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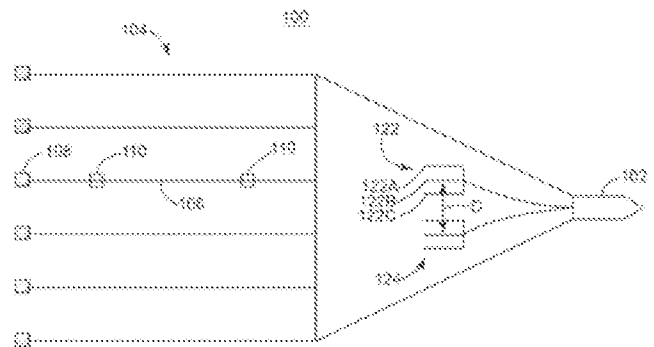
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(54) Title **A method and seismic survey apparatus for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators**

(57) Abstract

The present invention relates to methods for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, and seismic survey apparatuses.



A method and seismic survey apparatus for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators.

- 5 The present invention relates to methods for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, and seismic survey apparatuses.

Seismic surveying techniques represent an effective way to study the earth's
10 subsurface structure. The information obtained from such surveys is of wide scientific interest and can be used to study the make-up and history of the earth, as well as for locating and accessing underground reservoirs of hydrocarbon-based fossil fuels. Marine seismic surveys use acoustic sources, which are configured to emit acoustic energy at selected frequencies to then propagate through the earth's
15 surface and subsurface. The waves are reflected at boundaries between different materials within the subsurface, or are refracted, and travel back towards seismic sensors. The sensors convert the received acoustic signal into an electric signal which is sent to a processor for analysis. The collected signals carry with them information about the subsurface, i.e. the materials either side of the different
20 boundaries, and the positions of the boundaries themselves.

An example of a typical survey setup 100 is shown in figure 1, and includes a vessel 102 towing a seismic spread 104 including plural streamers 106 and associated equipment (such as floats 108 at the ends of the streamers). The streamers
25 themselves can be up to 8 km or 9 km in length, or more, and include plural seismic sensors 110 for recording seismic data. In order to survey the sub-surface structure, sensors are generally located either within the one or more streamers which are towed behind a marine survey vessel as shown, and/or are positioned at particular locations on the earth's surface (such as on the seabed), in which case they may be
30 located within nodes or along cables. The seismic sensors themselves can include one or more of a number of different types of device capable of detecting an acoustic wave within the surrounding material. Nodes can also include additional sensors for

measuring a node position, orientation, temperature, for location of the node, and for monitoring of other parameters.

Marine seismic surveys generally operate by towing acoustic sources behind a survey vessel so that they travel over the area to be surveyed as they are activated. The setup shown in figure 1 includes two source arrays 122 and 124 each including a plurality of sub-arrays 122A-C comprising one or more marine vibrators. Any number of arrays, each including any number of marine vibrators can be used, and these can be combined with seismic streamers for collecting data, with seabed nodes or cables, or with both. In the past, surveys have used impulsive sources, such as air guns, which emit acoustic waves over a very short duration. Herein, a “source” is used to refer to a radiating surface producing a sound wave in a surrounding medium. A marine vibrator can therefore include one or more sources depending on how many radiating surfaces are present.

More recently, marine vibrators have emerged as viable alternatives to air guns in this type of survey. These have a more complex structure, and operate by producing pressure waves in the surrounding water over a longer period of time, with each period over which a continuous signal is emitted by the vibrator being referred to as a sweep. The frequency and/or amplitude of the emitted signal may change during the course of the sweep. The amplitude of the emitted signal at any one time is lower than for an airgun, however, and this can reduce the environmental impact of the survey. Seismic sensors collect pressure or particle motion data representing the wavefield from an array of sources at the sensor position, and this data is processed to extract the desired information about the subsurface structure through which the acoustic waves have travelled to reach that position. In order to do so, an accurate estimate of the original acoustic signature emitted by all of the sources in the source array together is required. Interactions between waveforms emitted by different sources in the array, and inconsistencies between vibrators in terms of their physical structure, can make achieving an accurate estimate of the far-field waveform from the whole array together extremely difficult.

Inversion-based solutions for notional sources within airgun arrays using near-field pressure measurements have been discussed in Lasse Amundsen (1993), "Estimation of source array signatures," *GEOPHYSICS* 58: 1865-1869 and Neil Hargreaves et al. (2015), "Estimation of air-gun array signatures from near-gun measurements - least-squares inversion, bubble motion and error analysis," *SEG Technical Program Expanded Abstracts* : 149-153. These methods use hydrophones located near to the source, which can be towed behind the survey vessel in a "mini-streamer" or alternatively installed just above the air guns, to estimate the near-field signature for the array. From this, a far-field signature can be inferred. This type of measurement is usable to derive a fairly accurate source signature for an airgun array, for which each source can be considered a point source and the wavefield is short-lived. WO-A-2022/225400 describes a similar method for estimating a far-field waveform for a vibrator using pressure measurements of the near-field. US-A-2014/0283615 describes the use of data from accelerometers that are directly coupled to a marine vibrator and which are used to derive a volume acceleration of the vibrator. From this measured change in volume, a source signature in the far field can be inferred, but this will not take into account the signatures from other vibrators operating nearby nor interactions with the sea-surface, and will not take into account contributions to the emitted wavefield that are not measured.

Traditional methods used to determine a source signature for sources in marine seismic surveys all have drawbacks. Methods for more accurately determining a source signature in this type of survey are desirable.

