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(54) MARINE SEISMIC PROSPECTING

(71) We, WESTERN GEOPHYSICAL COMPANY OF AMERICA, a corporation organised and existing under the laws of the State of Delaware, United States of America, of 360 North Crescent Drive, Beverly Hills, California 90213, 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:—

It is well known in the art of seismic prospecting that the acoustic energy, also referred to as seismic energy, available from the detonation of an explosive charge (or more generally from any source of acoustic shock waves) increases if the detonator, i.e. the source, is confined under pressure, i.e. tamped. Thus, for example in seismic prospecting operations upon land, a hole is drilled in the earth, a charge is placed at the bottom of the hole, and the hole is filled with sand, water or mud prior to the detonation of the explosive. The column of fill material acts as a tamp upon the charge and greatly increases the proportion of energy, set free by the detonation reaction, converted into seismic energy. Ratios of seismic energy transmitted into the ground as between tamped and untamped charges may be as high as 50 to 1 or more.

To achieve the desirable effect of increased confining pressure in a seismic exploration survey at sea, it is necessary to detonate explosive charges as sources of seismic energy at an appreciable depth below sea level. The resulting gaseous products of the explosion form an expanding bubble, thereby to produce a pulse of acoustic energy constituting the seismic signal. However, subsequently to the initial expansion, which is desired, the gas bubble, upon contraction, begins an undesired sequence of alternate, secondary expansions and contractions which results in the production of so-called bubble pulses, as is well known in the seismic art. This phenomenon is more particularly described in the book *Underwater Explosion* by Cole, 1948,

Princeton University Press, and in United States Patent No. 2,622,691. Each of these bubble pulses, in turn, acts as a separate source of seismic energy, with the net result that the seismic signal emitted from the location of the explosion is a series of successive pulses, instead of only one pulse, as would be desirable.

To avoid this effect during seismic exploration at sea, it has been customary to detonate explosive charges as sources of seismic energy near the sea surface, in order that the gaseous products of the explosion be vented immediately to the atmosphere, thus preventing secondary expansions and contractions, i.e. bubble pulses. However, since placement of explosives in water at little depth below sea level necessarily results in relatively little tamping because the confining pressure of the water is low, explosives so used constitute a relatively inefficient source for acoustic signals of seismic energy.

As a consequence, in practice, the use of explosives at considerable depths in water has been restricted to the type of seismic exploration by the seismic refraction technique, in which only the first arrival of an acoustic energy signal is studied. In the seismic reflection technique, on the other hand, in which the entire train of returned seismic energy is required to be detected and recorded for the proper conduct and ultimate interpretation of the survey, it was not possible to lower charges sufficiently deep beneath the sea surface and still achieve satisfactory results, because of the confusion in the interpretation of the returned seismic energy signals which would be caused by the successive secondary train of bubble pulses produced by the successive contractions and expansions of the gaseous products of the explosion.

One known method which successfully overcame the bubble pulse problem is the method of Compagnie Generale de Geophysique de France described in United States Patent No. 3,368,641, which, in turn, is an embodiment of a more basic method believed to have been developed by Standard

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Oil Company of California. In this method of the prior art, the explosives are detonated deep underwater, but within a perforated enclosure forming a cage. The cage permits the initial shock wave to be emitted but, by slowing the subsequent inflow of water into the cage, it prevents the rapid collapse of the first bubble. While this known method may be successful with relatively small charges, relatively large cages are needed to suppress bubbles produced by relatively large charges. In addition, the cage acts as a damper of the generated seismic energy thus reducing the useful proportion thereof, requires additional towing force and is relatively costly.

It is precisely at this point where the present invention starts, inasmuch as it is based on the recognition that a useful system can be obtained by correcting for secondary bubble expansions at the stage of detecting and evaluating the signals produced by the seismic pulses reflected from sub-bottom strata. It has been recognized that if this can be done, embodiments can be provided which have no perforated enclosure.

