

(51) International Patent Classification:  
*G01V 1/38* (2006.01)(21) International Application Number:  
PCT/IB2015/001002(22) International Filing Date:  
13 March 2015 (13.03.2015)

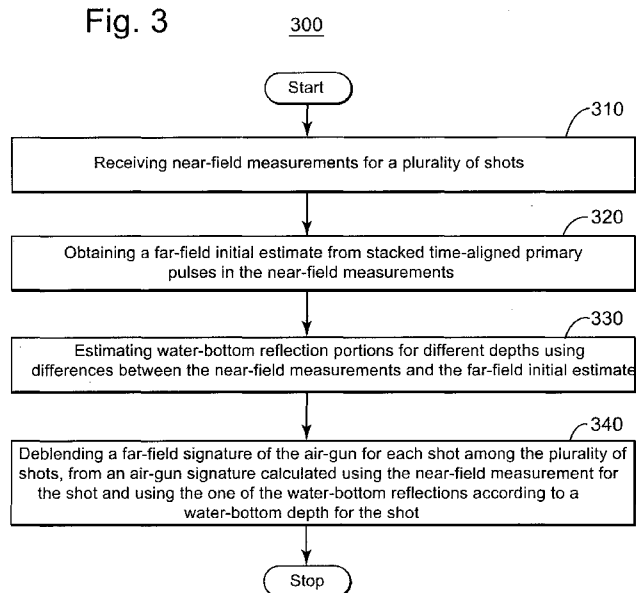
(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
61/952,900 14 March 2014 (14.03.2014) US(71) Applicant: **CGG SERVICES SA** [FR/FR]; 27, avenue  
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is Cedex 17 (FR).(81) Designated States (*unless otherwise indicated, for every  
kind of national protection available*): AE, AG, AL, AM,  
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY,  
BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM,DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,  
HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR,  
KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG,  
MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM,  
PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,  
SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,  
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.(84) Designated States (*unless otherwise indicated, for every  
kind of regional protection available*): ARIPO (BW, GH,  
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ,  
TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU,  
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,  
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,  
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,  
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ,  
GW, KM, ML, MR, NE, SN, TD, TG).**Declarations under Rule 4.17:**— *of inventorship (Rule 4.17(iv))***Published:**— *without international search report and to be republished  
upon receipt of that report (Rule 48.2(g))*

(54) Title: METHOD AND APPARATUS FOR ESTIMATING SOURCE SIGNATURE IN SHALLOW WATER

Fig. 3



(57) Abstract: In order to use near-field measurements to obtain signature of a signal penetrating seafloor in a shallow water surveyed area, the water-bottom reflections' effect is removed. The removal is performed by obtaining first a far-field initial estimate from stacked primary pulses in the near-field measurements, and then estimating water-bottom reflection portions for different depths using differences between the near-field measurements and the far-field initial estimate. The signature of the air-gun for each shot is then deblended from the near-field measurement for the shot using the one of the water-bottom reflection portions according to a water-bottom depth associated with the shot location.

**Method and Apparatus for Estimating Source Signature  
in Shallow Water**

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**CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims priority and benefit from U.S. Provisional Patent Application No. 61/952,900, filed March 14, 2014, for "Extreme shallow water source signature estimation using near field hydrophone recording," the content of which is  
10 incorporated in its entirety herein by reference.

**BACKGROUND**

**TECHNICAL FIELD**

[0002] Embodiments of the subject matter disclosed herein generally relate to  
15 methods and apparatuses for estimating signatures characterizing signals penetrating the seafloor in shallow water, or more specifically, to methods and apparatuses able to estimate these signatures using near-field measurements without comprehensive knowledge of the water-bottom's depth and reflectivity in the survey area.

**DISCUSSION OF THE BACKGROUND**

20 [0003] In seismic surveying, seismic signals (i.e., pressure variations propagating in an explored volume) are used to investigate geophysical structures under the ground surface or under the seafloor. Seismic data representing reflections of the seismic

signals in the investigated geophysical structure are acquired and processed to generate images of the investigated structure. These images may be used to evaluate oil and/or gas reservoirs. Improving seismic data acquisition and processing is an ongoing research topic.

5   **[0004]**        During a marine seismic survey, a submerged seismic source generates signals at different horizontal locations in the surveyed area. The signals propagate in all directions linearly until encountering interfaces where the propagation velocity changes (e.g., at an interface between water and air, water to rock, shale to sand, etc.). At these interfaces, the signals are reflected, refracted and/or transmitted. Some of the  
10 signals' energy eventually reaches detectors in streamers towed or placed on the seafloor. The detectors (also known as receivers) are configured to record information (seismic data) related to the source-generated signals that traveled through the investigated geophysical structure.