According to a first aspect of the present invention, there is provided a method for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, wherein the method comprises:

reducing the number of sensor measurements required by treating virtual sources as scaled versions of real sources; and,

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a first sensor measuring a property related to the wavefield in

the fluid surrounding that marine vibrator that is directly or indirectly related to a pressure response caused by the activation of that marine vibrator;

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a second sensor coupled to or internal to a radiating surface of that marine vibrator and measuring a property related to motion of the radiating surface; and

jointly inverting the data from the first and the second sensors for all marine vibrators in the array to recover a set of real and virtual notional source waveforms for the array, wherein jointly inverting the data from the first and second sensors is simplified by treating the virtual notional source waveforms as scaled versions of the real notional source waveforms and the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of real and virtual notional source waveforms for each marine vibrator in the array from the data from the first and second sensors.

The method may require the collection of data from the first and second sensor for each vibrator within an array, one measuring (directly or indirectly) a property of the wavefield in the fluid surrounding the vibrator and one measuring movement of the radiating surface itself. The collected data is then entered together as part of a single inversion process to retrieve a notional source waveform, and this allows a much more accurate estimate of the waveform to be obtained than would be possible if data from only one of the sensors were to be collected, or if these were to be processed separately. Motion data for the radiating surface is closely related to the behaviour of device itself and measurements of the wavefield in the fluid surrounding the vibrator are closely related to the interaction between different devices in the array. Combining these via joint inversion gives the best possible result.

Joint inversion refers to the process of treating the data together, either as input data for a particular model, or as a vector in a matrix equation from which a set of notional source waveforms including a contribution from each source in the array can be derived. The fact that the inversion of both types of data is carried out “jointly” means

that the data from the two sensor types are dealt with together and are dealt with in the same manner. This may mean that the data from the first and second sensors form a row/column vector to be operated on by a matrix as part of the inversion process. The sensor data will usually be entered together into a computational engine which will receive the data from the first and second sensors as input, as well as information about a forward model, and which will output the set of notional source waveforms in response. Selection of which computational engine to use for the inversion, and the configuration of this engine and the forward model, will depend on requirements for each particular survey and can be optimized for noise. Some ways in which the forward model can be simplified by making certain assumptions about the source wavefields emitted are set out below.

The radiating surface of the vibrator is the moving part of the structure which generates the pressure wavefield in the surrounding fluid in response to a pilot signal. In embodiments, the first sensor and second sensor are of different sensor types. There may be more than one sensor of the first type and/or more than one sensor of the second type. Reference to the second sensor being internal to the radiating surface means that the sensor is located within the vibrator housing, inward of the radiating surface. Reference to measurements being taken during operation of the vibrator is to recording data during a period in which the vibrator is being activated to produce an acoustic signal (i.e. one or more sweeps of the vibrator are ongoing). The first sensor may be positioned to measure a property of the wavefield (such as pressure) in the water close to the vibrator surface. Close may mean less than 5 meters from the surface of the vibrator. This will usually mean that the first sensor senses a near-field waveform for the vibrator with which it is associated. The first sensors together detect a near-field waveform for the array.

The method may be usable to estimate a set of one or more notional source waveforms that represent the emitted sweeps of a marine vibrator array comprising one or more vibrators. In this case the development of the waveform over time is accounted for. In embodiments, the joint inversion is carried out in the time domain. In embodiments, the joint inversion is carried out in the frequency domain. If

contributions are not combined by making certain assumptions, as set out below, there will be one notional source waveform in the set for each real and for each virtual source in the array. Each vibrator will be associated with one or more source, depending on the number of radiating surfaces present. For joint inversion, the

5 vibrators can be considered as acting as independent monopole sources or as including more than one source, such as two sources. If the latter, it can be assumed that the vibrators act as double monopole sources, wherein the two monopole sources are approximately in phase. The joint inversion can then be carried out on this basis including one notional source waveform for each vibrator, the notional

10 source waveform including a contribution from both monopole sources.

In embodiments, the method comprises wherein the marine vibrators are used to carry out a seismic survey of a subsurface structure, and wherein a far-field source waveform is derived from the notional source waveforms, and wherein the data from

15 the seismic survey is processed using the far-field source waveform to retrieve information about the subsurface structure.

According to a second aspect of invention a seismic survey apparatus is provided, comprising:

20 an array comprising a plurality of marine vibrators for emitting a source wavefield;

a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; wherein the apparatus comprises;

25 a first sensor associated with each marine vibrator in the array and positioned to measure, during activation of that marine vibrator, a property related to the source wavefield in the fluid surrounding that marine vibrator that is directly or indirectly related to a pressure response caused by the activation of that marine vibrator;

a second sensor coupled to or internal to a radiating surface of each marine

30 vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

a processor configured to receive data from the first sensor and data from the second sensor for each marine vibrator in the array, and to jointly invert the data from the first and the second sensors to recover a set of real and virtual notional source waveforms for the marine vibrator array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating virtual notional source waveforms as scaled versions of the real notional source waveforms and formulate an operator matrix linking the data from the first sensors and the data from the second sensors to the set of notional source waveforms and use the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first sensors and second sensors.

In embodiments, the processor is configured to derive a far-field source waveform from the set of notional source waveforms; and process the seismic data using the derived far-field source waveform to retrieve information about the subsurface structure.

According to a third aspect of the invention, a method is provided for deriving a set of notional source waveforms for an array comprising a plurality of marine vibrators, wherein the method comprises:

reducing the number of sensor measurements required by treating pairs of marine vibrators operating in phase as monopole sources; and,

during operation of the plurality of marine vibrators, for each pair of marine vibrators operating in phase, recording data from a first sensor measuring a property related to the wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a second sensor coupled to or internal to a radiating surface of that marine vibrator and measuring a property related to motion of the radiating surface; and

jointly inverting the data from the first and the second sensors for all marine vibrators in the array to recover a set of notional source waveforms for the array,

wherein jointly inverting the data from the first and second sensors is simplified by treating pairs of marine vibrators operating in phase as monopole sources by using averaged second sensor data and the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first second sensors.

