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SYSTEM AND METHOD FOR ACQUISITION OF MARINE SEISMIC DATA

Field of the invention

The present invention relates to a system and method for acquisition of marine seismic data. Such system and method may employ a system for inducing seismic waves.

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Background of the invention

Marine seismic acquisition has been of vital importance for exploration of hydrocarbons, such as oil and/or natural gas, from subsurface earth formations in marine environment, and it is becoming increasingly used in the context of monitoring the subsurface earth formations during production of these hydrocarbons as well.

Marine seismic acquisition typically involves firing of an array of acoustic sources, usually air guns, suspended in the water, and recording reflections using seismic receivers in the far field. Ziolkowski et al, as described in "The signature of an air gun array: Computation from near-field measurements including interactions," Geophysics Vol. 47(10) pp. 1413-1421 (1982) designed a system to enable the signature of an air gun array to be calculated at any point in the water from a number of simultaneous independent measurements of the near-field pressure field. The Ziolkowski method employs N independent hydrophones to determine the near field signatures of N air guns as operated in the array. The array of interacting guns is equivalent to a notional array of non-interacting guns whose combined seismic radiation is identical. The seismic signatures of the equivalent independent elements of this notional array are determined from the near-field measurements. The far-field signature of the air gun array is constructed by

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superposition of the near-field signatures (notionals), and assuming a sea surface reflection coefficient of -1.0.

Summary of the invention

5 In a first aspect, the present invention provides a system for acquisition of marine seismic data, comprising:
- an array of N acoustic sources suspended in a body of water from a float;
- at least N near-field sensor assemblies configured between
10 the array of N acoustic sources and the float, which sensor assemblies are configured to concurrently measure both a pressure and a vertical pressure gradient at any selected time.

In another aspect, the invention provides a method for
15 acquisition of marine seismic data, comprising:
- firing an array of N acoustic sources suspended in a body of water from a float;
- concurrently measuring both a pressure and a vertical pressure gradient at any selected time after said firing with
20 at least N near-field sensor assemblies configured between the array of N acoustic sources and the float.

The invention will be further illustrated hereinafter by way of example only, and with reference to the non-limiting drawing.

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Brief description of the drawing

Fig. 1 schematically shows a flow diagram setting forth an approach proposed herein; and

Fig. 2 schematically shows an example of a source array
30 system;

Fig. 3 schematically shows another example of a source array system;

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Fig. 4 schematically shows an example of a full marine seismic surveying system;

Fig. 5 schematically shows an example of a source array system comprising sub-arrays;

5 Fig. 6 (panels a to d) shows comparisons of the recovered far field source signature of a source array like shown in Fig. 5 vertically below the array, compared to the true signature;

10 Fig. 7 (panels a to d) shows comparisons of the recovered far field source signature of the same the array used for Fig. 6 at 45° to in-line forward direction, compared to the true signature;

15 Fig. 8 (panels a to d) shows comparisons of the recovered far field source signature of the same the array used for Figs. 6 and 7 at 30° to vertical in cross-line direction, compared to the true signature; and

Fig. 9 (panels a and b) shows a comparison between the recovered sea-surface reflection coefficient and the true sea-surface reflection coefficient.

20 In each of Figs. 6, 7, and 8, panels (a) and (c) show amplitude against frequency f and panels (b) and (d) show phase against frequency f . Panels (a) and (b) show the true (t) amplitude, respectively phase, compared with the recovered (r) amplitude, respectively phase as recovered
25 using the method and system described herein. Panels (c) and (d) are comparative examples wherein the amplitude, respectively phase, have been recovered using the method of Ziolkowski as described in "The signature of an air gun array: Computation from near-field measurements including
30 interactions," Geophysics Vol. 47(10) pp. 1413-1421 (1982), under the assumption that the sea-surface reflection coefficient is equal to -1 for all angles and frequencies.

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In Fig. 9, panel (a) represents the true reflection coefficient as a function of angle θ and frequency f as comparison for panel (b) which represents the reflection coefficient as recovered using the method and system described herein.

Figures 2-5 are not to scale. Identical reference numbers used in different figures refer to similar components. The person skilled in the art will readily understand that, while the invention is illustrated making reference to one or more specific combinations of features and measures, many of those features and measures are functionally independent from other features and measures such that they can be equally or similarly applied independently in other embodiments or combinations.

Detailed description of the invention

The present disclosure involves a system for inducing a seismic wave field (consisting of seismic waves) that can be employed in acquisition of marine seismic data. The system for inducing seismic waves includes an array of N acoustic sources suspended in a body of water from a float, and at least N near-field sensor assemblies configured between the array of N acoustic sources and the float. These N sensor assemblies are each configured to concurrently measure both a pressure and a vertical pressure gradient of the acoustic wave in the water at any selected time.

It has been found that by combining pressure data with vertical pressure gradient data that has been acquired concurrently, it is possible to remove the (down-going) component of the wave field that is due to reflections from the sea surface. It has been found that the magnitude of the sea surface reflection coefficient is uncertain in the vicinity of the acoustic source array. This may be due to various, not well understood, physical effects, including

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roughness of the sea surface, presence of residual bubbles in the water, possible cavitation effects, and more.

By combining pressure data with vertical pressure gradient data that has been acquired concurrently, it is possible to extract more accurately the notional acoustic source wavelets associated with the N acoustic sources in the array. As the down-going components of the wave field can be removed from the measured near-field wave field, far-field signatures of the array of acoustic sources can be constructed from the near-field data that is not corrupted by reflections from the sea surface.

Interestingly, as the proposed method and system now allow to separate the up-going wave field produced by the array of N acoustic sources and the down-going wave field reflected from the sea surface above the array of acoustic sources, the proposed method and system can also be used to measure and monitor the sea surface reflection coefficient at every shot during a seismic acquisition survey.

In an embodiment illustrated in Figure 1, the approach proposed herein may comprise the following parts:

- (i) deploying (110) a float having an array of N acoustic sources suspended therefrom and being equipped with N near-field sensor assemblies configured between the array of N acoustic sources and the float;
- (ii) inducing (120) shots of the array of N acoustic sources;
- (iii) collecting (130) near-field data for shots, wherein concurrently measuring both a pressure and a vertical pressure gradient at any selected time after each shot;
- (iv) processing (140) the near-field data as collected under (iii) by combining the pressure and the vertical pressure gradient data to cancel the contribution of sea-surface reflections; and

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(v) extracting (150) of notional wavelets from individual acoustic sources in the array from the sea-surface reflection free data obtained from the processing under (iv).

This approach may be used for subsequently performing one
5 or both of:

(vi) constructing (160) of a sea-surface reflection free far-field source-array signature of the full array of N acoustic sources by superimposing the reflection-free notional wavelets obtained by the extracting under (v); and

10 optionally:

(vii) calculating (170) the sea-surface reflection coefficient, for instance by subtracting of the sea-surface reflection free source signature from the measured near-field data.

15 In this description, pressure may be abbreviated by P and the expression "vertical pressure gradient" may be interchangeably expressed as $\Delta p / \Delta z$ or $\delta p / \delta z$. Mathematically, the symbol Δ is used to express a finite differential while the symbol δ is used to express an infinitesimal
20 differential. However, in the context of the disclosure both types of differentials can be used to characterize the vertical pressure gradient.

Figures 2 and 3 both schematically show an example of a source array system 20 for inducing seismic waves in a body
25 of water 24, which may be part of a surveying system for acquisition of marine seismic data. The source array system 20 comprises a float 22 designed to float along a surface 36 of the body of water. Typically, maritime seismic surveys are carried out on sea, whereby the surface 36 is a sea-surface.
30 An array 18 of N acoustic sources 28 is suspended in the body of water 34 from the float 22. Suitably, a string 38 supports the array 18 of N acoustic sources 28, which may be hanging from the string 38 via appropriate fasteners 35. The string

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38 may be hanging from the float 22 via appropriate suspension lines 34. The suspension lines 35 and/or the fasteners 35 may be embodied in any suitable manner, such as rods, cables, or chains, or combinations thereof.