In accordance with one aspect of the invention, there is provided a method of marine seismic prospecting, wherein an underwater explosion in the form of a rapidly expanding volume of gas under high pressure is produced to form a gas bubble at a depth sufficient to permit the gas bubble, subsequently to the initial, explosive expansion, at least once to collapse and again to expand, the initial explosive expansion and the subsequent expansion, or expansions, each creating an acoustic impulse which is reflected from sub-bottom strata, wherein a wave train of first signals representative of acoustic impulses as reflected from sub-bottom strata is produced and detected, wherein second signals are produced which are representative of the unreflected wave train caused by the initial and the subsequent expansion, or expansions, and wherein the first signals are combined with the second signals to form output signals such that the wave train of output signals thus obtained corresponds to the wave train of first signals which would have been produced in the absence of subsequent expansions of the bubble.

In accordance with one embodiment of the method of the invention, combining the first signals and the second signals is effected in such a manner as substantially to prevent the subsequent expansion or expansions from providing any component of said output signals. Alternatively, combining the first signals and the second signals may be effected in such a manner that the resulting wave train of output signals constitutes a combination of wave train components obtained from the initial and the subsequent expansions with appropriate time shifts of said components to

simulate the effect of a simultaneous occurrence of the first and subsequent expansions.

In accordance with a specific embodiment of the invention, an operator is constructed from the second signals, the operator representing a characteristic of the subsequent expansions, or expansions, followed by operating on the first signals with the operator. A characteristic from which the operator is constructed is preferably the time interval or intervals between the initial expansion and a subsequent expansion or expansions. Another characteristic from which the operator may be constructed is the ratios of amplitudes of the pressure pulse produced by subsequent expansions relative to the amplitude of the pressure pulse produced by the initial expansion, in addition to the time interval or intervals between the initial expansion and a subsequent expansion or expansions. Such operator performs the function of cross-correlating the second signals received at the said time interval or intervals with the first signals, thereby to remove the effect of the reflected signals corresponding to the subsequent expansion or expansions. Moreover, an inverse operator may be constructed by inverting the second signals into a preselected waveform, the method including filtering the first signals with the inverse operator thus constructed.

In an embodiment of the method of this invention, wherein the resulting output signals form a wave train which simulates the effect of a simultaneous occurrence of the initial expansion and the subsequent expansions, the operator is constructed to time-compress the wave train of second signals into a single occurrence.

In accordance with another aspect of the invention, there is provided an equipment for marine seismic prospecting, for use in conjunction with means for producing underwater explosions each in the form of an alternately expanding and contracting gas bubble to create acoustic impulses for reflection from sub-bottom strata, the equipment including pressure-transducing means for detecting the acoustic impulses reflected from sub-bottom strata to provide a train of first signals representative of said reflected acoustic impulses, at least one additional pressure transducer for producing second signals representative of the unreflected wave train caused by the initial and the subsequent expansion, or expansions, of the gas bubble, and means for combining the first signals and the second signals into output signals, such that the wave train of output signals thus obtained corresponds to the wave train of first signals which would have been produced in the absence of subsequent expansions of the bubble.

In accordance with one embodiment of the equipment of this invention, the additional

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pressure transducer is a hydrophone, secured to a charge launcher, to produce the second signals substantially exclusively. The first signals and the second signals may suitably be combined in such a manner as substantially to prevent the subsequent expansion or expansions from providing any component of said output signals. Alternatively, the first signals and the second signals may be combined in such a manner that the resulting wave train of output signals constitutes a combination of wave train components obtained from the initial and the subsequent expansions with appropriate time shifts of said components to simulate the effect of a simultaneous occurrence of the first and subsequent expansions. In practice, the function of combining the first signals and the second signals may be effected by means for constructing an operator from the second signal, the operator representing a characteristic of the subsequent expansion, or expansions, and for operating on the first signals with the operator. Suitably, the or each time interval between the initial expansion and a subsequent expansion, or subsequent expansions, is determined, the characteristic from which the operator is constructed being a function of the time interval thus determined.

