

tude of the force as a function of time. Since the force is directly proportional to the square of the current, the force is always positive. It will be noted that the force has a period equal to one half the period of the current, and that the amplitude of each decreases exponentially. From Equations 3 and 5, the force can be expressed as:—

$$F(t) = \frac{k V^2}{L_{eq}^2} \frac{1}{\beta^2} e^{-2\alpha t} \sin^2 \beta t. \quad (6)$$

The dominant or ringing frequency of the free oscillating series circuit is given by the Equation:—

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{L_{eq} C} - \frac{R_{eq}^2}{4L_{eq}^2}} \quad (7)$$

The period of the force function is governed by the term $\sin^2 \beta t$ and its amplitude is governed by the term $e^{-2\alpha t}$.

The force function can be expressed in a Fourier series and is comprised of an infinite number of unique frequency components of various magnitudes. It is important to note from the Fourier transform the frequency response of the force function, since this will determine its usefulness as a seismic force, since, according to what has been said previously, the lower frequencies, say from 0 to 120 c/s, are far more efficient as a seismic signal than are the higher frequencies, such as those extending into the kilocycle range. In order to obtain the frequency response of the force the Laplace transform of the force function is taken and can be expressed as:—

$$2\left(\frac{V^2}{L_{eq}^2}\right)$$

$$F(\omega) = k \sqrt{\omega^6 + \omega^4 \left(-\frac{8}{L_{eq} C} + \frac{5R_{eq}^2}{L_{eq}^2} \right) + \omega^2 \left(\frac{16}{L_{eq}^2 C^2} - \frac{8R_{eq}^2}{L_{eq}^3 C} + \frac{4R_{eq}^4}{L_{eq}^4} \right) + \frac{16R_{eq}^2}{L_{eq}^4 C^2}} \quad (8)$$

- 65 where $F(\omega)$ is the frequency response of the force function,
 $\omega = 2\pi f$, and
 $k_1 = \frac{R\mu_0 N_1 N_2}{d}$.

- 70 Many of the terms in the denominator of the equation can be neglected in most instances upon substitution for the various parameters of the circuit. For the series circuit the equivalent inductance L_{eq} can be expressed as:—

- 75 $L_{eq} = L_1 + L_2 - 2M$,
 where M is the mutual inductance.
 Assuming the series resistances R_1 and R_2 , respectively, of the two inductors are equal, that $L_1 = L_2$, and $M = KL_1$, then
 80 $L_{eq} = 2L_1 (1-K)$, and
 $R_{eq} = 2R_1$,

where K is constant of proportionality. For the parallel circuit where $L_1 = L_2$ and $R_1 = R_2$, the equivalent inductance and resistance can be, respectively, expressed as:—

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 + 2M}$$

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

Then,

$$L_{eq} = \frac{L_1}{2} (1-K), \text{ and}$$

$$R_{eq} = \frac{R_1}{2}$$

Representative curves of the frequency response for the force functions for a series and

a parallel circuit are shown in Fig. 4, where identical coils are shown connected in series and in parallel. The curves are calculated on the basis of using coils in the parallel circuits whose magnitudes of inductance are numerically identical to the coils in the series circuit, and thus a separation between the curves results from the slight difference in magnitude between the series and parallel currents. For values of $L=0.3$ henry, $R=6.0$ ohms, $C=4 \times 10^{-4}$ farads and $M=2/3$, the curves drop rapidly toward zero between 50–80 c/s, with the peaks occurring at slightly lower frequencies. For a series circuit having these values, there is a peak force component at about 37 c/s, and then components of the total force of frequencies greater than about 50 c/s have amplitudes negligible in comparison to those components of frequencies between 0–50 c/s. For a parallel circuit having these values, the peak component is at about 73 c/s, and the curve drops off rapidly over about 80 c/s. By change the parameters of the circuit in Equation 8, the bandwidth of the frequency response can be broadened or narrowed. It is readily seen, however, that for reasonable circuit parameters, a force can be generated that is comprised of components having frequencies within the useful range for seismic prospecting.