**[0005]**        Each recording in the seismic data is due to one receiver detecting energy  
15 after a shot and includes a convolution of the source signature (i.e., amplitude versus time characterizing the signal penetrating the seafloor following the shot) and the investigated structure's response function. The structure's response function associated with a location carries information about the nature and depth of interfaces between layers of the structure under the seafloor. During seismic data processing, the  
20 signature of the signal incident on the formation (i.e., penetrating the seafloor) is used to apply a designation procedure to the seismic data in order to extract the structure's response function. The structure response functions extracted from different recordings

(and thus corresponding to different locations in the surveyed area) are then used to create the investigated structure's image(s).

**[0006]** Marine seismic sources usually include multiple individual sources that are fired substantially simultaneously to generate a seismic signal stronger than achievable with a single individual source. An individual source may be an air-gun or a cluster of air-guns. The shape of the signal (i.e., amplitude versus time) generated by the source (i.e., due to all the individual sources) varies with distance until, at a great enough distance, it starts having a stable shape. After the signal's shape becomes stable, its overall amplitude decreases inversely proportional to the distance. The region where the signature shape no longer changes significantly with distance is known as the "far-field," in contrast to the "near-field" region where the shape varies.

**[0007]** For large water-bottom depths, the source signature may be calculated using equivalent notional signatures for the individual sources. The equivalent notional signature is a tool for representing the contribution of an individual source to the signal in the far-field region, with each individual source contribution being decoupled from contributions of the other individual sources. As described in U.S. Patent No. 4,476,553 and U.S. Patent Application No. 2013/0258808 (the entire contents of which are incorporated herewith by reference), equivalent notional signatures may be obtained using the near-field measurements and information about the individual sources' arrangement when the source is fired. The near-field measurements may be acquired by near-field sensors placed in proximity to each individual source (e.g., hydrophones about 1-2 m above each air-gun). The source signature that characterizes the signal

actually penetrating the seafloor is a superposition of the notional signatures corresponding to each of the individual sources.

**[0008]** In the case of shallow water (called also “extreme shallow water” and meaning water-bottom depths up to 150 m), calculating notional signatures from the near-field sensor measurements becomes problematic because the near-field sensors also detect water-bottom reflections related to the signals that do not penetrate the seafloor. As exemplarily illustrated in Figure 1, when air-gun 100 is fired in shallow water, a near-field sensor 110 placed above air-gun 100 detects: (A) an up-going direct (traveling straight from the air-gun to the near-field sensor) signal 120, (B) a water-air interface (i.e., water surface) reflection 130, (C) a first water-bottom reflection 140 of a down-going signal traveling from the air-gun to the seafloor, (D) a first water-bottom reflection 150 of a signal that has previously been reflected at the water-air interface, (E) a water-air interface reflection 160 of a signal similar to reflection 140, (F) a water-air interface reflection 170 of a signal similar to reflection 150, etc.

**[0009]** In contrast, if the water-bottom is deeper (i.e., not in the shallow water range), the near-field sensor detects only the up-going direct signal 120 and the water-air interface reflection 130. Figure 2 is a graph of near-field measurements (i.e., amplitude versus time) for the same air-gun. Continuous line 210 is the near-field measurement for water-bottom deeper than 150 m. Dashed line 220 corresponds to a simulated water-bottom reflection such as 140 in Figure 1. Dash double point line 230 corresponds to a simulated reflection such as 150 in Figure 1. Line 240 is the measurement acquired with the near-field sensor for water-bottom depth in the shallow

range. Line 240 is a sum of the values on lines 210, 220 and 230, and overlaps line 210 except for the time interval between 0.13 and 0.16 ms. Since the water-bottom reflections do not penetrate the seafloor, the near-field measurements in the shallow range are unsuitable for determining the signature usable in the seismic data

5 processing.

[0010] An attempt to overcome this problem has been made by including the water-bottom reflections in the propagation model (as described in "Source signature estimation – Attenuation of the seafloor reflection error in shallow water," by J-F.

Hopperstad and R. Laws, presented at EAGE 68<sup>th</sup> Conference & Exhibition, Vienna, 10 Austria 12-15 June 2006). However, this method requires precise knowledge of the water-bottom's depth and reflection coefficient over the surveyed area. These parameters with the required precision are not usually available throughout a complex surveyed area. Moreover, the water-bottom's reflection coefficient may not always be described as a scalar. Therefore, the propagation time to and from the water-bottom 15 and amplitudes of water-bottom reflections may not be evaluated correctly using this approach.

