

PATENT SPECIFICATION

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COMPLETE SPECIFICATION

Control of Energy Spectrum in Marine Seismic Exploration

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:—

This invention relates to underwater seismic exploration, and more particularly, to a method and system for generating seismic waves with control of the power spectra by multiple acoustic energy sources.

In marine seismic exploration, it has been the practice to create a seismic event by detonating an explosive charge or by generating gaseous explosions. More recently, methods for concentrating energy in a particular frequency band to produce a more effective seismic event have been developed. Electrical discharge systems are employed for generating an underwater spark which results in an acoustic pulse with a power spectrum that to some extent can be varied by changing the electrical parameters of the energy-discharge system. Such sources are generally broad band and inefficient with reference to the narrow frequency band of interest in seismic exploration.

The present invention is directed to adjustment of the power spectra of underwater acoustic signals by controlling the volumes and/or relative locations of gas bubbles produced by multiple sources. The invention provides a method for generating a seismic pulse having a controlled power spectrum, which method comprises producing a plurality of bubbles below the water surface by the simultaneous, abrupt release of predetermined quantities of gas, which

bubbles are separated from each other by a distance sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, wherein the quantities of gas are selected to produce bubbles having at least two different energy-frequency oscillation characteristics such that a seismic pulse having a combined power spectrum broader than the power spectrum produced by a bubble of either energy-frequency oscillation characteristic will be produced.

A gas bubble generated by an underwater acoustic energy source oscillates with a fundamental frequency and amplitude determined by the characteristics of the source and the boundary conditions of the surrounding liquid. The size of the bubble and its fundamental frequency of oscillation can be determined for any source under its particular boundary and initial conditions. The power spectrum that the bubble generates is a function of its size. The term energy spectrum as used herein refers to the level in decibels of the acoustic energy at frequencies within a range of frequencies. By simultaneously creating bubbles of different known volumes, a wavelet having a particular energy spectrum of interest can be produced.

In a method in accordance with the invention, at least one of the plurality of bubbles may be produced by the simultaneous release of predetermined quantities of gas at points spaced in a pattern such that those quantities of gas produce a plurality of primary bubbles which coalesce to form a single bubble having the desired energy-frequency oscillation characteristic. Some of the predetermined quantities of gas may, for example, be released at points in a first pattern which points are spaced from each other sufficiently to prevent

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coalescence of the bubbles produced by those quantities of gas, other predetermined quantities of gas being released at points in a second pattern, which points are spaced sufficiently close to each other to assure coalescence of the bubbles produced by the said other quantities of gas, the quantities of gas of the second pattern being spaced sufficiently from the quantities of gas of the first pattern to prevent coalescence of any bubble produced by the quantities of gas of the second pattern with any bubble produced by the quantities of gas of the first pattern.

In one method in accordance with the invention, the plurality of bubbles are produced below the water surface by simultaneously releasing different quantities of compressed gas from chambers spaced horizontally by a distance sufficient to prevent coalescence of at least two of the bubbles. At least one of the plurality of bubbles may be formed by gas released from each of at least two chambers which are disposed sufficiently close that the gases from those two or more chambers produce primary bubbles which coalesce to produce a single bubble.

The bubbles in the said plurality of bubbles produced by a method in accordance with the invention, may be of different sizes with each size bubble having approximately half of the volume of the next larger sized bubble.

The invention also provides apparatus for generating, in water, a seismic pulse having a controlled power spectrum, which apparatus comprises: a plurality of bubble-producing devices, each adapted when activated to produce a bubble by the abrupt release of gas at a point below the water surface, at least two of said bubble-producing devices being disposed at points spaced horizontally by a distance sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, and means for simultaneously activating the plurality of bubble-producing devices, said horizontally spaced bubble-producing devices being respectively effective to produce bubbles having at least two different energy-frequency oscillation characteristics so as to provide a seismic pulse having a combined power spectrum broader than the power spectrum produced by a bubble of either energy-frequency oscillation characteristic.