Referring now to Figs. 5 and 6 there are shown two embodiments of the impulse generator (antenna) useful for seismic work. In the elevational view of Fig. 5 there is shown a pair of members each containing one of the coils L_1 and L_2 above referred to. The electrical connection between the coils and the energising source and circuitry are not shown, but the blocks are shown to be held together by two compression springs attached between the surface of the upper member and a rigid frame S securely attached to the earth or some immovable object. When the force is generated between the blocks, the springs permit a slight separation between the members; enough to allow the force to be coupled to the earth at the interface between the member housing L_2 and the earth. The springs also serve the purpose of preventing destruction of any means that might be used to rigidly constrain the two blocks. In the elevational view of Fig. 6 there is shown another arrangement where a large mass limits the separation of the members. Both the resilient springs and the inertial mass act as a restoring force to bring the separated members back together.

A preferred embodiment of the coil housing is shown in Fig. 7, which is a view partly in section of the two coils housed in suitable plates or blocks. Here, each of the coils is housed in an electrically insulating plate or block, and the insulating nature of the housing precludes the generation of eddy currents that would reduce the total force generated. The

upper coil 24 is rigidly cast in a suitable insulating material, such as Scotchcast No. 241, a trade name of the Minnesota, Mining and Manufacturing Co. of Milwaukee, Wisconsin, to form a block or plate 20, with laminations of fibreglass added throughout the cast for extra strength. The axis of the coil is perpendicular to the faces of the block. The lower coil (not shown) is cast in a similar block 22. As an example, square wire of dimensions .072 inch by .072 inch with .007 inch cotton insulation is used to provide each coil with 1220 turns comprised of 13 layers of wire in depth perpendicular to the face of the block and about 94 turns of wire wide. The outside diameter of each coil is about 17 inches an inside diameter of about 1.9 inches. The total height of each coil was about 1.1 inches. Each coil is symmetrically housed in a block as above described of dimensions of about 20 inches by 20 inches area and about 2 inches thick. The relative current directions in the upper and lower coils are indicated where i_1 and i_2 correspond to the currents in the upper and lower coils, respectively, for generating an opposing force F therebetween.

As the blocks separate upon the generation of the force, it has been found that a "cavity" is produced between the opposing faces of the blocks. The cavity is more accurately described as a void or partial vacuum caused by the very rapid, although limited, separation of the blocks. It has been discovered that if the material comprising the blocks is electrically conducting, such that eddy currents are generated in the blocks when the currents are passed through the coils, the cavity effect causes pitting of the opposing faces and the blocks become worn, thus necessitating replacement. However, if the blocks are comprised of some suitable electrical insulating material, the cavity effect does not produce pitting of the blocks, and the replacement of the blocks is obviated.

Although the antenna above utilises coil configurations, it should be understood that any conductor configuration can be used where the current direction is such as to produce the force effect as described.

In Fig. 8 there is shown a block diagram of the preferred apparatus used to supply energy to the coils. A direct current supply of suitable output voltage is used to charge a capacitor bank. After the capacitor bank has been fully charged or charged to the percentage desired, a switch is triggered to discharge the capacitors through the coils of the antenna to generate the opposing force.

From the preceding Equations it can be seen that the amplitude and dominant frequency of the force can be controlled by a proper choice of the parameters R_{eq} , L_{eq} and C . The dominant frequency is usually selected within the useful bandwidth for the parti-

cular application, and in seismic work, the bandwidth is a range of approximately 0 to 120 c/s. The amplitude of the force is selected to be large enough to supply an amount of energy to the medium sufficient to provide strong signals for recording.