5 N near-field sensor assemblies 30 are configured between the array 18 of N acoustic sources 28 and the float 22. These sensor assemblies 30 are configured to concurrently measure both a pressure and a vertical pressure gradient at any selected time. Suitably, the N near-field sensor
10 assemblies are mounted onto the string 38. Suitably, the N near-field sensor assemblies form pairs with the N acoustic sources 28 in the array 18.

 In the example as illustrated in Figure 2, the N near-field sensor assemblies 30 each suitably comprise a primary
15 near-field hydrophone 31 and a secondary near-field hydrophone 32. The secondary near-field hydrophone 32 is configured vertically above the primary hydrophone 31 within each near-field sensor assembly. The secondary hydrophone 32 is displaced by a pre-determined finite vertical distance Δz
20 above the primary hydrophone 31.

 With primary and secondary hydrophones, the vertical pressure gradient can be determined by simply dividing a difference between a second pressure p_2 measured with the secondary hydrophone 32 at a time t and a first pressure p_1
25 measured with the first hydrophone 31 at the same time t , by the finite vertical distance Δz . The vertical distance Δz is advantageously selected such that it is large enough to measure a significant pressure differential with the primary and secondary hydrophones, and small enough to approximate a
30 linear pressure behavior over vertical distance. The pre-determined finite vertical distance may for example be selected within a range of from 5 cm to 50 cm, preferably within a range of from 15 cm to 50 cm. Suitably, the primary

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near-field hydrophone 31 is attached to a lower side of the string 38, while the secondary near-field hydrophone 32 is attached to an upper side of the string 38.

When using vertically displaced primary and secondary hydrophones, it is recommended to interpolate between the primary and secondary hydrophones by averaging of the concurrently measured first and second pressures p_1 and p_2 , as the vertical pressure gradient derived as explained above matches best with the location half-way between the primary and secondary near-field hydrophones. Thus, in this description it is assumed that the location half-way between the primary and secondary near-field hydrophones of each selected near-field sensor assembly is the effective location of that selected near-field sensor assembly.

In the example as illustrated in Figure 3, the N near-field sensor assemblies 30 each suitably comprise a primary near-field hydrophone 31 and a near-field accelerometer 33. The accelerometer is preferably sensitive at least to sense vertically directed accelerations. A suitable embodiment of an accelerometer is a (near-field) geophone. In this type of near-field sensor assembly, the primary hydrophone 31 and the accelerometer 33 are preferably configured at a coincident vertical distance Δh above the array 18 of N acoustic sources 28, in order to be able to derive the vertical pressure gradient as close as possible to the vertical distance above the array 18 where the pressure is measured. Suitably, the near-field hydrophone 31 and the near-field accelerometer 33 form part of one and the same multicomponent sensor device.

Near-field wavelets are best measured at a distance from the notional sources of much less than the dominant wavelength of the wavelet that is generated by the acoustic sources. For practical purposes, it is understood that the effective location of the near-field sensor assemblies is

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within 20 % of the dominant wavelength, preferably within 10 % of the dominant wavelength produced by each of the notional acoustic sources. Preferably, each of the N near-field sensor assemblies 30 is configured such that their effective location is within a distance of 2 m, preferably within a distance of 1.5 m, above the array 18 of N acoustic sources 28.

Referring again to both Figures 2 and 3, the source array system 20 further comprises a data acquisition system 40. The data acquisition system 40 may be operably connected to each of the at least N near-field sensor assemblies 30, for instance via suitable signal communication line 42, to receive signals from the at least N near-field sensor assemblies 30 that represent pressure $p(t)$ and vertical pressure gradient $\delta p(t)/\delta z$, at a plurality of selected times t . Suitably, the data acquisition system 40 is operably connected to a computing unit 50 to process data. The computing unit 50 is suitably configured with computer readable instructions to process data. The data may include the pressure $p(t)$ and vertical pressure gradient $\delta p(t)/\delta z$ for each the N near-field sensor assemblies 30 at various times. The data acquisition system 40 has been illustrated by a separate symbol in Figures 2 and 3, but it may, optionally, be integrated into the computing unit 50.

Furthermore, the source array system 20 may comprise a control unit 60 that is operably connected to at least the N acoustic sources 28, for instance via one or more suitable control lines 62. Many configurations are possible, but the control unit 60 may suitably be functionally in communication with the computing unit 50. The control unit 60 may issue control signals to the N acoustic sources 28 in the array 18. These control signal may be used to trigger the array 18 of N acoustic sources 28 to perform shots.

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Any of, each of, and/or parts of the data acquisition system 40, the computing unit 50, and the control unit 60 may suitably be positioned on a suitable towing vessel, or at other locations such as directly on the string 38.

5 The computing unit 50 may for example be configured with computer readable instructions, to determine from the signals an up-going and down-going acoustic wave field for each of the notional N acoustic sources. The up-going acoustic wave field is a representation of near-field acoustic wave fields
10 of each of the N acoustic sources free from any sea-surface reflection. The computer readable instructions configured in the computing unit may also include instructions to construct a far-field signature of the array 18 of N acoustic sources 28, from the surface-reflection free near-field acoustic wave
15 fields of each of the N acoustic sources. Advantageously, the computer readable instructions further comprise instructions to determine a surface-reflection coefficient at every shot of the array.

The system described herein is intended to be deployed in
20 a marine environment, off-shore. Air guns are, at present, the most commonly used acoustic sources for marine seismic surveying. However, the teachings herein can also be applied to marine vibrators. These are also available, as evidenced by for instance an article from WesternGeco: "Marine
25 Vibrators and the Doppler Effect", by Dragoset, which appeared in Geophysics, Nov. 1988, pp. 1388-1398, vol. 53, No. 11. More recently, Geokinetics has introduced its AquaVib(TM) marine vibrator. Other examples exist. The teachings herein can also be applied to water guns.

30 Generally, the system and method disclosed herein perform best if each acoustic source itself is much smaller than the dominant wavelength of the wave field that it produces. Acoustic sources that are smaller than 20 % of the dominant

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wavelength, preferably smaller than 10 % of the dominant wavelength, are considered to be much smaller than the dominant wavelength of the wave field that it produces.

The array is built up from distinct acoustic sources,
5 each of which can be one single impulsive energy device or a cluster of multiple impulsive energy devices suspended at a single specific source location. To function as one distinct acoustic source in the array, such multiple impulsive energy devices within one cluster are so close together that they
10 behave as a larger single impulsive energy device. For instance, multiple impulsive energy devices are within one cluster if they produce one common air bubble and thus effectively work together as a larger single impulsive energy device. Typically, the multiple impulsive energy devices
15 within one cluster are in each other's proximity within one meter, i.e. not farther removed from one another by more than one meter. Impulsive energy devices in a cluster are operated as one single acoustic source. A source array comprises (clusters of) impulsive energy devices at multiple source
20 locations.

The source array system 20 described above may be part of a surveying system for acquisition of marine seismic data. An example is schematically shown in Figure 4. Such surveying system is suitably provided with one or more streamers 12,
25 each comprising a line of seismic sensors 14. In the example four streamers 12A to 12D are shown, but any number of streamers may be employed. Ten to fifteen streamers would not be uncommon. The streamers 12 may have a length of several hundreds of meters, or much longer with lengths of up to
30 about 10 km or more. The seismic sensors 14 in these lines are generally positioned in the far-field, for instance the nearest of the seismic sensors 14 being at a distance of at least 10 m, preferably at least 50 m, removed from the array

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18 of N acoustic sources 28. The one or more streamers 12 and the source array system 20 are suitably towed by a surveying vessel 10. Paravanes 16 or the like may be deployed to create a lateral spread between the streamers.