[0011] Accordingly, it would be desirable to develop methods and apparatuses for determining the signature of the signal penetrating the seafloor during seismic surveys in shallow water.

**SUMMARY**

[0012] According to some embodiments, water-bottom reflection effect is removed from near-field measurements in shallow water, to enable their use for obtaining the signature of the signal penetrating the seafloor.

5 [0013] According to an embodiment, there is a seismic data processing method. The method includes receiving near-field measurements for a plurality of shots, the near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow water surveyed area. The method further includes obtaining a far-field initial estimate from stacked primary pulses in the  
10 near-field measurements. The method also includes water-bottom reflection portions for different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific depth and being estimated using a cluster of shots among the plurality of shots, the shots in the cluster corresponding substantially to the specific depth. Then, the  
15 method includes deblending a signature of the air-gun for each shot among the plurality of shots, from the near-field measurement for the shot and using the one of the water-bottom reflection portions according to a water-bottom depth for the shot. The deblended signature is then used to process seismic data related to the shot, the seismic data being acquired with receivers.

20 [0014] According to another embodiment, there is an apparatus for processing seismic data having a user interface and a data processing unit. The user interface is configured to receive or retrieve near-field measurements for a plurality of shots, the

near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow water surveyed area. The data processing unit is configured to obtain a far-field initial estimate from stacked primary pulses in the near-field measurements, to estimate water-bottom reflection portions at different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific depth and being estimated using a cluster of shots among the plurality of shots, the shots in the cluster corresponding substantially to the specific depth, and to deblend a far-field signature of the air-gun for each shot among the plurality of shots, by subtracting the one of the water-bottom reflections according to a water-bottom depth for the shot. The deblended signature of the signal is then used to process seismic data acquired with receivers and related to the shot.

**[0015]** According to yet another embodiment, there is a computer readable medium non-transitorily storing executable codes which when executed on a computer make the computer perform a seismic data processing method. The method includes receiving near-field measurements for a plurality of shots, the near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow water surveyed area. The method further includes obtaining a far-field initial estimate from stacked primary pulses in the near-field measurements. The method also includes water-bottom reflection portions for different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific

depth and being estimated using a cluster of shots among the plurality of shots, the shots in the cluster corresponding substantially to the specific depth. Then, the method includes deblending a signature of the air-gun for each shot among the plurality of shots, from the near-field measurement for the shot and using the one of the water-bottom reflection portions according to a water-bottom depth for the shot. The deblended signature is then used to process seismic data related to the shot, the seismic data being acquired with receivers.

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

- 10 [0016] The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate one or more embodiments and, together with the description, explain these embodiments. In the drawings:
- [0017] Figure 1 is a schematic representation of signals detected by a near-field sensor in shallow water;
- 15 [0018] Figure 2 is a graph illustrating amplitude versus time recorded by a near-field sensor placed near an air-gun;
- [0019] Figure 3 is a flowchart of a method according to an embodiment;
- [0020] Figure 4 is a graph illustrating an overlap (equivalent to a stack) of near-field measurements for different shots at locations having different water-bottom depths;
- 20 [0021] Figure 5 is a graph illustrating pressure variation generated by an air-gun being fired;
- [0022] Figure 6 is a graph of amplitude versus time for comparing signal signatures in shallow water and in deep water; and

[0023] Figure 7 is a block diagram of an apparatus according to an embodiment.

### **DETAILED DESCRIPTION**

[0024] The following description of the exemplary embodiments refers to the accompanying drawings. The same reference numbers in different drawings identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims. The following embodiments are discussed, for simplicity, with regard to a marine seismic source.

[0025] Reference throughout the specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with an embodiment is included in at least one embodiment of the subject matter disclosed. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” in various places throughout the specification is not necessarily referring to the same embodiment. Further, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

[0026] The following methods and apparatuses use near-field measurements to obtain signatures in shallow water. The effect of the water-bottom reflections in shallow water on the near-field measurements is removed so that the signatures calculated thereafter are usable to process seismic data. In shallow water, a sensor (e.g., a hydrophone) placed close to an air-gun (e.g., 1-2 m above the air-gun) records a direct signal (e.g., 120 in Figure 1), a reflection (e.g., 130 in Figure 1) of the direct signal at the