In embodiments, the marine vibrators are used to carry out a seismic survey of a subsurface structure, and wherein a far-field source waveform is derived from the notional source waveforms, and wherein the data from the seismic survey is processed using the far-field source waveform to retrieve information about the subsurface structure.

According to a fourth aspect of the invention, a seismic survey apparatus is provided, comprising:

- an array comprising a plurality of marine vibrators for emitting a source wavefield;

- a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; characterized in that the apparatus comprises;

- a first sensor associated with each pair of marine vibrators that operate in phase in the array, wherein the first sensor is positioned to measure, during activation of that pair of marine vibrators, a property related to the source wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

- a second sensor coupled to or internal to a radiating surface of each marine vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

- a processor configured to receive data from each of the first sensors and data from each of the second sensors, and to jointly invert the data from the first and the second sensors to recover a set of notional source waveforms for the marine vibrator

array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating pairs of marine vibrators that operate in phase as monopole sources and using averaged second sensor data and the joint inversion comprises formulating an operator matrix linking the data from the first and second
5 sensors to the set of notional source waveforms and use the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first and second sensors.

In embodiments, the processor is configured to derive a far-field source waveform
10 from the set of notional source waveforms; and process the seismic data using the derived far-field source waveform to retrieve information about the subsurface structure.

According to a fifth aspect of the invention, a method is provided for deriving a set of
15 real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, wherein the method comprises:

reducing the number of sensor measurements required by treating virtual sources as scaled versions of real sources; and,

further reducing the number of sensor measurements required by treating
20 pairs of marine vibrators operating in phase as monopole sources; and,

during operation of the plurality of marine vibrators, for each pair of marine vibrators operating in phase, recording data from a first sensor measuring a property related to the wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that
25 pair of marine vibrators;

during operation of the plurality of marine vibrators, for each vibrator recording data from a second sensor coupled to or internal to a radiating surface of that vibrator and measuring a property related to motion of the radiating surface; and

jointly inverting the data from the first and the second sensors for all vibrators
30 in the array to recover a set of real and virtual notional source waveforms for the array, wherein jointly inverting the data from the first and second sensors is simplified by treating the virtual notional source waveforms as scaled versions of the

real notional source waveforms and wherein the joint inversion is further simplified by treating pairs of marine vibrators operating in phase as monopole sources by using averaged second sensor data, and wherein the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of real and virtual notional source waveforms for each vibrator in the array from the data from the first and second sensors.

In embodiments, the marine vibrators are used to carry out a seismic survey of a subsurface structure, and wherein a far-field source waveform is derived from the notional source waveforms, and wherein the data from the seismic survey is processed using the far-field source waveform to retrieve information about the subsurface structure.

According to a sixth aspect of the invention, a seismic survey apparatus is provided, comprising:

- an array comprising a plurality of marine vibrators for emitting a source wavefield;

- a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; characterized in that the apparatus comprises;

- a first sensor associated with each pair of marine vibrators that operate in phase in the array, wherein the first sensor is positioned to measure, during activation of that pair of marine vibrators, a property related to the source wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

- a second sensor coupled to or internal to a radiating surface of each marine vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

- a processor configured to receive data from each of the first sensors and data from each of the second sensors, and to jointly invert the data from the first and the

second sensors to recover a set of real and virtual notional source waveforms for the marine vibrator array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating virtual notional source waveforms as scaled versions of the real notional source waveforms, and by treating pairs of
5 marine vibrators that operate in phase as monopole sources and using averaged second sensor data, and wherein the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first and second
10 sensors.

In embodiments, the processor is configured to derive a far-field source waveform from the set of notional source waveforms; and process the seismic data using the derived far-field source waveform to retrieve information about the subsurface
15 structure.

Embodiments of the present invention will now be described, by way of example only, with reference to the following diagrams wherein:

20 Figure 1 illustrates a possible set-up for a marine seismic survey;

Figure 2 shows the positions of sources, first sensors, and second sensors in one configuration of the array where sources are treated as monopole sources; and

25 Figure 3 shows the positions of sources, first sensors, and second sensors in another configuration of the array where sources are treated as double monopole sources.

The joint inversion method described herein combines different measurements made
30 in the vicinity of one or more acoustic sources, which may represent a plurality of sources arranged as an array. The measurement and subsequent processing using the measured data is carried out in such a way as to overcome many of the issues

with current methods for estimating a source signature for geological surveys, and particularly for marine geological surveys using one or more marine vibrators as the sources.

- 5 For marine vibrators, the input pilot signal used to drive the vibration is not always an accurate representation of the wavefield emitted in the water, and the advantage of including outboard measurements, such as measurements from hydrophones located in the water close to a vibrator, as well as onboard measurements, such as measurements from a motion sensor, is to provide a much more accurate estimate
10 of the signal emitted into the far-field. The processing of the measurements together by jointly inverting allows the data from different sensor types to be used together in the most effective way to provide the best possible estimate of the notional source waveform. This joint inversion method is particularly suitable in cases where the acoustic energy is emitted by driving one or more vibrating surfaces, and allows any
15 distortions in the wavefield and interactions with nearby interfaces to be accounted for.