5 The acoustic sources 28 and sensor assemblies 30 may be arranged in a variety of configurations. As illustrated in Figure 5, an example is given wherein the array 18 of N acoustic sources 28 is configured in a plurality of subarrays (three subarrays, 18a to 18c, are shown as example) thereby
10 effectively forming a two-dimensional array of N acoustic sources 28. For reasons of clarity, only the data acquisition system 40 is depicted in Figure 5.

 In the following paragraphs, more detailed information will be provided concerning the computer readable
15 instructions for processing processing the near-field data. Each acoustic source within the array 19 of N acoustic sources 28 will be numbered by index k , which represents the source number. Thus k is a natural number in the range of 1 to N ($k = 1, 2, \dots, N$). Each of the acoustic sources is paired
20 up by with a sensor assembly, which will be counted by index j ($j = 1, 2, \dots, N$). Table 1 contains a legend of mathematical symbols used herein.

Table 1

k	Index for counting (notional) acoustic sources in the array ($k = 1, 2, \dots, N$)
j	Index for counting sensor assemblies ($j = 1, 2, \dots, N$)
N	Total number of acoustic sources in the array
$\tilde{s}_k(\omega)$	The notional wavelet of acoustic source number k
r_{jk}	The distance from j -th sensor assembly to k -th acoustic source
r_{jk}^g	The distance from j -th sensor assembly to the reflected image of k -th acoustic source
$\tilde{R}(\omega, \varphi_{jk})$	The sea-surface reflection coefficient
θ_{jk}	Incidence angle between propagation direction of the wavelet and normal (vertical) at the sea surface
ω	Frequency in Fourier frequency domain
$\tilde{p}_j(\omega)$	Near-field pressure measured by the j -th sensor assembly in frequency domain
$\tilde{a}_{z,j}(\omega)$	z-component of the near-field acceleration measured by j -th sensor assembly in frequency domain
ρ	Density of the water in the body of water
c	Velocity of sound in the water
z_j	Vertical position of the effective location of the j -th sensor assembly
z_k	Vertical position of the effective location of the k -th acoustic source
A and B	Shallowness correction factors
σ	Root-mean square of the sea waves
h	Depth of the acoustic source array
L_{max}	Maximum linear size of the array

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For this example, the acoustic sources will be assumed to be air guns. In the interest of simplicity of the expressions, relative motion of air bubbles released by air guns relative to the sensor assemblies has been neglected.

5 Such relative motion exists in horizontal direction as a result of towing of the source array system 20 through the body of water, and in vertical direction due to buoyancy. However, the skilled person can readily work out the effects of relative motion.

10 In frequency domain, the near-field pressure measured by the j -th sensor assembly reads:

$$\tilde{p}_j(\omega) = \sum_{k=1}^N \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}/c}}{r_{jk}} + \sum_{k=1}^N \tilde{R}(\omega, \theta_{jk}) \frac{\tilde{s}_k(\omega) e^{-\frac{i\omega r_{jk}^g}{c}}}{r_{jk}^g}, \quad (1)$$

wherein $\tilde{s}_k(\omega)$ is the notional wavelet of acoustic source number k ; r_{jk} is the distance from j -th sensor assembly to k -th acoustic source, and r_{jk}^g is the distance from j -th sensor to the reflected image of k -th acoustic source, and $\tilde{R}(\omega, \theta_{jk})$ is the sea-surface reflection coefficient. It is noted that the sea-surface reflection coefficient can be a function of incidence angle θ_{jk} at the sea surface, and frequency ω . The (vertical) z -component of the near-field acceleration

20 measured by j -th sensor assembly in frequency domain reads:

$$\begin{aligned} \tilde{a}_{z,j}(\omega) = & \frac{1}{\rho} \sum_{k=1}^N \frac{(z_j - z_k)}{r_{jk}} \left(\frac{1}{r_{jk}} + \frac{i\omega}{c} \right) \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}/c}}{r_{jk}} \\ & + \frac{1}{\rho} \sum_{k=1}^N \frac{(z_j + z_k)}{r_{jk}^g} \left(\frac{1}{r_{jk}^g} + \frac{i\omega}{c} \right) \tilde{R}(\omega, \theta_{jk}) \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}^g/c}}{r_{jk}^g}. \end{aligned} \quad (2)$$

The task is now to combine Eq. (1) and Eq. (2) in such a way that the last terms of these expressions containing $\tilde{R}(\omega, \theta_{jk})$ will cancel out. Such cancelation is advantageous,

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because the values of $\tilde{R}(\omega, \theta_{jk})$ are unknown. Cancellation of terms containing $\tilde{R}(\omega, \theta_{jk})$ effectively means removal of contribution of sea-surface reflections, or, in other words, separation of the up-going field from the reflected down-
 5 going field. By careful statistical analyses, it can be shown that the second term in Eq. (2) can be well approximated by the following expression:

$$\begin{aligned} \sum_{k=1}^N \frac{(z_j + z_k)}{r_{jk}^g} \left(\frac{1}{r_{jk}^g} + \frac{i\omega}{c} \right) \tilde{R}(\omega, \theta_{jk}) \frac{\tilde{s}_k(\omega) e^{-\frac{i\omega r_{jk}^g}{c}}}{r_{jk}^g} \\ = \left(A \left\langle \frac{(z_j + z_k)}{(r_{jk}^g)^2} \right\rangle + B \frac{i\omega}{c} \left\langle \frac{(z_j + z_k)}{r_{jk}^g} \right\rangle \right) \sum_{k=1}^N \tilde{R}(\omega, \theta_{jk}) \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}^g/c}}{r_{jk}^g}, \end{aligned} \quad (3)$$

in which r_{jk}^g represents the distance from the reflected image of the k -th acoustic source (k -th “ghost”) to the j -th sensor
 10 assembly, and wherein factors A and B are shallowness correction factors that behave as:

$$A = \left\langle \frac{e^{-\frac{i\omega r_k^g}{c}}}{(r_k^g)^3} \right\rangle / \left(\left\langle \frac{1}{(r_k^g)^2} \right\rangle \left\langle \frac{e^{-\frac{i\omega r_k^g}{c}}}{r_k^g} \right\rangle \right) \quad (3.1)$$

$$B = \left\langle \frac{e^{-\frac{i\omega r_k^g}{c}}}{(r_k^g)^2} \right\rangle / \left(\left\langle \frac{1}{r_k^g} \right\rangle \left\langle \frac{e^{-\frac{i\omega r_k^g}{c}}}{r_k^g} \right\rangle \right) \quad (3.2)$$

These factors approach values of 1 for deep acoustic sources and are slightly greater than 1 for shallower acoustic sources. Deep, in this context, may typically be any depth
 15 larger than 6m. For shallower acoustic source arrays, they can be approximated with the following expressions:

$$A = 1 + (0.006 + 0.00004|f|)(L_{max}/h)^2 \quad (3.1a)$$

$$B = 1 + (0.003 + 0.00004|f|)(L_{max}/h)^2 \quad (3.2a)$$

wherein L_{max}/h represents the ratio of a maximum linear size of the array L_{max} (maximum distance between two air guns in

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the array) to the depth h of the array. In a range of seismic frequencies of interest, factors A and B deviate from 1 only for very shallow arrays for which $\frac{L_{max}}{h} \gg 1$. For instance, $A = 1.09$ and $B = 1.07$ at $f = 100$ Hz and $L_{max}/h = 3$. The latter, for instance, corresponds to the depth of 6 meters for an array of linear size of 18 meters. The expressions in $\langle \rangle$ brackets indicate averages of the $1/r$ drop-off relationships over all of the N acoustic sources in the array.