In shooting a seismic pattern, the seismic signal is reflected or refracted from sub-surface strata and is picked up by a seismometer and recorded. The time of travel of the signal from its point of origination to the seismometer is usually in the order of milliseconds. To provide proper synchronisation of the recording of the seismic signal with the initiation of the signal in the earth, it is necessary to know the instant the signal is initiated. When the capacitor bank is discharged through the antenna, the time delay between the closing of the switch to discharge the capacitor bank and the initiation of the force in the earth is in the order of microseconds. Thus the time delay here is negligible as compared to the travel time of the signal from the antenna to the seismometer, and accurate synchronisation is achieved.

The total energy that is stored in the capacitor bank is proportional to the capacitance and the charge voltage, or:—

$$E = \frac{1}{2} CV^2, \quad (9)$$

where V = charging voltage.

There will be some loss of this energy during excitation of the antenna, although a large percentage will be coupled into the earth. Typical parameters for seismic exploration are a total capacitance of the system of several thousand microfarads with a charging voltage of several thousand volts. The equivalent inductance is normally in the millihenry range with as little series resistance as possible to avoid heat losses. As one example the charging voltage was set at 4000 volts, the total equivalent capacitance was set at about 1000 microfarads with an equivalent inductance of about 5—10 milli-henries. An antenna having these electrical parameters will produce a force whose frequency spectrum is substantially that as shown in Fig. 4, wherein almost all of the energy in the pulse is within the useful frequency range below about 100—120 c/s. The energy delivered by such a system having these parameters will be about 10,000 joules, this being equivalent to about 10 BTU. This energy can be increased by increasing either the charging voltage or the capacitance, where the range of energies that is adequate for seismic work with this system is from about 10,000 to 20,000 joules.

The impulse apparatus provides an efficient means for transforming a force into a pressure wave and coupling this wave into a medium. The substantial area of the earth-antenna interface is effective in causing the force generated between the coils to be transformed into the earth as a pressure impulse. An important feature of the apparatus is that

by regulating the current in the coils, it is possible to accurately determine the frequency spectrum and bandwidth of the force produced. A pressure wave of exactly the same frequency spectrum and bandwidth is introduced into the medium adjacent the coils. Since it can be determined exactly what shape and magnitude current pulse is necessary to produce a force of given magnitude and frequency spectrum, the desired pressure wave can be produced by providing the necessary current pulse. This is very desirable in the seismic art, since the knowledge gained from seismic traces is largely dependent upon the knowledge of the characteristics of the pressure wave used.

Several of the antennae of this invention can be used together in spaced relation on the earth's surface to provide, in effect, an array source as is commonly known in the seismic art. The antennae can be activated simultaneously or in sequence, whichever will produce the best results. Thus there is effected a superposition of the several pressure waves to provide a complete seismic pattern.

Referring now to Figs. 9—13, a preferred embodiment of this invention may be observed.

This embodiment provides an acoustical antenna of finite length which is equivalent to a continuous array of point sources distributed along the length thereof. Thus this embodiment provides apparatus possessing specially advantageous features for certain applications of which prior apparatus is not capable.

In seismic prospecting the most commonly used sources of seismic energy are those which are equivalent to point sources. For example, a charge of dynamite when exploded appears as a point source of acoustical energy in relation to the seismometers that record this energy after reflection of the wave from sub-surface strata. A point source of acoustical energy is equivalent to saying that the lateral dimensions of the area over which the energy is generated at the source are small as compared to the wavelength of the frequency components of the reflected impulsive signal.

A large amount of the source energy is lost due to spreading or the geometrical divergence factors. This embodiment overcomes this difficulty to a large extent by providing a line transmitter that functions as an acoustical antenna of finite, but extended length. The total energy of the antenna is distributed over an area of much greater lateral dimensions than previous seismic sources, and in this manner, a large degree of directivity of the pressure wave is achieved. Consequently, much less of the total energy is lost to spreading as compared to conventional sources, and a higher acoustical efficiency results. For a discussion of an antenna of finite length which is equivalent to a continuous array of point sources distributed along the length, reference is had to Kraus, John D., *Antennas*, McGraw-

Hill Book Company Inc., (1950), pp. 110—114.