The method requires that one or more first sensors be positioned and configured to measure a property related to the wavefield in the surrounding fluid close to the
20 sources (i.e. pressure) and that one or more second sensors be positioned and configured to measure a property related to the movement of one or more vibrating parts of the vibrator itself (i.e. acceleration). The first sensors need not be coupled to the vibrator or array, but can be located on a streamer, on a frame coupled to the source array or to the vibrator, or on another structure located near to the array
25 during the survey. The second sensors must be usable to detect or infer movement of the vibrator housing itself, and so will usually be directly coupled or attached to the vibrating parts of the housing. Suitable sensors for use as the first sensors are hydrophones for measuring pressure changes in the water close to the sources (i.e. the near-field pressure component of the emitted wavefield). Suitable sensors for
30 use as the second sensors are accelerometers for measuring an acceleration of the vibrating surfaces. These measurements can be inverted jointly to solve for a set of real notional source signatures, which are then used to construct a reliable estimate

of the far-field signature for the source, including the array response and any transducer-related distortion and reflection from nearby interfaces. Both sets of measurements have limitations and are subject to noise. However, when the measurements are combined in a joint inversion as described herein, such as a least-squares inversion, they offer the best opportunity to obtain a robust estimate of the complete source signature in the far field.

In order to take account of reflections from a nearby boundary, such as the surface of the water, the joint inversion method can be used to solve also for a number of virtual sources, each representing the reflected signal from a real source in the array. Certain assumptions can simplify the treatment of these virtual sources. For example, they can be assumed to emit the same signal as the corresponding real source but scaled using reflection coefficients to account for energy losses at the reflection boundary.

The joint inversion method is particularly suitable for use with an array of marine vibrators having dimensions that are not small compared to the shortest wavelength of interest in the seismic survey to be completed (largest dimension at least one tenth of the size of the shortest wavelength of interest), and which have a fairly simple structure which changes shape in a predictable way during emission of a signal. The array in question may, for example, be made up of a plurality of marine vibrators having one, two, or more rigid or semi-rigid surfaces which reciprocate to create a pressure wave in the surrounding fluid. These are the moving or radiating surfaces of the vibrator, and each represents a real source. The surfaces may be driven by electro-hydraulic actuators, piezoelectric actuators, or in any other way. The reciprocating surfaces may be located on the end of pistons, and there may be two pistons driving two vibrating surfaces in opposite directions at either end of the vibrator. The vibrator will therefore lengthen and shorten as the pistons move in and out over the course of a sweep. Rubber components may surround the end surfaces of the vibrator, which can in principle complicate the emitted signal and make this more difficult to predict from the pilot signal alone.

For this type of vibrator, measurements of the pressure field in the water alone will not provide an accurate representation of the far-field (as it can do in the case of airgun arrays). Measurements of the movement of the vibrator surface will also not allow accurate representation of the notional source to be derived, due to local resonances or imperfections in the vibrator housing. The joint inversion method, described in detail below, can be used to mitigate issues with both types of measurement, and is associated with particular advantages as discussed herein.

In connection with figure 2, the joint inversion method is described in a situation in which two real sources and two virtual sources are present, and where the first sensors are hydrophones and the second sensors are accelerometers. The virtual sources each represent a part of the waveform that is emitted by one of the real sources and is reflected from the surface of the water. The same method can be used for an array containing any number of real sources, with or without equivalent virtual sources, and the number of measurements from first and second sensors can be adjusted accordingly. Preferably, motion sensors (in this case representing the second sensors) should be coupled to each vibrator in the array, and pressure sensors (in this case representing the first sensors) should be located near to each vibrator to measure a waveform in the water close to that vibrator, typically less than 5 meters from the closest point on the vibrator surface. The length of the left-hand and right-hand vectors in the matrix equation below (representing the hydrophone and accelerometer data and notional source signatures/waveforms respectively) can be adapted depending on the data available and the number of sources, with the size of the matrix operator adjusted to correspond. Where other types of sensors are used as the first and second sensors, rather than hydrophones and accelerometers, the forward model will need to be adapted to properly link the data to the set of notional source waveforms to be output. In the examples described below with reference to figures 2 and 3, this will mean adaption of the elements of the operator matrix.

Figure 2 shows an example of a survey set-up in which the array comprises two separated monopole sources (i.e. each can be a vibrator with a simple piston

operated end plate). Each source is instrumented with one accelerometer and two near-field hydrophones, and is located in close proximity to an air-water interface which gives rise to a ghost response from each source at mirror locations. These are referred to as virtual sources, as mentioned above, and are shown as sources m_3 and m_4 in figure 2. For each angular frequency ω , the forward model is posed as a matrix equation, including two vectors and an operator matrix, as follows:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \\ f_{11} & 0 & 0 & 0 \\ 0 & f_{22} & 0 & 0 \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \end{pmatrix}$$

where h_i represents the data from hydrophone i , a_i represents the data from accelerometer i , m_j are the notional source waveforms (including two real and two virtual sources in this case), g_{ij} is an element of the upper part of the matrix operator which is concerned with propagation from the j th source to the i th hydrophone with a term for geometric scaling for the distance between them r_{ij} and a phase shift (based on this distance and v , the sound speed in water), and f_{ij} is an element of the lower part of the operator which converts the pressure notional signature to acceleration for a vibrating surface with piston area A . For this simple case where the radiated acoustic field from each vibrating piston can be described by a simple monopole and is unmodified by the presence of the vibrator body, these terms are given as:

$$g_{ij} = \frac{e^{-j\omega(r_{ij}-1)/v}}{r_{ij}} \quad \text{and} \quad f_{ij(i=j)} = \frac{4\pi}{\rho A} e^{j\omega/v}$$

In a more general case, in order to take account of the finite source extent and the effect upon the acoustic wavefield of the presence of the vibrator body, the coefficients g_{ij} that describe the measured pressure at a given hydrophone due to a given source element can be calculated via a modelling approach such as the Helmholtz-Kirchhoff integral method or utilizing a finite difference numerical model for each sensor position. These methods may modify or replace completely the simple monopole term.