In an embodiment described further below, there are provided means for determining the ratios of amplitudes of the pressure pulses produced by subsequent expansions relative to the amplitude of the pressure pulse produced by the initial expansion, the characteristic from which the operator is constructed being a function of the ratios thus determined, in addition to the time interval between the initial expansion and a subsequent expansion. More specifically, a cross-correlator may be used to which is applied the operator as derived from the second signals, together with the first signals, the cross-correlator being operable to remove the effect of the reflected signals corresponding to the subsequent expansion, or expansions. In accordance with another embodiment, there is used a convolver to which is applied an inverse operator, as it is constructed by inverting the second signals into a preselected waveform, for filtering the first signals with the inverse operator thus constructed. When it is intended that the output signals form a wave train which simulates the effect of a simultaneous occurrence of the initial expansion and the subsequent expansions, the operator is constructed to time-compress the wave train of second signals into a single occurrence.

In order to summarize what has been explained thus far, it is proposed that explosive charges are detonated at any desired depth, the bubble pulse train is permitted to form without hindrance, and either the effects of the secondary bubble expansions are removed in the stage of processing the

recorded seismic data, or the characteristic pulse train produced by the secondary bubble expansions is used to enhance the quality of the resulting seismic data by means of time-compressing their occurrence into coincidence with the initial expansion. In this way there can be produced an output wave train which corresponds (as to data content or as to the relative timing and relative amplitudes of the impulses) with the wave train of output signals which would have been produced, and with the seismic wave train which would have been obtained from the reflections, in the absence of any secondary bubble expansions.

To practice the method of this invention, an explosion generating a bubble containing a high-pressure expanding volume of gas is established at a sufficient depth to prevent the gas from directly venting to the atmosphere. The initial expansion of the gas bubble creates in the water an initial acoustic impulse for subsequent reflection from the sub-bottom strata. The gas bubble, subsequent to the initial expansion, collapses and again expands to create in the water at least a first secondary bubble acoustic impulse which is also reflected from the sub-bottom strata. The reflections of the initial acoustic impulse and of the first secondary bubble acoustic impulse are detected to provide a seismic wave train. An operator can then be constructed from a characteristic of the first secondary bubble acoustic impulse, and the seismic wave train is operated on by the operator. Preferred operators and their manner of construction are described further below in conjunction with the drawings.

The invention will become better understood from the following detailed description of embodiments thereof, when taken in conjunction with the drawings, wherein:—

Figure 1 is a schematic illustration of a system for producing underwater a bubble containing a high-pressure, initially expanding volume of gas;

Figure 2 illustrates the initial and subsequent expansions and contractions of the gas bubble;

Figure 3 is a waveform representing a bubble pulse train generated by the initial and secondary bubble expansions;

Figure 4 represents the received seismic wave train;

Figure 5 represents the desired seismic wave train;

Figure 6 schematically illustrates a processing system using a cross-correlator; and

Figure 7 schematically illustrates a processing system using a convolver.

Referring now to Figure 1, there is shown a firing system for producing explosions in a body of water, each explosion generating a bubble containing a high-pressure, expanding volume of gas at a sufficient depth to prevent the gas from directly venting to the atmos-

phere. The preferred firing system includes a charge launcher 10, which receives percussion-initiable, explosive charges 12. Each charge 12 includes a delay fuse which causes the charge to detonate at a distance removed from launcher 10, because, during operation,, launcher 10 is towed by a seismic ship 14 at a predetermined depth below the water level. The directional stability of launcher 10 is maintained by suitable paravanes 15. A flexible conduit 16 couples a charge loader 18 on deck of ship 14 to the charge launcher 10. The charges 12 pass through conduit 16 under the propulsion of water pressure.