5 This antenna has particular application as a seismic source where it is important to know precisely the frequency and power characteristic of the source and the exact instant the impulse generated thereby is initiated. Moreover, the frequency content of the impulse can be varied to optimise the results achieved for the particular geographical location of operation.

10 Another significant feature is the decrease in the cavitation impulse pressure, which is caused as a result of a high pressure impulse generated in a fluid when the fluid collapses into the void created by the impulse. This cavitation impulse is undesirable because of its uncontrolled frequency content and because it adds noise to the seismic signal. By spreading the total signal over a large area, as will become apparent from a description of a preferred embodiment of the invention, the cavitation pressure is reduced to a minimum and is no longer troublesome.

25 Referring now to Fig. 9 there is shown a view, partly in section, of a preferred embodiment of the conductor configuration of the seismic line transmitter. The preferred form of the conductor itself is shown partly in section in Fig. 10, which is a metal cable 60 (for example, copper) having a thin coating of electrical insulation 62. Any suitable flexible metal cable of the proper current carrying capacity can be used such as that used for battery cable. A preferred insulation is a Scotch electric tape No. 5, a trade name of the Minnesota Mining and Manufacturing Company of Minneapolis, Minnesota, although any other suitable insulation will suffice. A long length of the cable is wound back and forth on itself such as illustrated in Fig. 9 to provide a parallel conductor configuration of several cable layers in thicknesses and of several cable widths across. To one end 40 of the cable there is attached an electrical connection 44, and to the other end 42 there is attached an electrical connection 46. There is no space provided between the upper and lower rows of cable when no current is flowing, although there is shown in Fig. 9 a small separation 52 between the upper and lower rows to illustrate the flexibility of the conductors to permit a slight separation upon the generation of the opposing force. The insulation prevents any electrical shorting between the several lengths of the cable. As the cable is wrapped back and forth on itself, there is formed at the two ends loops 48 and 50. As a current is passed through the lengths of cable via the connections 44 and 46, as shown by the respective polarities (+) and (—), the current direction in all of the upper rows is the same, and the current in allow the lower rows is the same but oppositely directed to the current in the upper

rows. Moreover, since the conductor configuration of Fig. 9 is comprised of one continuous cable, each of the lengths thereof carries a current identical to all the other lengths. The current causes the opposing force previously described, and the loops 48 and 50 at the ends permit the slight separation between the upper and lower rows under the influence of the force. Because of the separation, a pressure wave or impulse is coupled to the medium adjacent the faces of the conductor configuration, whereas all the energy represented by the force would be dissipated as heat if the upper and lower rows were restricted and not allowed to separate.

It is to be understood that several individual lengths of cable can be used as an alternative to the one continuous length. In that event, each of the lengths of cable can be commonly connected at their ends to provide a configuration of several parallel connected conductors.

The conductor of Fig. 9 is cast in a suitable insulating substance 80, such as plastic or rubber, as shown in Fig. 11, to encapsulate and seal the conductor and provide a supporting structure. A preferred substance for this purpose is a neoprene rubber because of its excellent resiliency and durability. The neoprene is flexible enough to permit separation of the conductor portions as explained. For most applications the length of the conductor portions is several feet. The electrical connections 44 and 46 are sealed through the neoprene for connection to a current source, and a suitable handle 82 or equivalent is provided at one end for towing the line transmitter, as will be presently described. Upon the generation of a force between the conductor portions, the antenna flexes in a direction perpendicular to the faces thereof as a result of the force. The plastic nature of the neoprene 80 permits the flexure of the antenna, and additionally, acts as a restoring force for the opposing conductor portions after the expenditure of the energy represented by the pulse. When the antenna is used as an underwater acoustical source, there is an additional restoring force of about 15 pounds per square inch acting on each side of the transmitter for a depth of about 30 feet beneath the surface of the water. In this manner the antenna is made ready for the next current pulse.