The f_{ij} terms given for the accelerometers still hold for the general case and are as above, but can still be adapted if desired for a more complex relationship between the measurement and notional source. The zero terms in the operator relate to the acceleration measurements for $i \neq j$ and are due to the fact that the accelerometers only measure the output from the source they are attached to. This is true particularly in the case of a high impedance driver.

The compound linear operator can be summarized as below:

$$\begin{pmatrix} h \\ a \end{pmatrix} = \begin{pmatrix} g \\ f \end{pmatrix}_m$$

It is possible to invert for the real and virtual notional sources, m , using any method. The inversion is, however, carried out jointly, meaning that pressure and accelerometer data is used as input data for a model with the notional source

waveform for each of the sources as the output. Inversion allows the hydrophone and accelerometer data to be used to derive a notional wavefield vector including a contribution from all of the sources. Once notional source waveforms are known, they can be used to calculate the far-field wavefield, with the same method routinely used for airgun array sources. As an example, a suitable method may be to use an

iterative solver such as LSQR (iterating to find the wavefield which minimises the difference between the predicted data and the measured data). Note that here the problem is set up in the frequency domain, but the problem can equivalently be posed in the time domain. Sensitivity to noise when inverting for virtual notional sources depends strongly on the separation between the hydrophone and the virtual source, so that the use of a ghost model or a hybrid methodology can be preferred in practice in particular when the distance between the sources and the surface of the water is larger. For example, at low frequencies a simple mirror-like ghost model, assuming that a dipole source can be sufficiently represented as two dipole sources that are in phase, may represent the physics of reflection with sufficient accuracy, while at higher frequencies, perturbations of the ghost due to non-linear effects and/or interaction with a rough and dynamic surface profile may be better captured by solving explicitly for virtual notional sources, meaning that the virtual sources are

treated in a similar manner to the real sources during the joint inversion and are solved separately (matrix equation above).

If using a ghost model, the virtual sources can be expressed as reflected (and scaled) versions of the real sources, meaning that it is possible to solve only for the unknown real notional source. In the example shown in figure 2 with two real sources, because of the fact that the virtual source is a mirror image of the real source, the terms in the third column of the operator matrix can be combined with those in the first, and the second with the fourth, invoking an interface reflection coefficient, r . If this is done, the modified matrix equation is as follows:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} g_{11} + r \cdot g_{13} & g_{12} + r \cdot g_{14} \\ g_{21} + r \cdot g_{23} & g_{22} + r \cdot g_{24} \\ g_{31} + r \cdot g_{33} & g_{32} + r \cdot g_{34} \\ g_{41} + r \cdot g_{43} & g_{42} + r \cdot g_{44} \\ f_{11} & 0 \\ 0 & f_{22} \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \end{pmatrix}$$

This method of combining terms for real and virtual sources can be applied for any number of real sources in a similar manner. This simplification method, applying assumptions about the behaviour of the virtual sources to reduce the size of the operator matrix for the joint inversion, reduces processing power required to determine the notional source waveforms and can reduce the required number of pressure and motion sensors required to achieve an accurate result. One pressure sensor for each real source can be sufficient, for example, rather than including two pressure sensors as shown in figure 2.

The above joint inversion method can also easily be extended to source types where the mechanism is represented more closely by a double piston (each instrumented) through modelling the unit as two separated monopoles. An example of such a setup is shown in figure 3.

If solving for each monopole separately we would have the following forward model:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{12} & g_{13} & g_{14} & g_{15} & g_{16} & g_{17} & g_{18} \\ g_{21} & g_{22} & g_{23} & g_{24} & g_{25} & g_{26} & g_{27} & g_{28} \\ g_{31} & g_{32} & g_{33} & g_{34} & g_{35} & g_{36} & g_{37} & g_{38} \\ g_{41} & g_{42} & g_{43} & g_{44} & g_{45} & g_{46} & g_{47} & g_{48} \\ f_{11} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & f_{22} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & f_{35} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & f_{46} & 0 & 0 \end{pmatrix} \begin{pmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ m_5 \\ m_6 \\ m_7 \\ m_8 \end{pmatrix}$$

If the double monopole sources are coupled and in phase, then an average measurement and response might be more appropriate, and this then makes it possible to solve only for the monopole contribution by making the assumption that the wavefield for each of the monopole sources are the same, i.e. that $m_1 = m_2$ and $m_3 = m_4$ and $m_5 = m_6$ and $m_7 = m_8$. Propagation terms can then be combined while still preserving the true distances to each of the coupled elements but posed to solve for a smaller number of unknowns:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ (a_1 + a_2)/2 \\ (a_3 + a_4)/2 \end{pmatrix} = \begin{pmatrix} g_{11} + g_{12} & g_{13} + g_{14} & g_{15} + g_{16} & g_{17} + g_{18} \\ g_{21} + g_{22} & g_{23} + g_{24} & g_{25} + g_{26} & g_{27} + g_{28} \\ g_{31} + g_{32} & g_{33} + g_{34} & g_{35} + g_{36} & g_{37} + g_{38} \\ g_{41} + g_{42} & g_{43} + g_{44} & g_{45} + g_{46} & g_{47} + g_{48} \\ f_{11} & 0 & 0 & 0 \\ 0 & 0 & f_{35} & 0 \end{pmatrix} \begin{pmatrix} m_1 \\ m_3 \\ m_5 \\ m_7 \end{pmatrix}$$