By way of illustration of the operation of the charge launcher 10, the launcher is towed behind the seismic ship 14 at six to ten knots at a depth which may range from 20 to 50 feet below the water surface. An operator successively causes each charge 12 to move under water pressure to the charge launcher 10. When charge 12 reaches the end of its trajectory, its motion is arrested by a percussion element 20 which strikes a firing pin in charge 12, thereby to actuate a primer in charge 12. Charge 12 is then ejected from launcher 10 by the flow of water under pressure between the charge and the wall 22 of launcher 10. The detonation of the ejected charge 12 is delayed by the time-delay fuse until a distance of say seven to ten feet is established between the initiated charge and the moving launcher 10.

With reference to Figure 2, upon detonation, the chemical energy in charge 12 is suddenly converted into kinetic energy of a rapidly expanding mass of gas. There is thus established, in the body of water, a bubble 30 containing a high-pressure, expanding volume of gas. Because gas bubble 30 is generated at a depth of say 30 to 50 feet, it cannot directly vent to the atmosphere. The gas bubble 30 undergoes a very fast initial expansion, as illustrated by the radially outwardly oriented arrows in the bubble 30 in Figure 2, which causes the surrounding water to become suddenly strongly compressed. The compression of the water creates the desired initial acoustic impulse 30', shown in Figure 3, which is radiated outwardly throughout the body of water for subsequent reflection from sub-bottom strata, thereby to be detected and recorded by a streamer cable 24 of detectors, usually hydrophones.

Subsequent to its initial expansion, gas bubble 30 collapses, as is well known, into a contracted condition 32, as illustrated by the radially inwardly oriented arrows. The contracted bubble 32 then again expands into an expanded condition 34. The expansion of bubble 34 creates in the water a first secondary bubble acoustic impulse 34' (Figure 3) which is radiated outwardly throughout the water. This first secondary impulse 34' also becomes reflected from the sub-bottom strata.

Thereafter, bubble 34 collapses into a contracted gas bubble 36 which then undergoes a third expansion, i.e. a second secondary expansion, etc.

The entire sequence of gas bubble expansions and contractions forms a pulse train of acoustic impulses.

One technique for detecting this pulse train is to employ a suitable detecting device 40, such as a pressure transducer or hydrophone, in addition to those of the streamer cable 24, positioned as near as practicable to an exploding charge 12. The placement of detector 40 relative to launcher 10 is governed by the ability of detector 40 to withstand the large overpressures generated in the water by the explosions following the detonations of charges 12, and the ability of detector 40 to reproduce faithfully the pressure waveform generated by the explosion of charge 12. Detector 40 is therefore placed sufficiently far from the location of detonation, so that it is not damaged or overdriven by the detonation.

Detector 40 transmits to a recorder on deck of ship 14 the time of occurrence of each of the successive bubble acoustic impulses and also, if possible, the amplitudes and the pulse shapes of the initial pulse and of the first and subsequent secondary pulses. A recording is made of the sequence of pulses received by detector 40, preferably by the conventional seismic recording equipment and simultaneously with the recording of the detected seismic signals caused by the reflected signals from the sub-bottom strata. The reflected seismic signals are detected by the conventional seismic streamer cable 24, which provides a seismic wave train 24', as shown in Figure 4.

Figure 3 represents a typical recording of a bubble pulse train 40', as detected by transducer 40, usually a hydrophone. As mentioned above, the initial expansion of bubble 30 creates a relatively large initial pulse 30'. The second expansion of bubble 34 creates the first secondary bubble pulse 34', the third bubble expansion creates the second secondary bubble pulse 37, the fourth bubble expansion creates the third secondary bubble pulse 38, etc. Simultaneously with the recording of the bubble pulse train 40' by means of transducer 40, there is recorded on the seismic recording equipment on the ship 14 the seismic wave train 24' (Figure 4) by means of the streamer cable 24 of Figure 1.