The application of the antenna for off-shore exploration is illustrated in Fig. 12. Here, it is towed behind a vessel with buoys 100 supporting it at the desired depth. A towing cable 110 connects the antenna with the vessel with electrical connections 44 and 46 being connected to a current generator on board. As a current is passed through the antenna a pressure wave is generated in a vertical direction as illustrated by the compressions and rarefactions beneath the an-

halves. The antenna is supported in a resilient body, such as neoprene, as discussed above.

5 The antenna of Fig. 13 can be considered as the equivalent of three antennas; viz. coils A, B and C, each of different length and symmetrically disposed about a common transverse axis and commonly aligned. When power is supplied to the terminal leads 160 and 170, each of the coils pulse to generate an acoustical pressure wave the directions of which are perpendicular to their broad surfaces, i.e. perpendicular to the current flows. Over the length of coil A, the impulse pressure is due to that of coil A added to that of coils B and C whose portions are co-extensive with the length of coil A, all as indicated in the figure. Beyond each end of coil A and between the ends thereof and the ends of coil B, the impulse pressure is the addition of the forces exerted by coils B and C over this length. Beyond each end of coil B and between the ends thereof and the ends of coil C, the pressure is the result of coil C alone, all as shown in the figure. The net effect of this configuration is an antenna constructed so as to cause an attenuation of pressure along its length.

30 The embodiment shown in Fig. 13 is illustrative of one example of how the energy of the pressure impulse can be attenuated along its length. Any combination of individual coils, however, to provide any desired function of pressure magnitude along the length of the antenna is contemplated by this invention. The desirability of different attenuations along the length of a line source for different geographical locations is discussed in the publication by J. O. Parr, Jr. and W. H. Mayne, entitled "A New Method of Pattern Shooting", Geophysics, Vol. XX, No. 3 (July, 1955), pp. 539-564.

WHAT WE CLAIM IS:—

45 1. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics comprising; a conductive means wound back and forth on itself to provide a parallel conductor configuration several layers in thickness, said parallel conductor configuration providing first and second portions each of which is elongated and substantially straight along its length, terminal means connected to each of the conductive means, said first portion and said second portion carrying oppositely directed currents in response to a voltage applied across said terminal means, the current direction in any segment of any said first portion being opposite to the current direction in the opposing segment of said second portion, and resilient insulating means encapsulating said first and said second portions and having a surface for engaging said medium, said oppositely directed currents pro-

65 ducing an opposing force and separation between said first and second portions causing said resilient insulating means to flex along a line perpendicular to and connecting opposing segments of said first portion and said second portion producing a pressure impulse along the length of said antenna and imparting said impulse to said medium through the surface of said insulating means.

2. Apparatus according to claim 1 including means for limiting the movement between said first portion and said second portion.

3. Apparatus according to claim 1 including resilient means for limiting the movement between said first portion and said second portion.

4. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics, comprising;

- (a) conductor means including
 - (i) a first plurality of parallel, elongated and substantially straight conducting segments,
 - (ii) a second plurality of parallel, elongated and substantially straight conducting segments disposed in opposing parallel relation to said first plurality of segments, said first and second conducting segments connected electrically in series with one another forming a continuous winding,
 - (b) terminal means connected to said conductor means,
 - (c) each of said first plurality of segments carrying current in one direction and each of said second plurality of segments carrying current in a direction opposite to said one direction in response to a voltage applied across said terminal means, and
 - (d) resilient insulating means encapsulating said first and said second plurality of segments and having a surface for engaging said medium, said oppositely directed currents producing an opposing force and separation between said first and said second plurality of segments and causing said resilient insulating means to flex along a line perpendicular to and connecting said first and said second plurality of segments,
 - (e) whereby a pressure impulse is imparted to said medium through said surface upon flexing of said resilient insulating means.
5. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics, comprising;
- (a) a flattened conducting coil having elongated, substantially straight first and second conducting portions disposed in parallel relation,
 - (b) terminal means connected to said coil,



halves. The antenna is supported in a resilient body, such as neoprene, as discussed above.