By way of example, a method and apparatus in accordance with the invention will now be described with reference to the accompanying drawings in which:

FIGURE 1 is an isometric view of a mechanical source for producing a bubble;

FIGURE 2 illustrates bubble production by a source shown in FIGURE 1;

FIGURE 3 is the power spectrum generated by the source system of FIGURE 1 under boundary and initial conditions;

FIGURE 4 shows a grouping of bubble sources;

FIGURE 5 illustrates another grouping of bubble sources;

FIGURE 6 is the power spectrum produced by the grouping of bubble sources as shown in FIGURE 5;

FIGURE 7 illustrates a preferred embodiment of the invention; and

FIGURE 8 illustrates the power spectrum from the system of FIGURE 7.

Referring now to FIGURE 1, an underwater acoustic energy source 10 of an air gun type has been shown. It is comprised of a cylinder 11 interconnected by a cylinder 13 which has four exhaust ports, three of which, the ports 14, 15 and 16, are shown in FIGURE 1. The ports are located around the periphery of cylinder 13 near the lower end thereof and at right angles to each other. Atop the upper housing is an entrance conduit 18 for air and electrical connections. Such an air gun is designed to have a predetermined chamber volume, such as 3 and 10 cubic inches in one configuration, and 200 and 600 cubic inches in another configuration. Examples of such guns are those manufactured and sold by Bolt Associates Inc., East Norwalk, Connecticut.

Upon triggering such a gun to open ports therein, four bubbles A-D will be produced which coalesce to form a single approximately toroidal bubble E as shown by the dotted outlines in FIGURE 2. The maximum radius of bubbles A-D produced by such an underwater acoustic energy source

can be approximated by the equation $r_o = \frac{3}{4\pi}$

$$\left[\frac{P_o V_o}{P_o} \right]^{1/3}$$

where P_o = absolute hydrostatic pressure at depth of source

P_o = initial chamber pressure (absolute) of source

V_o = 1/4th of the total chamber volume of source

r_o = maximum bubble radius

$\pi = 3.14159$

The bubbles A-D produced by gun 10 coalesce to oscillate as a single bubble E having a certain fundamental frequency of oscillation. An example of a power spectrum produced by such a gun is shown in FIGURE 3. It will be noted that under boundary and initial conditions, peak power is developed primarily in a narrow band of from 30 to 40 cycles per second.

About one-third of the acoustic energy is concentrated in about 5 CPS centered about peak in the power spectrum, i.e., at the fundamental frequency of bubble oscillation.

5 FIGURE 4 shows a group of six sources 10a-10f spaced so that the bubble from each source oscillates independently. The resulting power spectrum of the six guns fired simultaneously is about the same as 10 for the firing of a single gun, except that the energy level is 6 times, or about 7.8 decibels, higher at each frequency.

A broader frequency band is highly desirable for seismic operations and may be achieved in accordance with the invention. In accordance with one embodiment of the invention, sources 21-26 are arranged as shown in FIGURE 5 to form three groups of sources. The bubble 21a formed from source 21 does not coalesce with any other source and thus oscillates independently of them and at a frequency determined by its size. The bubbles 22a-23a formed in one group 22-23 will coalesce and the common bubble oscillates in a mode peculiar to its size. The bubbles 24a-26a from sources 24-26 are so spaced that they will coalesce and the common bubble oscillates in a mode peculiar to its size. The fundamental frequency of the composite bubble produced by the coalesced bubbles from sources 24-26 is lower than the fundamental frequency of the composite bubble produced by the coalesced bubbles from sources 22-23 and the bubble 21a from source 21 has a frequency higher than either of the other bubble groups where coalescence occurs. The bubble produced by sources 24-26 is three times larger than the separate bubble produced by source 21 and the bubble produced by sources 22-23 is two times larger than the separate bubble produced by source 21. The power spectrum of the signal resulting from the grouping of 40 FIGURE 5 is illustrated in FIGURE 6. Note that the power spectrum has been considerably broadened.

Having described the invention in connection with FIGURES 1-6, reference should now be had to FIGURES 7 and 8 which illustrate the preferred embodiment. In FIGURE 7, a plurality of floats are towed behind a vessel 100. The line 101 leading from the vessel 100 will include 55 compressed air hose. In this embodiment, twenty-three floats are coupled in tandem. They are towed in tandem at spaced points along line 101. Float 102 provides support for a pair of air guns 103 and 104. Guns 60 103 and 104 preferably are spaced such that the bubbles produced upon actuation of the guns will coalesce. Three floats 105 support guns 106, 107, 108 spaced one from another such that the bubbles produced 65 thereby will not coalesce. Six floats similarly

support guns 109 at spaced locations so that the bubbles produced thereby will not coalesce. Finally, twelve floats support guns 110 spaced such that the bubbles produced thereby will not coalesce. In this embodiment, the two guns 103 and 104 are preferably of 40 cubic inch capacity. Similarly 106-108 are 40 cubic inch guns. The guns 109 preferably are 20 cubic inch guns. The guns 110 preferably are 10 cubic inch guns. 75 In this system, the total volume of 400 cubic inches is provided. The guns are located at a depth preferably 10' or more below the water surface.