It will be appreciated that, alternatively, the bubble pulse train 40' may be deduced from the conventional seismic data, as recorded by means of the streamer cable 24 in the conventional fashion, by recording the direct arrival of seismic signals at each detector group in streamer cable 24. This can be accomplished by adjusting the origin times of the recordings obtained from the plurality of

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seismic detector groups in the streamer cable, so that all first-arriving signals are recorded as if they were received simultaneously. Otherwise expressed, this technique resides in removing the direct-arrival moveout from the individual traces, one trace for each detector group. All the traces are then summed. Random noise will tend to be cancelled in such a sum, while the initial pulse and the following secondary bubble pulses will tend to reinforce, so that the sum trace will be a reasonably faithful reproduction of the pulses forming pulse train 40' (Figure 3).

In any event, for each detonation of a charge 12, a bubble pulse train 40' is recorded and a tabulation is made of the time intervals between each bubble pulse relative to the initial pulse. For example, as shown in Figure 3, the time interval between the first secondary bubble pulse 34' and the initial pulse 30' is t_1 , the time interval between the second secondary bubble pulse 37 and the first secondary bubble pulse 34' is t_2 , etc., and these intervals are summed as necessary to obtain the values for tabulation. If possible, although not necessary for carrying out some embodiments of the method of this invention, a tabulation is also made of the amplitude ratios of each secondary bubble pulse relative to the amplitude a_1 of the initial pulse 30', i.e. the amplitudes a_2, a_3, a_4 , etc. are measured and the ratios $a_2/a_1, a_3/a_1$, etc. are determined.

In accordance with an important feature of the present embodiments, there is constructed an operator from a characteristic of the first secondary bubble pulse 34' and the seismic wave train 24' is operated on with this operator, to obtain a desired seismic wave train 24'', illustrated in Figure 5, which would have been detected by streamer cable 24 if the pulse train 40' consisted of a single pulse, i.e. only the initial pulse 30'.

In a first embodiment, as shown in Figure 6, the bubble pulse train 40' is used to construct a correlation operator 60 which operates in a cross-correlator 62 on the seismic wave train 24'. In other words, the bubble pulse wave train 40', consisting of the initial pulse 30' and of the following secondary bubble pulses 34', 37, 38, etc., is cross-correlated against the received seismic wave train 24' in exactly the same manner as the variable-frequency input signal is cross-correlated against the received signal in the method well known as the "Vibroseis (Trade Mark) method". The Vibroseis method was firstly fully described in a paper by Crawford, et al., entitled "Continuous Signal Seismograph" (GEOPHYSICS, Vol. XXV, No. 1, Page 95). It is covered additionally in a large number of United States and other patents. The output of cross-correlator 62 produces the desired seismic wave train 24''.

Alternatively, the correlation operator 60

may consist of a single value for the initial pulse 30' and corresponding single values for each of the following secondary bubble pulses. These values are spaced in time and have their own magnitude, both in accordance with the above-described tabulation. Such an operator is known as a discrete, time-delay operator.

Either the correlation operator 60 or the discrete, time-delay operator may be validly applied to the received seismic wave train 24', because the bubble pulse train 40' is not periodic. That is, the time intervals between pulses emitted by successive bubble expansions and their corresponding amplitudes change, as illustrated in Figure 3.

In another embodiment, shown in Figure 7, a more involved operator 70 may be constructed from the inverse to the bubble pulse train 40' in the well-known fashion developed by Wiener. The Wiener operator is applied to the detected seismic wave train 24' in a convolver 72 by the convolution process. In this connection, reference is made to the entire field of mathematics devised by Norbert Wiener and first published in book form under the title *Extrapolation, Interpolation and Smoothing of Stationary Time Series* (New York, John Wiley and Sons, 1949). A whole series of books and papers have been written perfecting this art. In the construction of an inverse filter, as is well known in the art of communication theory, an operator 70 is constructed which converts a given, observed waveform to a desired output waveform 74. Operator 70 is constructed as the inverse Fourier transform of the quotient of the complex spectra of the observed and desired waveforms. For example, in the seismic method herein described, the observed waveform could be the bubble pulse train 40' and the desired waveform could be an impulse, a Ricker wavelet or a minimum phase wavelet having a conventional, restricted-band amplitude spectrum. The steps to be followed are well known in the art of processing, or of analysis of, stationary time series. Accordingly, the received seismic wave train 24' is processed by convolver 72 to provide the desired wave train 24''.