Using the definition

$$\gamma_j(\omega) = A \left\langle \frac{(z_j + z_k)}{(r_{jk}^g)^2} \right\rangle + B \frac{i\omega}{c} \left\langle \frac{(z_j + z_k)}{r_{jk}^g} \right\rangle \quad (4)$$

Eqs. (1), (2) and (3) can now be combined in such a way that the terms containing $\tilde{R}(\omega, \theta_{jk})$ are cancelled out:

$$\begin{aligned} \tilde{p}_j(\omega) - \frac{\rho}{\gamma_j(\omega)} \tilde{a}_{z,j}(\omega) &= \sum_{k=1}^N \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}/c}}{r_{jk}} \\ &- \frac{1}{\gamma_j(\omega)} \sum_{k=1}^N \frac{(z_j - z_k)}{r_{jk}} \left(\frac{1}{r_{jk}} + \frac{i\omega}{c} \right) \frac{\tilde{s}_k(\omega) e^{-\frac{i\omega r_{jk}}{c}}}{r_{jk}}. \end{aligned} \quad (5)$$

For a known geometry of air gun array, Eq. (5) is equivalent to the system of linear equations for $\tilde{s}_k(\omega)$ of the form

$$\tilde{p}_j(\omega) - \frac{\rho}{\gamma_j(\omega)} \tilde{a}_{z,j}(\omega) = L_{jk}(\omega) \tilde{s}_k(\omega), \quad (6)$$

in which both the left hand side $\tilde{p}_j(\omega) - \frac{\rho}{\gamma_j(\omega)} \tilde{a}_{z,j}(\omega)$ and the matrix $L_{jk}(\omega)$ on the right-hand side, defined by Eq. (5), are known.

Solving Eq. (6) for $\tilde{s}_k(\omega)$ provides wavelets of individual airguns in the array which are not corrupted by reflections from the sea surface, since Eq. (6) does not contain reflection terms $\tilde{R}(\omega, \theta_{jk})$. These notionals are used to

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construct the total signature $P(t)$ of the full array by superposition:

$$P(t) = \sum_{k=1}^N \frac{s_k \left(t - \frac{r_k}{c} \right)}{r_k}.$$

By substituting solution $\tilde{s}_k(\omega)$ of Eq. (6) back to Eq. (1), another system of linear equations is arrived at, but now for the unknown reflection coefficient $\tilde{R}(\omega, \theta_{jk})$:

$$\tilde{p}_j(\omega) - \sum_{k=1}^N \frac{\tilde{s}_k(\omega) e^{-i\omega r_{jk}/c}}{r_{jk}} = \sum_{k=1}^N \frac{\tilde{s}_k(\omega) e^{-\frac{i\omega r_{jk}^g}{c}}}{r_{jk}^g} \tilde{R}(\omega, \theta_{jk}). \quad (7)$$

The system given by Eq. (7) allows one to find ω -dependence of $\tilde{R}(\omega, \theta_{jk})$, but contains insufficient number of equations to find $\tilde{R}(\omega, \theta_{jk})$ for every value of θ_{jk} . The latter is because the number of different angles θ_{jk} in Eq. (7) is $N(N-1)/2$, while the number of equations is N . Yet, the problem simplifies by noticing that values of angles θ_{jk} lie on the bounded interval from 0 to θ_{max} . Thus, $\tilde{R}(\omega, \theta_{jk})$ can be represented with an interpolating function on the interval $[0, \theta_{max}]$:

$$\tilde{R}(\omega, \theta_{jk}) = \sum_{i=1}^n \tilde{R}_i(\omega) \prod_{\substack{k=1 \\ k \neq i}}^n \frac{\theta_{jk} - \theta_k}{\theta_i - \theta_k}. \quad (8)$$

wherein $n \leq N$. This can be solved for unknown coefficients $\tilde{R}_i(\omega)$. In this way, angle- and frequency-dependent sea-surface reflection coefficients can be determined at every shot.

Some examples will now be presented to demonstrate the accurateness of the proposed approach. A typical air gun array may be configured along the lines of Figure 5: 18 air guns towed, in three subarrays each counting six air guns, at a pre-determined depth below the sea surface.

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The total spread of the array used in the examples below is 15m long by 16 m wide, whereby the air guns in each subarray are positioned with a regular 3-m periodicity in the length direction at a depth of 6 m below the average sea surface. In each subarray, the two air guns being the closest to the towing vessel are assumed to be cluster guns, clustered close enough together to produce one common air bubble per cluster and thus effectively work as a single large air gun. The sensor assemblies 30 in the examples are formed of vertical pairs of primary and secondary near-field hydrophones, the vertical distance Δz between these primary and secondary hydrophones is between 20 and 40 cm. In the specific examples, $\Delta z = 30$ cm whereby one primary near-field hydrophone is installed 0.85m vertically above each air gun and one secondary near-field hydrophone is installed 1.15 m vertically above each air gun. Pressure and its vertical gradient are both interpolated at the middle point between the two hydrophones, to obtain one reading for each sensor assembly as follows:

$$p(t) = \frac{p_2(t) + p_1(t)}{2},$$

$$\frac{dp(t)}{dz} = \frac{p_2(t) - p_1(t)}{\Delta h}.$$
(9)

The results below have been obtained using a synthetic model, which uses parameters of a real air gun array, as well as real wavelets of air guns. Rayleigh-type frequency-dependent reflection coefficient has been used to simulate the wave field reflected from the sea surface:

$$R(f, \theta) = -e^{-2\left(\frac{2\pi\sigma f}{c}\cos\theta\right)^2},$$
(10)

wherein RMS (root-mean square) of sea waves is assumed to be $\sigma = 1$ m and velocity of sound in water $c = 1500$ m/s. θ is the angle of incidence between the propagation direction of the

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wave field and the normal (vertical) direction at the sea surface, and f is the frequency in Hz.

Using real wavelets of each individual airgun (notionals) and reflection coefficient given by Eq. (10), synthetic data
5 has been generated for each near-field hydrophone, and used to see how well notionals and reflection coefficients can be recovered from the synthetic data. The results are presented in Figs. 6-9, wherein Fig. 6 represents the far-field
signature of the array vertically below the array, Fig. 7 at
10 an angle of 45° to in-line, and Fig. 8 at an angle of 30° to cross-line. The far-field signatures in panels (a) and (b) are recovered with invariance to the sea-surface reflection coefficient, and the far-field signatures in panels (c) and (d) are recovered using Ziolkowsky's method assuming $R = -1$.
15 Fig. 9 represents the reflection coefficients which can be derived from these far-field signatures.

The lines r in panels (a) and (b) of Fig. 6 show the amplitude and phase, respectively, as a function of frequency as recovered using the method and system described above.
20 This is a representation of the far-field signature of the array. For comparison, lines t show the true amplitude and phase when were used as input to generate the synthetic data. Panels (c) and (d) provide another comparison. The lines r in panels (c) and (d) represent the far-field array signature as
25 recovered using the method of Ziolkowsky, co-plotted with the same lines t from panels (a) and (b) for reference. The benefits of the presently disclosed system and method can become particularly apparent at frequencies exceeding 80 Hz, and even more at frequencies exceeding 100 Hz. Thus, while
30 the frequency spectrum of the acoustic sources may include low frequencies, for example 1 or 2 Hz, it preferably extends to higher frequencies that exceeds 80 Hz or 100 Hz. For instance, the frequency spectrum may include at least

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frequencies up to 200 Hz, so that frequencies between 80 Hz and 200 Hz, more preferably between 100 Hz and 200 Hz are represented in the frequency spectrum as well. The system and method disclosed herein are shown to be particularly

5 beneficial in these ranges.

Fig. 9 shows another benefit, which is that the true sea-surface frequency- and angle dependent reflection coefficient $R(\theta, f)$ can be recovered thanks to the presently disclosed system and method, with fairly good accuracy for all

10 frequencies.