Again, this combination method can be applied similarly for arrays with different numbers of vibrators by considering at least some of the vibrators as two similar monopole sources that are in phase. This can be simplified further to solve for just two unknowns if a ghost model is used, as before:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ (a_1 + a_2)/2 \\ (a_3 + a_4)/2 \end{pmatrix} = \begin{pmatrix} g_{11} + g_{12} + r(g_{13} + g_{14}) & g_{15} + g_{16} + r(g_{17} + g_{18}) \\ g_{21} + g_{22} + r(g_{23} + g_{24}) & g_{25} + g_{26} + r(g_{27} + g_{28}) \\ g_{31} + g_{32} + r(g_{33} + g_{34}) & g_{35} + g_{36} + r(g_{37} + g_{38}) \\ g_{41} + g_{42} + r(g_{43} + g_{44}) & g_{45} + g_{46} + r(g_{47} + g_{48}) \\ f_{11} & 0 \\ 0 & f_{35} \end{pmatrix} \begin{pmatrix} m_1 \\ m_5 \end{pmatrix}$$

When virtual sources are ignored, the number of first sensors required to achieve an accurate estimate of the source wavefield can be halved by treating dipole sources as two monopole sources vibrating in phase if it is assumed that the two monopole terms for a dipole source are equal, as set out above. This will be the case for
 5 vibrators having a more or less symmetrical shape (i.e. two similar vibrating surfaces at each end). This simplifies both the method and the survey set-up. More first sensor measurements (in this case hydrophone measurements) can obviously be used if desired, but this is not a requirement in such a case. In general, the total number of sensors (i.e. hydrophones plus accelerometers) needs to be equal or
 10 greater than the number of marine vibrators in the array. A greater number of sensors is beneficial for the reasons discussed earlier.

As mentioned, although the specific examples use hydrophones as the first sensors and accelerometers as the second sensors other types of sensors can be used in
 15 place of these to measure properties relating to the wavefield in the fluid close to the vibrator and the movement of the radiating surface (e.g. temperature sensors, piezoelectric sensors, voltmeters). This will require only adaption of the forward model, and specifically of the elements of the operator matrix, to account for the change and to properly link the data with the waveforms produced by the sources.

For any of the examples set out above, weighting factors can be introduced to weight the contribution of the data from one, some, or all of the sensors present to the output set of one or more notional wavefield. These can represent a fixed number (i.e. 0, 1, or any number in between) or can represent a function in which case the
 25 weight can be allowed to vary with frequency, time, angle, and so on as desired. The weight or the weighting function can be introduced to the left-hand vector in the matrix equations shown above as a multiplier for each of the elements representing the sensor data. Including weighting factors allows account to be taken of the reliability of the data. Weights can depend on a measured noise in the sensor data,
 30 for example, or on an expected reliability of the sensor. Including the option of a 0 weight can also allow defunct sensors to be dealt with in a simple way. Frequency dependence of the weighting functions can be useful in that sensors having different

sensitivity ranges and with different frequency responses can be easily introduced as part of the apparatus, resulting in an extremely flexible setup.

5 The above methods can be applied to arrays comprising more than one different vibrator type. Some vibrators in the array can be treated as monopole sources, for example, and some as dipole sources.

Claims

1. A method for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, characterized in that the method
5 comprises:

reducing the number of sensor measurements required by treating virtual sources as scaled versions of real sources; and,

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a first sensor measuring a property related to the wavefield in
10 the fluid surrounding that marine vibrator that is directly or indirectly related to a pressure response caused by the activation of that marine vibrator;

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a second sensor coupled to or internal to a radiating surface of that marine vibrator and measuring a property related to motion of the radiating
15 surface; and

jointly inverting the data from the first and the second sensors for all marine vibrators in the array to recover a set of real and virtual notional source waveforms for the array, wherein jointly inverting the data from the first and second sensors is simplified by treating the virtual notional source waveforms as scaled versions of the
20 real notional source waveforms and the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of real and virtual notional source waveforms for each marine vibrator in the array from the data from the first and second sensors.

2. The method of claim 1, wherein the marine vibrators are used to carry out a seismic survey of a subsurface structure, and wherein a far-field source waveform is derived from the notional source waveforms, and wherein the data from the seismic survey is processed using the far-field source waveform to retrieve information about
30 the subsurface structure.

3. A seismic survey apparatus, comprising:

an array comprising a plurality of marine vibrators for emitting a source wavefield;

a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; characterized in that the apparatus comprises;

a first sensor associated with each marine vibrator in the array and positioned to measure, during activation of that marine vibrator, a property related to the source wavefield in the fluid surrounding that marine vibrator that is directly or indirectly related to a pressure response caused by the activation of that marine vibrator;

a second sensor coupled to or internal to a radiating surface of each marine vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

a processor configured to receive data from the first sensor and data from the second sensor for each marine vibrator in the array, and to jointly invert the data from the first and the second sensors to recover a set of real and virtual notional source waveforms for the marine vibrator array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating virtual notional source waveforms as scaled versions of the real notional source waveforms and formulate an operator matrix linking the data from the first sensors and the data from the second sensors to the set of notional source waveforms and use the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first sensors and second sensors.

4. The apparatus of claim 3, wherein the processor is configured to:

derive a far-field source waveform from the set of notional source waveforms; and

process the seismic data using the derived far-field source waveform to retrieve information about the subsurface structure.