For completeness, though well known in the art, it could be mentioned that cross-correlators are mathematical devices or mechanical devices designed to produce cross-correlation filtering. References include the paper "Cross-correlation-filtering" by Jones and Morrison (GEOPHYSICS, Vol. XIX, Page 660). The Vibroseis system of Nigal Anstey of England, as described in the paper mentioned above, makes use of a mechanical cross-correlator, and the basic idea of cross-correlation filtering is covered in the Wiener reference mentioned above. The cross-correlation operator consists of values representing time shifts of signals and amplitude adjust-

ments. In other words, the cross-correlation operator represents a recipe for shifting, scaling and combining signals. Moreover, a discussion of minimum phase can be found in the book by Norbert Wiener, see above, and other references on seismic filtering. An excellent reference on seismic filtering discussing most of these concepts is *Le Filtrage en Sismique*. Ricker wavelets were first described in a paper "The Form and Laws of Propagation of Seismic Wavelets" by Norman Ricker (GEOPHYSICS, Vol. XVIII, page 10).

In yet another embodiment, through data processing techniques available to the seismic processing art, it is possible to time-compress the bubble pulse train 40' of Figure 3 into the initial pulse 30' to produce the effect of an enhanced single pulse source and, hence, to produce an enhanced form of the waveform 24''.

One technique for carrying out this embodiment of the method of the invention is described as follows: remove the sequence of secondary bubble expansions from the original seismic trace 24' in accordance with any of the embodiments described above, to form the processed trace 24''; subtract processed trace 24'' from the original trace 24' to obtain a bubble trace A which now contains only the reflected signals from the secondary bubble pulse sequence; assume that the first secondary bubble is equivalent to, i.e. that it could be considered, an initial pulse and, with this assumption, process the bubble trace A in accordance with any of the embodiments described above, to remove all subsequent bubble pulses and thereby to obtain a processed trace B which will contain only the reflected signals from the first secondary bubble pulse; time-shift processed trace B by time t_1 which operation will align the signals corresponding to reflections from the first secondary bubble pulse with those from the initial pulse on processed trace 24'', and add time-shifted trace B to processed trace 24'' to enhance the reflected signals from the initial pulse. This process can then be repeated for each subsequent bubble pulse, to further enhance the reflected signals from the initial pulse.

WHAT WE CLAIM IS:—

1. A method of marine seismic prospecting, wherein an underwater explosion in the form of a rapidly expanding volume of gas under high pressure is produced to form a gas bubble at a depth sufficient to permit the gas bubble, subsequently to the initial, explosive expansion, at least once to collapse and again to expand, the initial explosive expansion and the subsequent expansion, or expansions, each creating an acoustic impulse which is reflected from sub-bottom strata, wherein a wave train of first signals representative of acoustic impulses as reflected

from sub-bottom strata is produced and detected, wherein second signals are produced which are representative of the unreflected wave train caused by the initial and the subsequent expansion, or expansions, and wherein the first signals are combined with the second signals to form output signals such that the wave train of output signals thus obtained corresponds to the wave train of first signals which would have been produced in the absence of subsequent expansions of the bubble.

2. A method according to claim 1, wherein the first and second signals are combined in such a manner as substantially to prevent the subsequent expansion or expansions from providing any component of said output signals.

3. A method according to claim 1, wherein the first and second signals are combined in such a manner that the resulting wave train of output signals constitutes a combination of wave train components obtained from the initial and the subsequent expansions with appropriate time shifts of said components to simulate the effect of a simultaneous occurrence of the first and subsequent expansions.