5 The antenna of Fig. 13 can be considered as the equivalent of three antennas; viz. coils A, B and C, each of different length and symmetrically disposed about a common transverse axis and commonly aligned. When power is supplied to the terminal leads 160 and 170, each of the coils pulse to generate an acoustical pressure wave the directions of which are perpendicular to their broad surfaces, i.e. perpendicular to the current flows. Over the length of coil A, the impulse pressure is due to that of coil A added to that of coils B and C whose portions are co-extensive with the length of coil A, all as indicated in the figure. Beyond each end of coil A and between the ends thereof and the ends of coil B, the impulse pressure is the addition of the forces exerted by coils B and C over this length. Beyond each end of coil B and between the ends thereof and the ends of coil C, the pressure is the result of coil C alone, all as shown in the figure. The net effect of this configuration is an antenna constructed so as to cause an attenuation of pressure along its length.

30 The embodiment shown in Fig. 13 is illustrative of one example of how the energy of the pressure impulse can be attenuated along its length. Any combination of individual coils, however, to provide any desired function of pressure magnitude along the length of the antenna is contemplated by this invention. The desirability of different attenuations along the length of a line source for different geographical locations is discussed in the publication by J. O. Parr, Jr. and W. H. Mayne, entitled "A New Method of Pattern Shooting", Geophysics, Vol. XX, No. 3 (July, 1955), pp. 539-564.

WHAT WE CLAIM IS:—

45 1. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics comprising; a conductive means wound back and forth on itself to provide a parallel conductor configuration several layers in thickness, said parallel conductor configuration providing first and second portions each of which is elongated and substantially straight along its length, terminal means connected to each of the conductive means, said first portion and said second portion carrying oppositely directed currents in response to a voltage applied across said terminal means, the current direction in any segment of any said first portion being opposite to the current direction in the opposing segment of said second portion, and resilient insulating means encapsulating said first and said second portions and having a surface for engaging said medium, said oppositely directed currents pro-

ducing an opposing force and separation between said first and second portions causing said resilient insulating means to flex along a line perpendicular to and connecting opposing segments of said first portion and said second portion producing a pressure impulse along the length of said antenna and imparting said impulse to said medium through the surface of said insulating means.

2. Apparatus according to claim 1 including means for limiting the movement between said first portion and said second portion.

3. Apparatus according to claim 1 including resilient means for limiting the movement between said first portion and said second portion.

4. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics, comprising;

- (a) conductor means including
 - (i) a first plurality of parallel, elongated and substantially straight conducting segments,
 - (ii) a second plurality of parallel, elongated and substantially straight conducting segments disposed in opposing parallel relation to said first plurality of segments, said first and second conducting segments connected electrically in series with one another forming a continuous winding,
 - (b) terminal means connected to said conductor means,
 - (c) each of said first plurality of segments carrying current in one direction and each of said second plurality of segments carrying current in a direction opposite to said one direction in response to a voltage applied across said terminal means, and
 - (d) resilient insulating means encapsulating said first and said second plurality of segments and having a surface for engaging said medium, said oppositely directed currents producing an opposing force and separation between said first and said second plurality of segments and causing said resilient insulating means to flex along a line perpendicular to and connecting said first and said second plurality of segments,
 - (e) whereby a pressure impulse is imparted to said medium through said surface upon flexing of said resilient insulating means.
5. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics, comprising;
- (a) a flattened conducting coil having elongated, substantially straight first and second conducting portions disposed in parallel relation,
 - (b) terminal means connected to said coil,



5 tenna. The wave is generated by the opposing
force between the upper and lower rows of
conductors and causes the resilient antenna
to flex in a vertical direction. The force is
coupled to the water as a pressure disturbance
at the antenna-water interface. The wave
front propagates from the antenna to the
water-earth interface in the same manner as a
10 wave propagated from an antenna of finite,
but extended length. It is coupled to the earth
and is eventually reflected or refracted by
subsurface strata, whence it returns to the
surface and is picked up by recording seismo-
meters (not shown). Because of the antenna
15 effect, the pressure pulse takes the form of a
plane propagating wave, or a wave front sub-
stantially similar to a plane wave. Hence a
large percentage of the acoustical energy
generated at the source (antenna) returns to
20 the seismometers, and consequently, the effi-
ciency of the system is quite high.