Results of similar quality and accuracy have been demonstrated for source array depths of 4 m and 9 m.

The person skilled in the art will understand that the present invention can be carried out in many various ways

15 without departing from the scope of the appended claims.

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C L A I M S

1. A system for acquisition of marine seismic data,
comprising:
 - 5 - an array of N acoustic sources suspended in a body of water
from a float;
 - at least N near-field sensor assemblies configured between
the array of N acoustic sources and the float, which near-
field sensor assemblies are configured to concurrently
 - 10 measure both a pressure and a vertical pressure gradient at
any selected time.
2. The system of claim 1, wherein each of the N near-field
sensor assemblies comprise a primary hydrophone and a
secondary hydrophone configured vertically above the primary
- 15 hydrophone displaced by a pre-determined finite vertical
distance above the primary hydrophone.
3. The system of claim 2, wherein the pre-determined finite
vertical distance is within a range of from 5 cm to 50 cm.
4. The system of claim 1, wherein each of the N near-field
- 20 sensor assemblies comprise a primary hydrophone and an
accelerometer both configured at a coincident vertical
distance above the array of N acoustic sources.
5. The system of any one of the preceding claims, wherein
each of the N near-field sensor assemblies is configured at
- 25 an effective location that is within a distance of 2 m,
preferably within a distance of 1.5 m, above the array of N
acoustic sources.
6. The system of any one of the preceding claims, further
comprising a data acquisition system operably connected to
- 30 each of the at least N near-field sensor assemblies to
receive signals from the at least N near-field sensor
assemblies representing pressure and vertical pressure
gradient at a plurality of selected times, and operably

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connected to a computing unit configured with computer readable instructions to determine an up-going and down-going acoustic wave field for each of the N acoustic sources from the signals.

5 7. The system of claim 6, wherein the computer readable instructions further comprise instructions to construct a far-field signature of the array of N acoustic sources from surface-reflection free near-field acoustic wave fields of each of the N acoustic sources.

10 8. The system of claim 6 or claim 7, the computer readable instructions further comprise instructions to determine a surface-reflection coefficient at every shot of the array.

9. The system of any one of the preceding claim, further comprising one or more streamers comprising seismic sensors
15 at a distance of at least 10 m removed from the array of N acoustic sources.

10. Method for acquisition of marine seismic data, comprising:

- firing an array of N acoustic sources suspended in a body
20 of water from a float;
- concurrently measuring both a pressure and a vertical pressure gradient at any selected time after said firing with at least N near-field sensor assemblies configured between the array of N acoustic sources and the float.

25 11. The method of claim 10, further comprising:

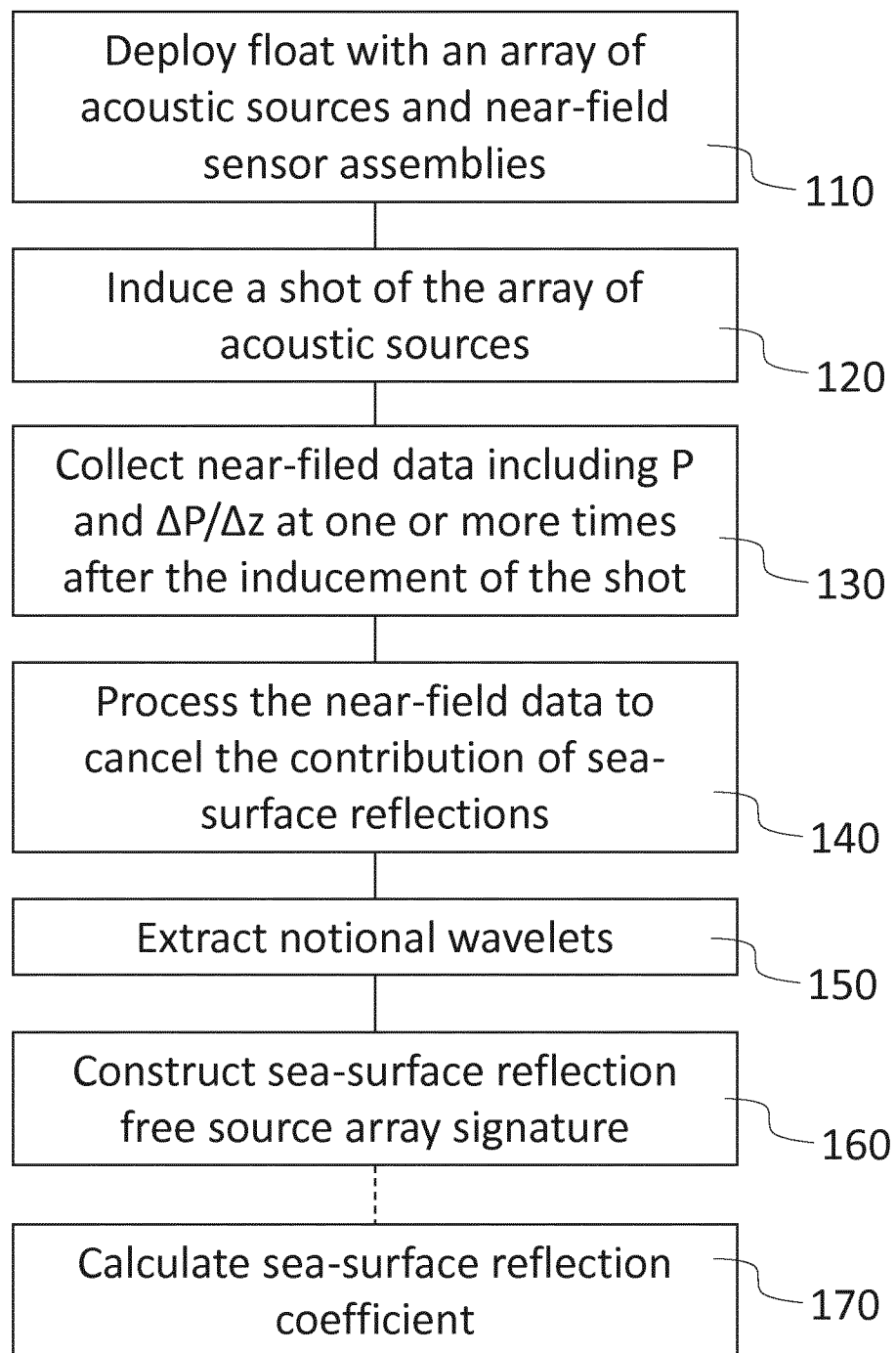
- receiving signals from the at least N near-field sensor assemblies representing pressure and vertical pressure gradient at a plurality of selected times, and
- determining, with a computer unit, an up-going and down-
30 going acoustic wave field for each of the N acoustic sources from the signals.