FIGURE 8 illustrates the energy spectrum 80 resulting from simultaneous actuation of all of the guns of FIGURE 7. In this system, energy level has been plotted as a function of frequency. The dotted curve 120 represents the energy spectrum produced by 85 charging the guns of FIGURE 7 at a pressure of 1900 psig. and supporting the guns at a depth of 17 feet below the surface. The first peak 121 is the energy resulting from the single bubble produced by 90 coalescence of bubbles from guns 103 and 104. Peak 122 results from the bubbles from guns 106-108. Peak 123 results from energy produced by the six bubbles from guns 109. Finally, peak 124 results from bubbles 95 produced from guns 110.

This energy-frequency spectrum may be compared with the energy-frequency spectrum produced by the simultaneous detonation of eight guns at a 7 foot depth wherein the resultant energy spectrum is illustrated by the curve 125. It will be seen that by using a plurality of guns which produce bubbles of different sizes, a much broader energy frequency spectrum is produced. 105

In order to illustrate the effect of variation in depth, a second curve 126 has been produced in FIGURE 8 which illustrates the results of tests with the same system as used for curve 120 but with the guns located 110 at a depth of 22 feet. It will be apparent that the selection of the sizes of the units, the spacings therebetween and the depth at which they are supported may be varied to provide wide latitude in the control of the 115 energy frequency spectrum.

While the foregoing description has centered around the use of compressed air sources, it will be appreciated that the invention may be employed in connection 120 with the detonation of explosive sources, either by detonating quantities of combustible gas or the use of high explosives. In any such case, at least two sources will be employed to produce bubbles of different 125 sizes. Preferably, a minimum of three sources will be used with two of them spaced such that bubbles produced thereby will coalesce to form a single bubble the size and character of which may be different from 130

that produced by the third source. The third source may be spaced from the other two a sufficient distance as to make certain that the bubble produced by the third
5 source will not coalesce with the bubbles produced by the first two sources. The sources will be simultaneously actuated. The character of the energy-frequency content of the pressure waves produced by the
10 coalesced bubble may be different from that of the third bubble. Preferably patterns of sources will be employed where the bubbles ultimately produced differ in size in a manner designed to control the energy-
15 frequency spectrum. For this purpose, compressed air guns of sizes ranging from 10 cubic inches to 600 cubic inches and greater employed in combinations will provide sound waves having a power spectrum
20 tailored to a given need.

WHAT WE CLAIM IS:—

1. In marine seismic exploration, the method for generating a seismic pulse having a controlled power spectrum, said
25 method comprising: producing a plurality of bubbles below the water surface by the simultaneous, abrupt release of predetermined quantities of gas, which bubbles are separated from each other by a distance
30 sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, wherein the quantities of gas are selected to produce bubbles having at least
35 two different energy-frequency oscillation characteristics such that a seismic pulse having a combined power spectrum broader than the power spectrum produced by a bubble of either energy-frequency oscillation characteristic will be produced.

2. The method according to claim 1, wherein the abrupt release of predetermined quantities of gas is produced by simultaneous releases of predetermined
45 volumes of compressed gas or by simultaneous detonation of a plurality of explosive charges.

3. The method according to either of Claims 1 or 2, wherein at least one of the plurality of bubbles is produced by the
50 simultaneous release of predetermined quantities of gas at points spaced in a pattern such that those quantities of gas produce a plurality of primary bubbles which
55 coalesce to form a single bubble having the desired energy-frequency oscillation characteristic.

4. The method according to claim 1, wherein the plurality of bubbles are produced below the water surface by simultaneously releasing different quantities of compressed gas from chambers spaced horizontally by a distance sufficient to prevent
60 coalescence of at least two of the bubbles.