Another distinct advantage of this antenna
for underwater applications is that the cavi-
tation impulse is maintained at a minimum.
25 When a large disturbance is created in water,
such as an explosion or the like, a void is
created for a short duration. The collapse of
the water into the void acts as an explosion
or pressure burst itself, and the recording of
30 these waves makes it difficult to distinguish
them from the true impulse. Because the
force generated by the antenna is distributed
over an extended distance, the force at one
point along its length is relatively small,
35 although the total force generated is large.
Thus the cavitation problem is maintained at
a minimum and the seismic records produced
thereby are more accurate.

As an example of the parameters and di-
mensions of the transmitter, battery cable
40 (copper) having a thin coating of the Scotch
electric insulating tape noted above is wound
on itself as shown in Fig. 9 to provide a
conductor configuration of five rows across,
45 and each of the upper and lower rows are
comprised of 3 or 4 layers of cable. A braided
copper battery cable of dimensions of about
0.75 inch by about 0.050 inch is used and
is the braided equivalent of about No. 7
50 wire, A.W.G. Each of the rows (the length
of the antenna) is about 50 feet long. This
gives a total series resistance of about 2 ohms,
and an equivalent inductance of a few milli-
henries, usually from 5—10 millihenries. As
55 previously described, the cable is cast in a
neoprene rubber.

The current supply comprises a capacitor
bank of total capacitance of about 1000 micro-
farads, and a direct-current supply voltage of
60 about 4000 volts. The discharge of the ca-
pacitor bank through the antenna produces a
force the frequency components of which are
within the range of 0—100 c/s. The amount
of energy generated by the antenna is pro-
65 portional to the product of the capacitance

and the square of the charging voltage. For
the parameters noted above, the total energy
released by the antenna is in the order of
several thousand joules, which is adequate for
most seismic prospecting. 70

It is apparent that the above parameters
can be varied to produce pressure impulses
of a wide variety of frequency characteristics.
The parameters for producing a pressure im-
pulse of any particular frequency band can be
75 determined, of course, from the preceding
Equations. The physical dimensions of the
antenna are also subject to variation, but in
general the greater the area producing the
impulse, the more directional is the propagated
80 wave. For example, as the length of the an-
tenna is reduced, the less directional is the
propagated wave. It should not be construed,
however, that a length of 50 feet is the mini-
mum length that can be used with effectiveness
85 but rather this length is suitable for the
purpose herein disclosed. On the other hand,
the length of the antenna is substantially
greater than the width in order to approxi-
mate or be equivalent to an antenna having
90 a substantial degree of directivity.

A modification of the acoustical antenna is
shown in Fig. 13, which is a side elevational
view of an antenna comprised of three sepa-
rate coils A, B and C. Coil A comprised of
95 layers 120 of braided wire constitutes the
innermost section of the antenna and is con-
structed similarly to the coil shown in Fig.
9. Coil B surrounds and has a greater length
than coil A. Likewise, coil C surrounds both
100 coils A and B and has a greater length than
either coil A or B. Coil B comprised of
layers 122 and coil C comprised of layers
124 are each constructed similarly to coil A.
The only difference in construction of the
105 coils and that shown in Fig. 9 is that the
layers comprising the coil are electrically con-
nected in parallel, whereas the layers of the
antenna of Fig. 9 are electrically connected
in series. However, this is immaterial as long
110 as the upper layers of the coil are intercon-
nected for carrying currents in the same direc-
tion. To the ends 130 and 132 a coil A
are connected lead wires 134 and 136, respec-
tively; likewise to ends 138 and 140 of
115 coil B are connected lead wires 142 and 144,
respectively; and to ends 146 and 148 of coil
C are connected lead wires 150 and 152,
respectively. Lead wires 134, 142 and 150
are commonly connected to terminal lead 160
120 and lead wires 136, 144 and 152 are commonly
connected to terminal lead 170. A voltage
source the same as described previously is
connected across terminal leads 160 and 170
to provide power to the antenna. Because of
125 the connections, the current directions in the
upper halves of coils A, B and C are all
the same, whereas the current directions in
the lower halves of the coils are all the same
but opposite to the direction of the upper
130