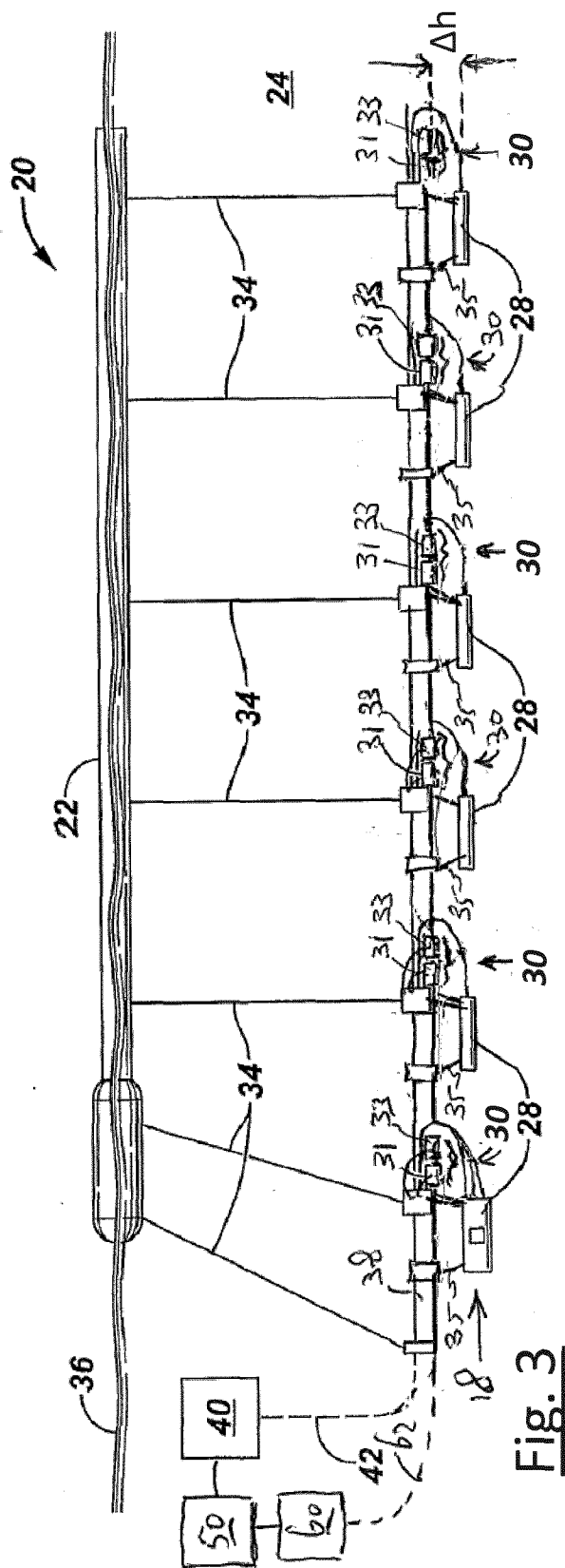
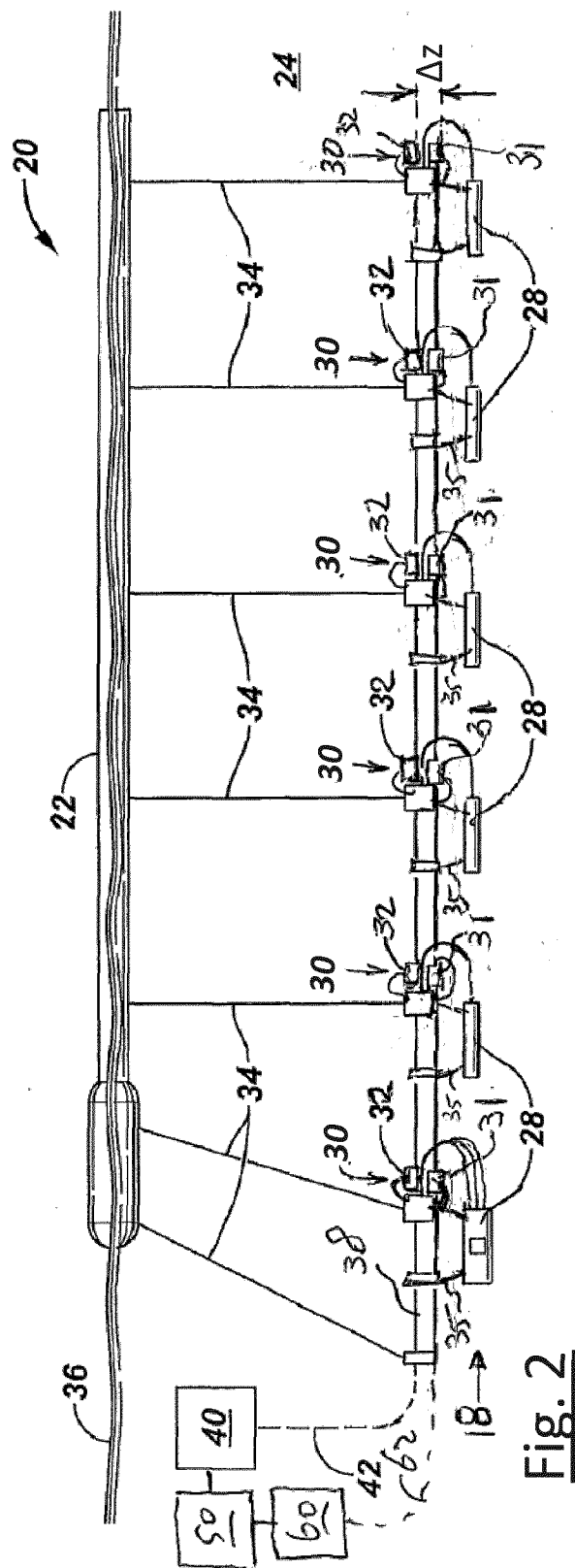
12. The method of claim 11, further comprising:

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- constructing, with the computer unit, a far-field signature of the array of N acoustic sources from surface-reflection free near-field acoustic wave fields of each of the N acoustic sources.
- 5 13. The method of claim 11 or claim 12, further comprising:
- determining, with the computer unit, a surface-reflection coefficient at every shot of the array.
14. The method of any one of claims 10 to 13, further comprising:
- 10 - recording far field seismic signals with one or more streamers comprising seismic sensors at a distance of at least 10 m removed from the array of N acoustic sources.

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Fig. 1



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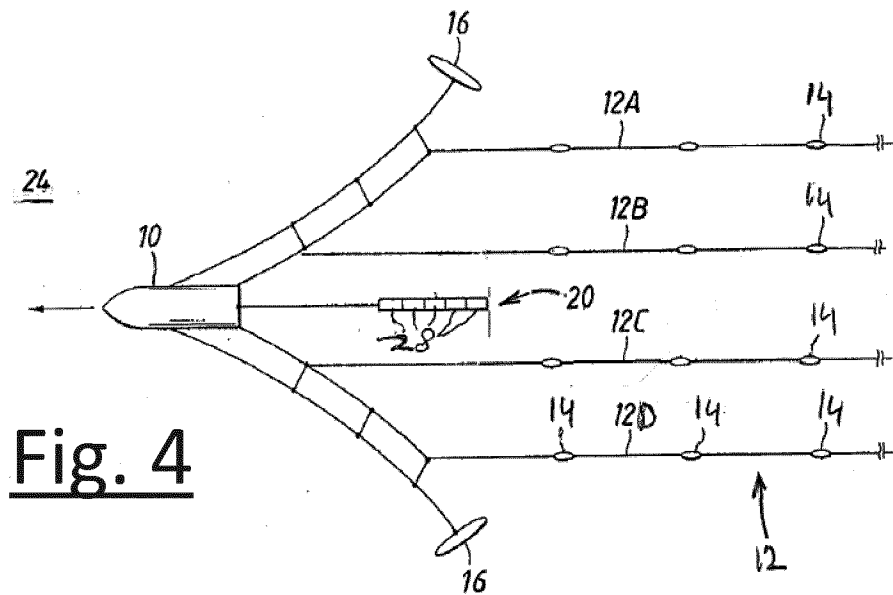