4. A method according to any one of the preceding claims, wherein an operator is constructed from the second signals, said operator representing a characteristic of the subsequent expansion, or expansions, and the first signals are operated on with the operator.

5. A method according to claim 4, wherein a characteristic from which the operator is constructed is the time interval or intervals between the initial expansion and a subsequent expansion or expansions.

6. A method according to claim 5, wherein a characteristic from which the operator is constructed is the ratios of amplitudes of the pressure pulses produced by subsequent expansions relative to the amplitude of the pressure pulses produced by the initial expansion, in addition to the time interval or intervals between the initial expansion and a subsequent expansion or expansions.

7. A method according to claim 5 or claim 6, and including cross-correlating the second signals received at the said time interval or intervals with the first signals, thereby to remove the effect of the reflected signals corresponding to the subsequent expansion, or expansions.

8. A method according to claim 4, wherein the operator is an inverse operator constructed by inverting the second signals into a preselected waveform, the method further comprising filtering the first signals with the inverse operator thus constructed.

9. A method according to claim 3 and claim 4, wherein the operator is constructed to time-compress the wave train of said second signals into a single occurrence.

10. An equipment for marine seismic

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In yet another embodiment, through data processing techniques available to the seismic processing art, it is possible to time-compress the bubble pulse train 40' of Figure 3 into the initial pulse 30' to produce the effect of an enhanced single pulse source and, hence, to produce an enhanced form of the waveform 24''.

One technique for carrying out this embodiment of the method of the invention is described as follows: remove the sequence of secondary bubble expansions from the original seismic trace 24' in accordance with any of the embodiments described above, to form the processed trace 24''; subtract processed trace 24'' from the original trace 24' to obtain a bubble trace A which now contains only the reflected signals from the secondary bubble pulse sequence; assume that the first secondary bubble is equivalent to, i.e. that it could be considered, an initial pulse and, with this assumption, process the bubble trace A in accordance with any of the embodiments described above, to remove all subsequent bubble pulses and thereby to obtain a processed trace B which will contain only the reflected signals from the first secondary bubble pulse; time-shift processed trace B by time t_1 which operation will align the signals corresponding to reflections from the first secondary bubble pulse with those from the initial pulse on processed trace 24'', and add time-shifted trace B to processed trace 24'' to enhance the reflected signals from the initial pulse. This process can then be repeated for each subsequent bubble pulse, to further enhance the reflected signals from the initial pulse.

WHAT WE CLAIM IS:—

1. A method of marine seismic prospecting, wherein an underwater explosion in the form of a rapidly expanding volume of gas under high pressure is produced to form a gas bubble at a depth sufficient to permit the gas bubble, subsequently to the initial, explosive expansion, at least once to collapse and again to expand, the initial explosive expansion and the subsequent expansion, or expansions, each creating an acoustic impulse which is reflected from sub-bottom strata, wherein a wave train of first signals representative of acoustic impulses as reflected

from sub-bottom strata is produced and detected, wherein second signals are produced which are representative of the unreflected wave train caused by the initial and the subsequent expansion, or expansions, and wherein the first signals are combined with the second signals to form output signals such that the wave train of output signals thus obtained corresponds to the wave train of first signals which would have been produced in the absence of subsequent expansions of the bubble.

2. A method according to claim 1, wherein the first and second signals are combined in such a manner as substantially to prevent the subsequent expansion or expansions from providing any component of said output signals.

3. A method according to claim 1, wherein the first and second signals are combined in such a manner that the resulting wave train of output signals constitutes a combination of wave train components obtained from the initial and the subsequent expansions with appropriate time shifts of said components to simulate the effect of a simultaneous occurrence of the first and subsequent expansions.

4. A method according to any one of the preceding claims, wherein an operator is constructed from the second signals, said operator representing a characteristic of the subsequent expansion, or expansions, and the first signals are operated on with the operator.