- (c) said first and said second portions carrying oppositely directed currents in response to a voltage applied across said terminal means, and
- 5 (d) resilient insulating means encapsulating said first and said second portions and having a surface for engaging said medium, said oppositely directed currents producing an opposing force and separation between said first and said second portions and causing said resilient insulating means to flex along a line perpendicular to and connecting said first and said second portions, whereby a pressure impulse is imparted to said medium through said surface upon flexing of said resilient insulating means.
- 10 6. Apparatus according to claim 5 including means for limiting the movement between said first and said second conducting portions.
- 15 7. Apparatus according to claim 5 including resilient means for limiting the movement between said first and said second conducting portions.
- 20 8. Apparatus according to claim 5 including inertial means for limiting the movement between said first and said second conducting portions.
- 25 9. An acoustical antenna for generating in a medium a directional pressure impulse having controlled frequency characteristics, comprising:
- 30 (a) conductor means including a plurality of flattened conducting coils each having elongated, substantially straight first and second conducting portions disposed in parallel relation,
- 35 (b) each of said coils having a different length as defined by the length of its respective first and second portion,
- 40 (c) said plurality of coils being disposed in concentric relation as defined by an axis passing between said first and second portions perpendicular thereto and symmetrical therewith, with the coils of smaller lengths being surrounded by the coils of larger lengths,
- 45 (d) said plurality of coils being interconnected in electrical parallel.
- 50 (e) terminal means connected to said conductor means,
- 55 (f) each of said first portions of each of said plurality of coils carrying currents in one direction and each of said second portions of each of said plurality of coils carrying currents in a direction opposite to said one direction in response to a voltage applied across said terminal means, and
- (g) resilient insulating means encapsulating said first and said second portions of said plurality of coils and having a surface for engaging said medium,
- 60 (h) said oppositely directed currents producing an opposing force and separation between said first and said second portions of each of said plurality of coils and causing said resilient insulating means to flex along a line connecting said first and said second portions perpendicular to said axis,
- 65 (i) whereby a non-uniform pressure impulse is generated in said medium at said surface along the lengths of said plurality of coils, the pressure at any point along said surface being related to the number of coils acting in co-operation at said point.
- 70 10. Apparatus according to claim 9 including means for limiting the movement between said first and second conducting portions.
- 75 11. Apparatus according to claim 9 including resilient means for limiting the movement between said first and second conducting portions.
- 80 12. Apparatus according to claim 9 including inertial means for limiting the movement between said first and second conducting portions.
- 85 13. Apparatus according to any one of the preceding claims wherein the ratio of the area of said surface to the magnitude of said force is sufficiently large that the elastic limit of said medium is not exceeded upon the production of said force.
- 90 14. Apparatus according to any one of the preceding claims including means connected to said terminal means for discharging a capacitor through said conductor means.
- 95 15. Apparatus for generating in a medium a directional pressure impulse having controlled frequency characteristics, substantially as described herein with reference to and as illustrated by Figs. 1 to 4, in conjunction either with Figs. 5, 7 and 8 or with Figs. 6, 7 and 8 or with Figs. 9, 10 and 11 or with Fig. 13 of the accompanying drawings.
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