Fig. 4

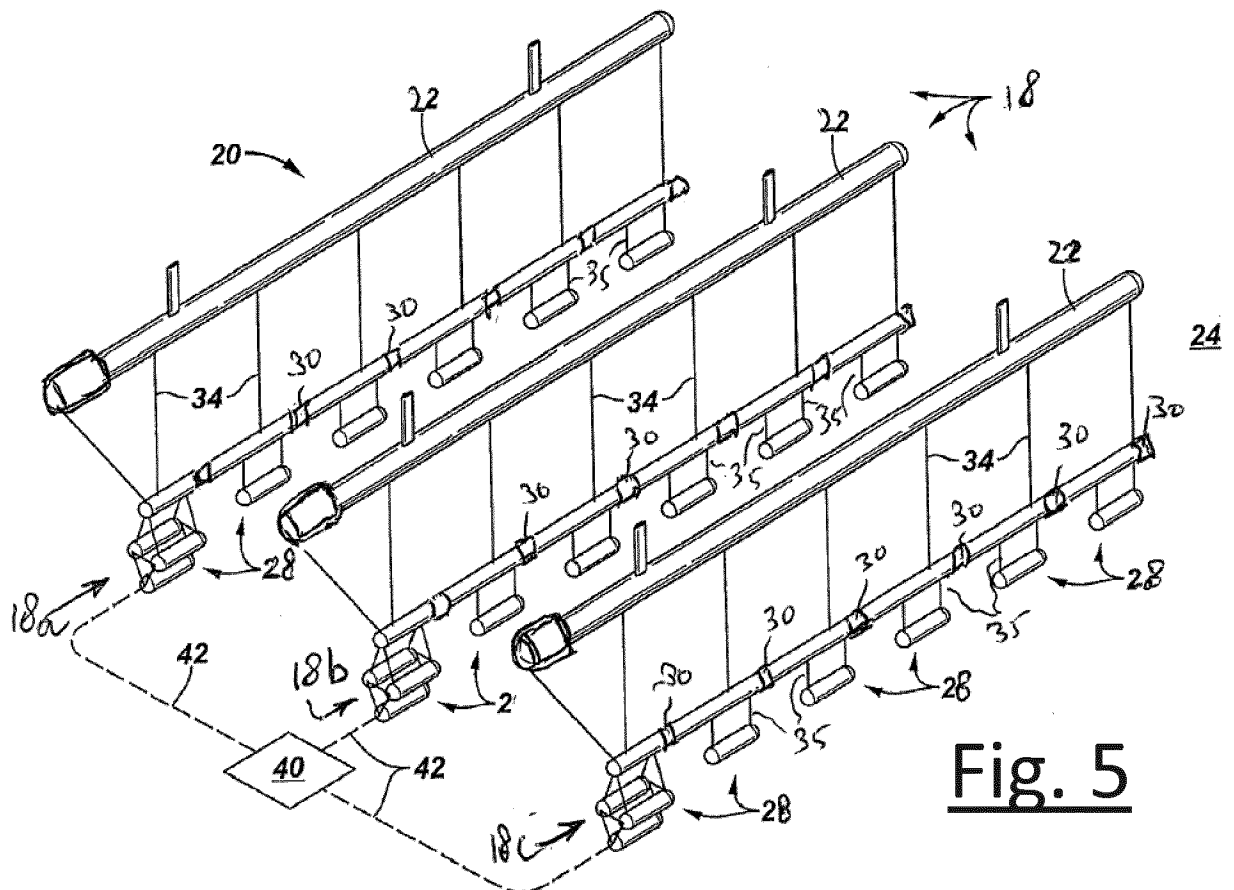
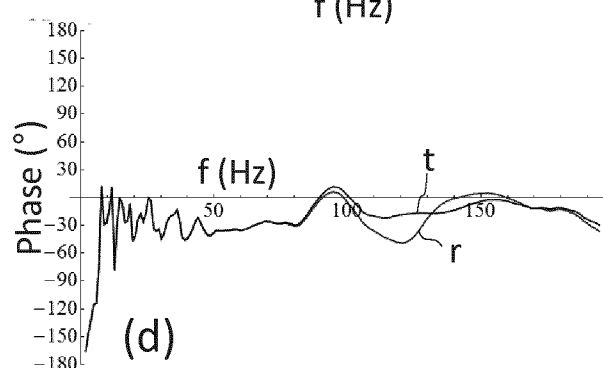
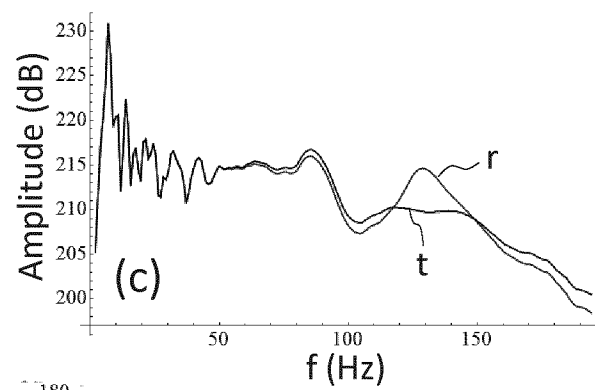
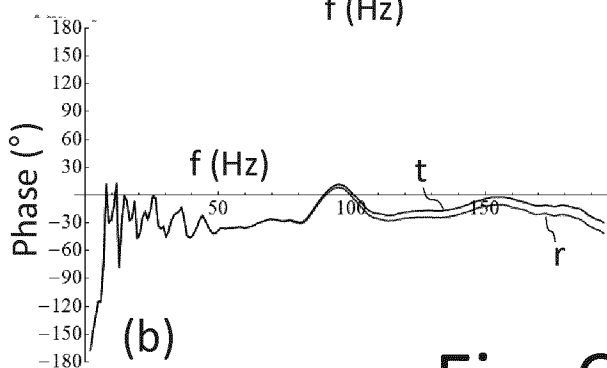
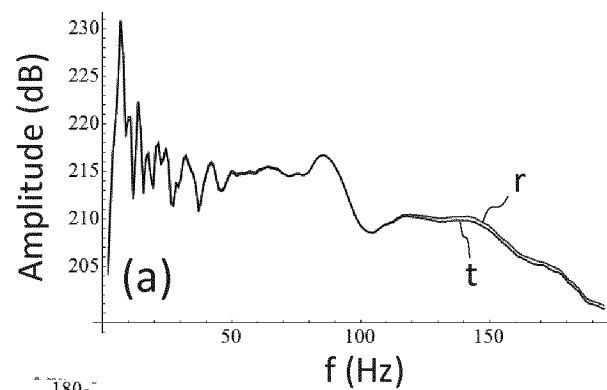
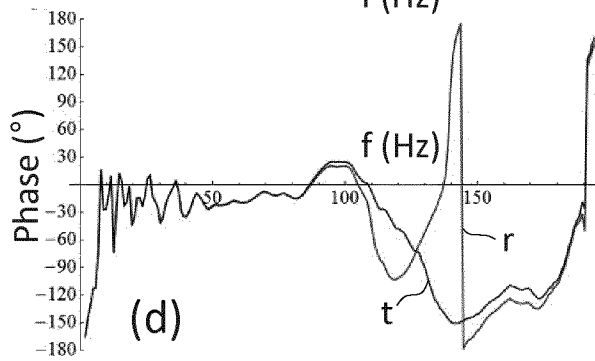
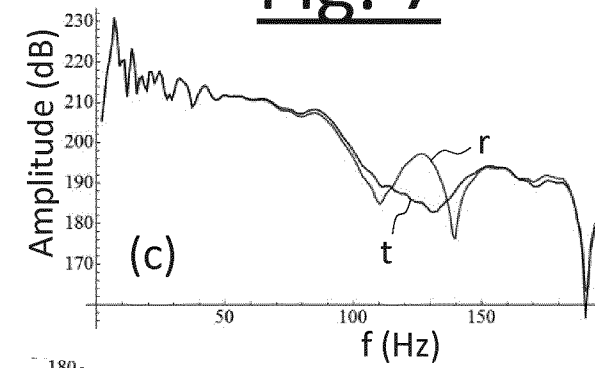
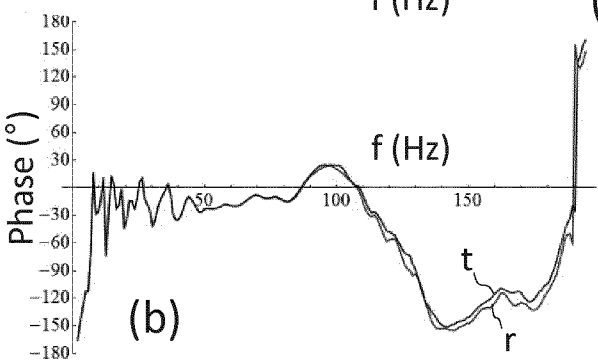
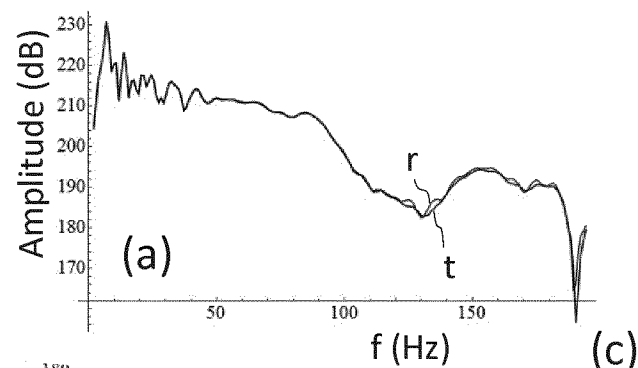
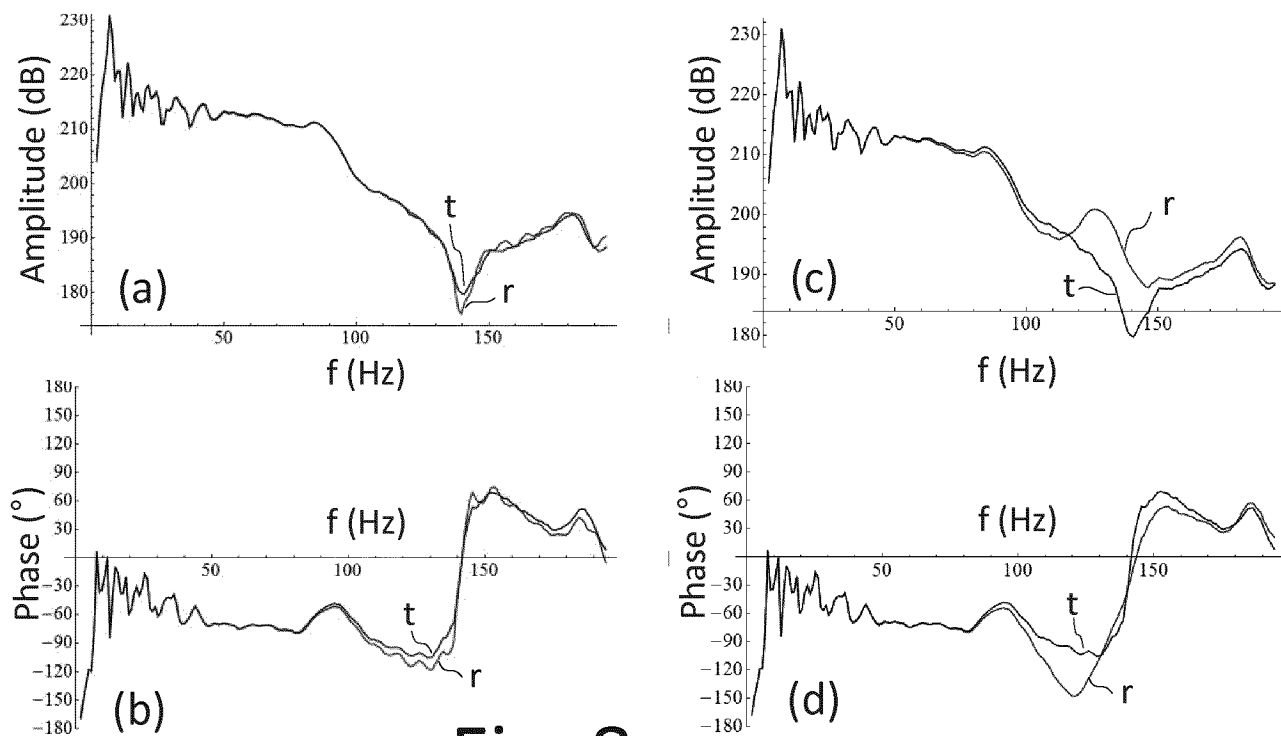
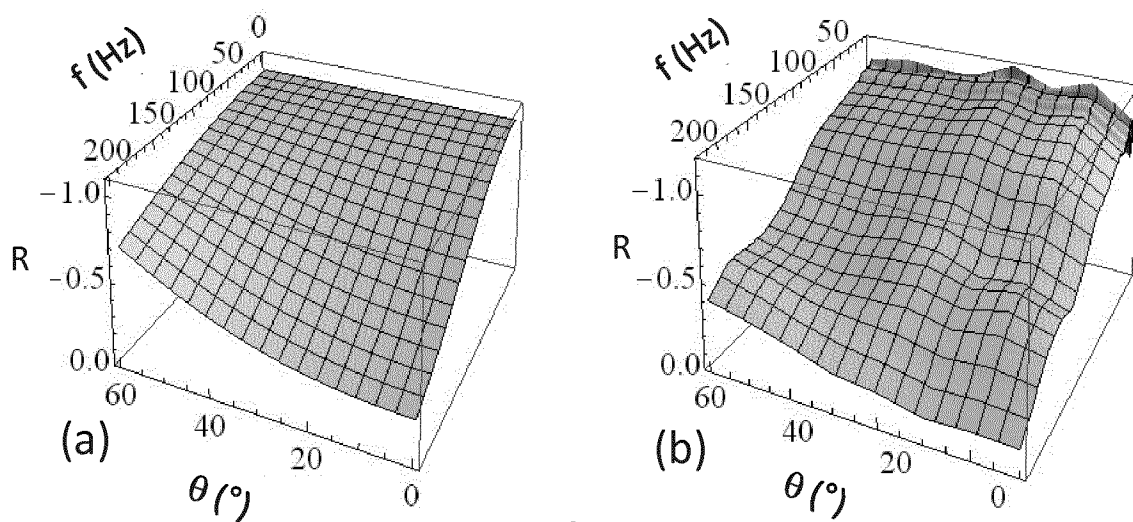