65 5. The method according to Claim 4,

wherein at least one of the plurality of bubbles is formed by gas released from each of at least two chambers which
disposed sufficiently close that the gases from those two or more chambers produce
70 primary bubbles which coalesce to produce a single bubble.

6. The method according to any preceding claim, wherein the bubbles in the said plurality of bubbles are of different sizes
75 with each size bubble having approximately half of the volume of the next larger sized bubble.

7. The method according to any preceding claim, wherein some of the predetermined quantities of gas are released at points in a first pattern, which points are spaced from each other sufficiently to prevent coalescence of the bubbles produced by those quantities of gas, other predetermined quantities of gas being released at points in a second pattern, which points are spaced sufficiently close to each other to assure coalescence of the bubbles produced by the said other quantities of gas, the quantities of gas of the second pattern being spaced sufficiently from the quantities of gas of the first pattern to prevent coalescence of any bubble produced by the quantities of gas of the second pattern with any bubble produced by the quantities of gas of the first pattern.

8. The method according to Claim 1, wherein at least three predetermined quantities of gas are released at respective points in producing the plurality of bubbles such that at least three bubbles are produced a first one of which is spaced from a second one of the three bubbles sufficiently to prevent coalescence with the second bubble and is spaced sufficiently close to a third one of the three bubbles to assure coalescence thereof with the third bubble, the first and third bubbles thereby forming a single bubble having an energy-frequency
100 oscillation characteristic different from that of the second bubble.

9. Apparatus for generating, in water, a seismic pulse having a controlled power spectrum, said apparatus comprising: a
115 plurality of bubble-producing devices, each adapted when activated to produce a bubble by the abrupt release of gas at a point below the water surface, at least two of said bubble-producing devices being disposed at points spaced horizontally by a distance
120 sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, and means for simultaneously activating the plurality of bubble-producing devices, said horizontally spaced bubble-producing devices being respectively effective to produce bubbles having at least two different energy-frequency oscillation characteristics so as to provide a seismic pulse
130



that produced by the third source. The third source may be spaced from the other two a sufficient distance as to make certain that the bubble produced by the third source will not coalesce with the bubbles produced by the first two sources. The sources will be simultaneously actuated. The character of the energy-frequency content of the pressure waves produced by the coalesced bubble may be different from that of the third bubble. Preferably patterns of sources will be employed where the bubbles ultimately produced differ in size in a manner designed to control the energy-frequency spectrum. For this purpose, compressed air guns of sizes ranging from 10 cubic inches to 600 cubic inches and greater employed in combinations will provide sound waves having a power spectrum tailored to a given need.

WHAT WE CLAIM IS:—

1. In marine seismic exploration, the method for generating a seismic pulse having a controlled power spectrum, said method comprising: producing a plurality of bubbles below the water surface by the simultaneous, abrupt release of predetermined quantities of gas, which bubbles are separated from each other by a distance sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, wherein the quantities of gas are selected to produce bubbles having at least two different energy-frequency oscillation characteristics such that a seismic pulse having a combined power spectrum broader than the power spectrum produced by a bubble of either energy-frequency oscillation characteristic will be produced.

2. The method according to claim 1, wherein the abrupt release of predetermined quantities of gas is produced by simultaneous releases of predetermined volumes of compressed gas or by simultaneous detonation of a plurality of explosive charges.

3. The method according to either of Claims 1 or 2, wherein at least one of the plurality of bubbles is produced by the simultaneous release of predetermined quantities of gas at points spaced in a pattern such that those quantities of gas produce a plurality of primary bubbles which coalesce to form a single bubble having the desired energy-frequency oscillation characteristic.

4. The method according to claim 1, wherein the plurality of bubbles are produced below the water surface by simultaneously releasing different quantities of compressed gas from chambers spaced horizontally by a distance sufficient to prevent coalescence of at least two of the bubbles.

5. The method according to Claim 4,

wherein at least one of the plurality of bubbles is formed by gas released from each of at least two chambers which are disposed sufficiently close that the gases from those two or more chambers produce primary bubbles which coalesce to produce a single bubble.

6. The method according to any preceding claim, wherein the bubbles in the said plurality of bubbles are of different sizes with each size bubble having approximately half of the volume of the next larger sized bubble.