5. A method for deriving a set of notional source waveforms for an array comprising a plurality of marine vibrators, characterized in that the method comprises:

reducing the number of sensor measurements required by treating pairs of marine vibrators operating in phase as monopole sources; and,

during operation of the plurality of marine vibrators, for each pair of marine vibrators operating in phase, recording data from a first sensor measuring a property related to the wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

during operation of the plurality of marine vibrators, for each marine vibrator recording data from a second sensor coupled to or internal to a radiating surface of that marine vibrator and measuring a property related to motion of the radiating surface; and

jointly inverting the data from the first and the second sensors for all marine vibrators in the array to recover a set of notional source waveforms for the array, wherein jointly inverting the data from the first and second sensors is simplified by treating pairs of marine vibrators operating in phase as monopole sources by using averaged second sensor data and the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first second sensors.

6. The method of claim 5, wherein the marine vibrators are used to carry out a seismic survey of a subsurface structure, and wherein a far-field source waveform is derived from the notional source waveforms, and wherein the data from the seismic survey is processed using the far-field source waveform to retrieve information about the subsurface structure.

7. A seismic survey apparatus, comprising:

an array comprising a plurality of marine vibrators for emitting a source wavefield;

a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; characterized in that the apparatus comprises;

a first sensor associated with each pair of marine vibrators that operate in phase in the array, wherein the first sensor is positioned to measure, during activation of that pair of marine vibrators, a property related to the source wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

a second sensor coupled to or internal to a radiating surface of each marine vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

a processor configured to receive data from each of the first sensors and data from each of the second sensors, and to jointly invert the data from the first and the second sensors to recover a set of notional source waveforms for the marine vibrator array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating pairs of marine vibrators that operate in phase as monopole sources and using averaged second sensor data and the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and use the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first and second sensors.

8. The apparatus of claim 7, wherein the processor is configured to:

derive a far-field source waveform from the set of notional source waveforms; and

process the seismic data using the derived far-field source waveform to retrieve information about the subsurface structure.

9. A method for deriving a set of real and virtual notional source waveforms for an array comprising a plurality of marine vibrators, characterized in that the method comprises:

reducing the number of sensor measurements required by treating virtual
5 sources as scaled versions of real sources; and,

further reducing the number of sensor measurements required by treating
pairs of marine vibrators operating in phase as monopole sources; and,

during operation of the plurality of marine vibrators, for each pair of marine
vibrators operating in phase, recording data from a first sensor measuring a property
10 related to the wavefield in the fluid surrounding that pair of marine vibrators that is
directly or indirectly related to a pressure response caused by the activation of that
pair of marine vibrators;

during operation of the plurality of marine vibrators, for each vibrator recording
data from a second sensor coupled to or internal to a radiating surface of that
15 vibrator and measuring a property related to motion of the radiating surface; and

jointly inverting the data from the first and the second sensors for all vibrators
in the array to recover a set of real and virtual notional source waveforms for the
array, wherein jointly inverting the data from the first and second sensors is
simplified by treating the virtual notional source waveforms as scaled versions of the
20 real notional source waveforms and wherein the joint inversion is further simplified by
treating pairs of marine vibrators operating in phase as monopole sources by using
averaged second sensor data, and wherein the joint inversion comprises formulating
an operator matrix linking the data from the first and second sensors to the set of
notional source waveforms and using the inverse of the operator matrix to recover
25 the set of real and virtual notional source waveforms for each vibrator in the array
from the data from the first and second sensors.

10. The method of claim 9, wherein the marine vibrators are used to carry out a
seismic survey of a subsurface structure, and wherein a far-field source waveform is
30 derived from the notional source waveforms, and wherein the data from the seismic
survey is processed using the far-field source waveform to retrieve information about
the subsurface structure.

11. A seismic survey apparatus, comprising:

an array comprising a plurality of marine vibrators for emitting a source wavefield;

a set of seismic sensors for collecting seismic data representing the source wavefield after reflection from subsurface structure; characterized in that the apparatus comprises;

a first sensor associated with each pair of marine vibrators that operate in phase in the array, wherein the first sensor is positioned to measure, during activation of that pair of marine vibrators, a property related to the source wavefield in the fluid surrounding that pair of marine vibrators that is directly or indirectly related to a pressure response caused by the activation of that pair of marine vibrators;

a second sensor coupled to or internal to a radiating surface of each marine vibrator in the array to measure motion of the radiating surface of that marine vibrator during activation of that marine vibrator;

a processor configured to receive data from each of the first sensors and data from each of the second sensors, and to jointly invert the data from the first and the second sensors to recover a set of real and virtual notional source waveforms for the marine vibrator array, wherein the processor is configured to jointly invert the data from the first and second sensors by treating virtual notional source waveforms as scaled versions of the real notional source waveforms, and by treating pairs of marine vibrators that operate in phase as monopole sources and using averaged second sensor data, and wherein the joint inversion comprises formulating an operator matrix linking the data from the first and second sensors to the set of notional source waveforms and using the inverse of the operator matrix to recover the set of notional source waveforms from the data from the first and second sensors.

12. The apparatus of claim 11, wherein the processor is configured to:

derive a far-field source waveform from the set of notional source waveforms; and

process the seismic data using the derived far-field source waveform to retrieve information about the subsurface structure.