5. A method according to claim 4, wherein a characteristic from which the operator is constructed is the time interval or intervals between the initial expansion and a subsequent expansion or expansions.

6. A method according to claim 5, wherein a characteristic from which the operator is constructed is the ratios of amplitudes of the pressure pulses produced by subsequent expansions relative to the amplitude of the pressure pulses produced by the initial expansion, in addition to the time interval or intervals between the initial expansion and a subsequent expansion or expansions.

7. A method according to claim 5 or claim 6, and including cross-correlating the second signals received at the said time interval or intervals with the first signals, thereby to remove the effect of the reflected signals corresponding to the subsequent expansion, or expansions.

8. A method according to claim 4, wherein the operator is an inverse operator constructed by inverting the second signals into a preselected waveform, the method further comprising filtering the first signals with the inverse operator thus constructed.

9. A method according to claim 3 and claim 4, wherein the operator is constructed to time-compress the wave train of said second signals into a single occurrence.

10. An equipment for marine seismic



- prospecting, for use in conjunction with means for producing underwater explosions each in the form of an alternately expanding and contracting gas bubble to create acoustic impulses for reflection from sub-bottom strata, the equipment including pressure-transducing means for detecting the acoustic impulses reflected from sub-bottom strata to provide a train of first signals representative of said reflected acoustic impulses, at least one additional pressure transducer for producing second signals representative of the unreflected wave train caused by the initial and the subsequent expansion, or expansions, of the gas bubble, and means for combining the first signals and the second signals into output signals, such that the wave train of output signals thus obtained corresponds to the wave train of first signals which would have been produced in the absence of subsequent expansions of the bubble.
11. An equipment according to claim 10, in combination with a charge launcher for producing said underwater explosions.
12. An equipment according to claim 11, wherein the additional pressure transducer is a hydrophone secured to the charge launcher to produce said second signals substantially exclusively.
13. An equipment according to claim 10, 11 or 12, wherein the means for combining the first signals and the second signals are operable in such a manner as substantially to prevent the subsequent expansion or expansions from providing any component of said output signals.
14. An equipment according to claim 10, 11 or 12, wherein the means for combining the first signals and the second signals are operable in such a manner that the resulting wave train of output signals will constitute a combination of wave train components obtained from the initial and the subsequent expansions with appropriate time shifts of said components to simulate the effect of a simultaneous occurrence of the first and subsequent expansions.
15. An equipment according to any one of claims 10 to 14, wherein the means for combining the first signals and the second signals include means for constructing an operator from the second signals, said operator representing a characteristic of the subsequent expansion, or expansions, and for operating on the first signals with the operator.
16. An equipment according to claim 15, and comprising means for determining the time interval or intervals between the initial expansion and a subsequent expansion or expansions, the characteristic from which the operator is constructed being a function of the time interval or intervals thus determined.
17. An equipment according to claim 16, and comprising means for determining the ratios of amplitudes of the pressure pulses produced by subsequent expansions relative to the amplitude of the pressure pulses produced by the initial expansion, the characteristic from which the operator is constructed being a function of the ratios thus determined, in addition to the time interval or intervals between the initial expansion and the subsequent expansion or expansions.
18. An equipment according to claim 16 or 17, and comprising a cross-correlator connected to receive the operator, as derived from the second signals, together with the first signals, the cross-correlator being operable to remove the effect of the reflected signals corresponding to the subsequent expansion, or expansions.
19. An equipment according to claim 15, and comprising a convolver connected to receive an inverse operator constructed by inverting the second signals into a pre-selected waveform, and the convolver being arranged to filter the first signals with the inverse operator thus constructed.
20. An equipment according to claim 14 and claim 16, and comprising means for constructing the operator so as to time-compress the wave train of said second signals into a single occurrence.
21. A method of, or an equipment for, marine seismic prospecting, substantially as hereinbefore described with reference to the accompanying drawings.

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