Fig. 5

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Fig. 6Fig. 7

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Fig. 8Fig. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/059677

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V1/38 G01V1/36
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2010/002539 A1 (KRAGH JUIAN EDWARD [GB] ET AL) 7 January 2010 (2010-01-07) paragraphs [0004], [0028], [0034] - [0039], [0054], [0062] - [0063], [0068], [0070]; figures 1A-C, 3B -----	1-14
A	WO 97/37246 A1 (SCHLUMBERGER TECHNOLOGY CORP [US]) 9 October 1997 (1997-10-09) page 5, paragraph 2; figure 4b -----	2,3
A	US 2013/182536 A1 (VASSALLO MASSIMILIANO [GB] ET AL) 18 July 2013 (2013-07-18) paragraph [0036] -----	8,13



Further documents are listed in the continuation of Box C.



See patent family annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 June 2017

Date of mailing of the international search report

29/06/2017

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Naujoks, Marco

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/059677

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010002539	A1	07-01-2010	BR PI0714730 A2 29-10-2013
			CA 2662195 A1 06-03-2008
			GB 2441344 A 05-03-2008
			US 2010002539 A1 07-01-2010
			WO 2008025944 A1 06-03-2008

WO 9737246	A1	09-10-1997	AU 1936997 A 22-10-1997
			WO 9737246 A1 09-10-1997

US 2013182536	A1	18-07-2013	EP 2802902 A1 19-11-2014
			US 2013182536 A1 18-07-2013
			WO 2013106803 A1 18-07-2013