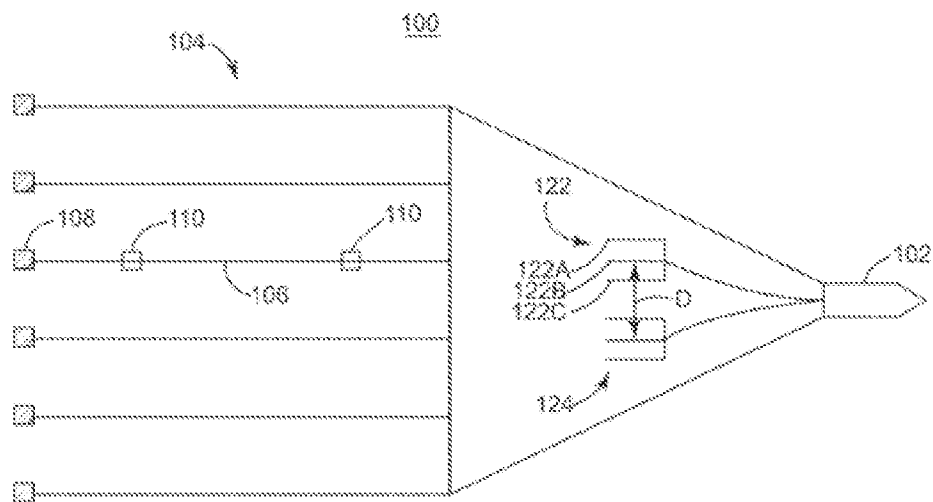


Fig. 1 (PRIOR ART)

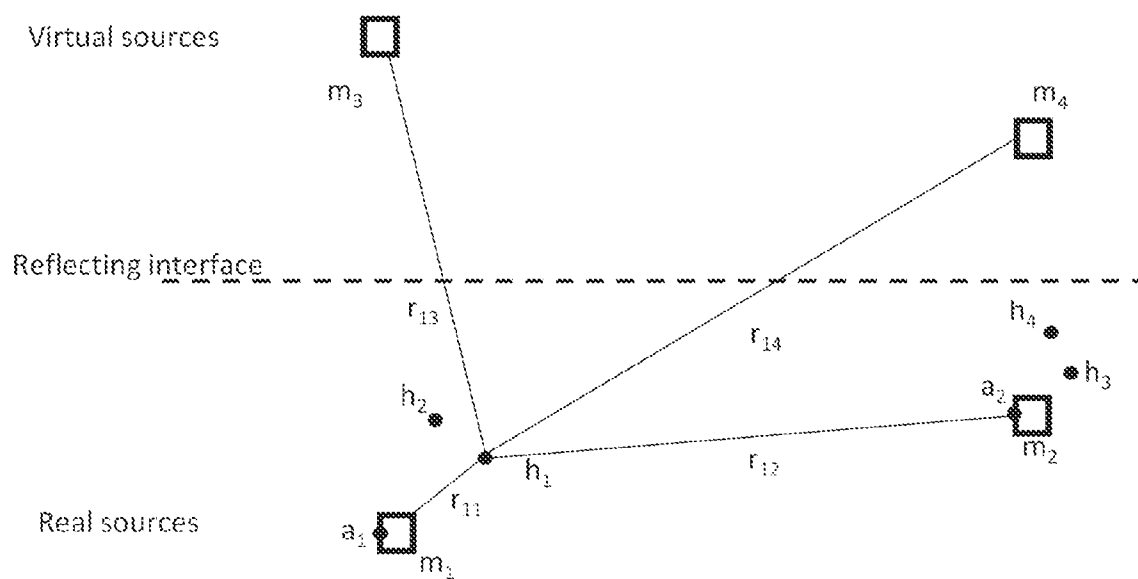


Fig. 2

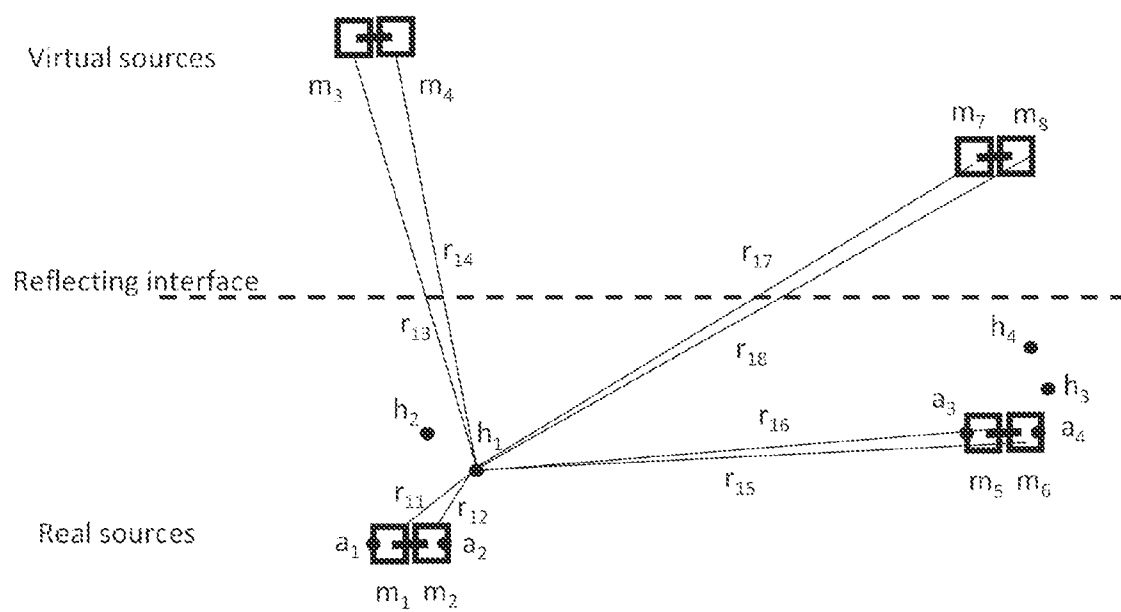


Fig. 3