7. The method according to any preceding claim, wherein some of the predetermined quantities of gas are released at points in a first pattern, which points are spaced from each other sufficiently to prevent coalescence of the bubbles produced by those quantities of gas, other predetermined quantities of gas being released at points in a second pattern, which points are spaced sufficiently close to each other to assure coalescence of the bubbles produced by the said other quantities of gas, the quantities of gas of the second pattern being spaced sufficiently from the quantities of gas of the first pattern to prevent coalescence of any bubble produced by the quantities of gas of the second pattern with any bubble produced by the quantities of gas of the first pattern.

8. The method according to Claim 1, wherein at least three predetermined quantities of gas are released at respective points in producing the plurality of bubbles such that at least three bubbles are produced a first one of which is spaced from a second one of the three bubbles sufficiently to prevent coalescence with the second bubble and is spaced sufficiently close to a third one of the three bubbles to assure coalescence thereof with the third bubble, the first and third bubbles thereby forming a single bubble having an energy-frequency oscillation characteristic different from that of the second bubble.

9. Apparatus for generating, in water, a seismic pulse having a controlled power spectrum, said apparatus comprising: a plurality of bubble-producing devices, each adapted when activated to produce a bubble by the abrupt release of gas at a point below the water surface, at least two of said bubble-producing devices being disposed at points spaced horizontally by a distance sufficient to prevent dissipation of the useful energy by migration of one bubble toward the other, and means for simultaneously activating the plurality of bubble-producing devices, said horizontally spaced bubble-producing devices being respectively effective to produce bubbles having at least two different energy-frequency oscillation characteristics so as to provide a seismic pulse



having a combined power spectrum broader than the power spectrum produced by a bubble of either energy-frequency oscillation characteristic.

- 5 10. Apparatus according to Claim 9, wherein said plurality of bubble-producing devices comprises compressed gas containers, said activating means being operably associated with said compressed gas
10 containers to release compressed gas from the containers simultaneously and abruptly.

11. Apparatus according to Claim 9, wherein said plurality of bubble-producing devices comprises explosive charges, and
15 said activating means comprises a detonating mechanism operably associated with said explosive charges for simultaneously detonating said explosive charges.

12. Apparatus according to any one of
20 Claims 9 to 11, further including a vessel adapted to move along a marine traverse, and a trailing float structure connected to said vessel for towing therebehind, said plurality of bubble-producing devices being
25 attached to said float structure so as to depend therefrom at a predetermined depth below the water surface.

13. Apparatus according to any one of
30 claims 9 to 12, wherein said plurality of bubble-producing devices are of different sizes with at least two of said bubble-producing devices being spaced to assure coalescence of the bubbles produced thereby, and at least one of said bubble-producing devices being spaced from the other
35 bubble-producing devices to prevent coalescence of the bubble produced thereby with any other bubble.

14. Apparatus according to Claim 13,
40 wherein said plurality of bubble-producing devices are constructed for producing

bubbles of decreasing size in accordance with the series 40-20-10, and wherein at least two of said devices constructed to produce bubbles of relative size 40 are
45 spaced to assure coalescence of the bubbles produced thereby, and the remainder of said bubble-producing devices are spaced to prevent coalescence of the bubbles produced thereby.

15. Apparatus according to any one of
claims 9 to 12, wherein at least some of the bubble-producing devices are disposed in a pattern such that the bubbles produced
50 thereby immediately coalesce to form a bubble having the desired energy-frequency oscillation characteristic.

16. Apparatus according to any one of
Claims 9 to 12, wherein said plurality of bubble-producing devices are so constructed
60 to abruptly release at least two different volumes of gas upon activation.

17. The method for generating a seismic pulse having a controlled power spectrum
65 for use in marine seismic exploration, substantially as described herein and as illustrated in Figs. 1, 2, 3 and 4, or Figs. 1, 2, 3, 5 and 6, or Figs. 1, 2, 3, 7 and 8 of the accompanying drawings.

18. Apparatus for generating a seismic
70 pulse having a controlled power spectrum for use in marine seismic exploration, substantially as described herein with reference to, and as illustrated by, Figure 7 of the accompanying drawings.

ABEL & IMRAY,
Chartered Patent Agents,
Quality House,
Quality Court,
Chancery Lane,
London, W.C.2.