water surface (i.e., water-air interface), and other reflections at the water-bottom (e.g., 140-170 in Figure 1). The direct signal and the reflection of the direct signal at the water surface form a primary pulse being stronger and arriving at the sensor earlier than the following reflections. If the contribution to the signature due to the air-gun for a shot  $i$  is calculated using the near-field sensor measurement, the result,  $sig_i$ , includes a substantially stable portion of the far-field signature  $FF$ , a shot-by-shot variation of the far-field signature  $\delta FF_i$ , a water-bottom-related portion  $WB(d_i)$  due to the water-bottom reflections (which portion depends on the water-bottom depth  $d_i$  for shot  $i$ ), and a shot variation  $\delta WB_i$  of this water-bottom-related portion:

$$sig_i = FF + \delta FF_i + WB(d_i) + \delta WB_i. \quad (1)$$

**[0027]** Magnitude of the terms added according to formula (1) have the following relationship:

$$FF > WB(d_i) \gg \delta FF_i \gg \delta WB_i. \quad (2)$$

**[0028]** Shot  $i$ 's signature of the signal (or portion of the signal due to the air-gun if the source includes plural air-guns) actually penetrating the seafloor is:

$$sig_i^* = FF + \delta FF_i. \quad (2)$$

**[0029]** If the source includes plural air-guns, the air-guns' near-field measurements are used to calculate the notional signature for each of the air-guns (notional signatures taking into consideration, for example, arrangement and interaction of the air-guns). This type of methods (subject to continuous improvement) are well-known in seismic data processing, as described, for example, in the article, "The signature of an air gun array: Computation from near-field measurements including

interactions – Practical considerations,” by Ziolkowski *et al.*, published in *Geophysics*, 48(2), 1984, pp 105-111, the entire content of which is incorporated herein by reference.

[0030] Figure 3 is a flow diagram of a method 300 deblending  $sig_i^*$  from  $sig_i$  according to an embodiment. Method 300 includes receiving near-field measurements for a plurality of shots, with the near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow-water surveyed area, at 310. Although the following description refers to a single sensor close to a single air-gun, it should be understood that near-field measurements may be recorded by plural near-field sensors associated with plural air-guns of a marine seismic source. Method 300's steps would then be applied for each of the air-guns separately, and notional signatures obtained for the air-guns would be combined to obtain source signatures for each shot.

[0031] Method 300 then includes obtaining a far-field initial estimate from stacked primary pulses in the near-field measurements at 320. Figure 4 is a graph of amplitude versus time illustrating an overlap (equivalent to a stack) of near-field measurements for different shots at locations having different water-bottom depths (between 20 m and 100 m). The primary pulses due to the direct signal (e.g., 120 in Figure 1) and a direct signal reflection at the water surface (e.g., 130 in Figure 1) occur substantially at the same time. The primary pulses' times depend on air-gun's depths, the near-field sensor's depths (the current depths at the time of the shot not the planned values) and the signal propagation velocity through water. Fluctuation of these parameters may yield small time shifts, which make a time-alignment necessary. However, up to about

0.75 ms, the near-field measurements substantially overlap independent of the different water-bottom depths. The pressure variations due to the water-bottom reflections occur at different later times after the primary pulses, depending on the water-bottom's depth, and have different phases (as seen, for example, in region 0.75-0.21 ms of the graph in Figure 4). The stacked near-field measurements are used to obtain a far-field initial estimate calculated using the average common portion (e.g., up to 0.75 ms in Figure 4).

**[0032]** Step 320 may include selecting a subset of the plurality of shots such that the selected shots have substantially the same signature, and time-aligning the primary pulses in the near-field measurements of the selected shots. During the seismic survey, the pressure variation output by the air-gun may change as a fluctuation (e.g., the air-gun occasionally operates at less than its full volume or at a lower pressure) or as a trend (e.g., the air-gun operating at lower pressure for a portion of the survey). In one embodiment, the shots used to obtain the far-field initial estimate are selected such that pressure in the air-gun has substantially the same value for the selected shots. This pressure may be measured by a sensor in the air-gun. If during the survey, the air-gun starts operating differently, then different far-field initial estimates are determined for the two (or more) operation periods.

**[0033]** In another embodiment, the shots used to obtain the far-field initial estimate are selected such that a bubble period of the air-gun for the selected shots has substantially the same value. To explain the bubble period parameter of an air-gun, a brief description of air-gun operation follows. An air-gun stores compressed air and releases it suddenly underwater when fired. The released air forms a bubble that

expands because pressure inside the bubble is initially greater than the hydrostatic pressure in the surrounding water. As the bubble expands, the air pressure decreases, eventually becoming lower than the hydrostatic pressure. The bubble then begins to contract until the air pressure again becomes greater than the hydrostatic pressure.

- 5 The process of expansion and contraction may continue through few cycles, causing a pressure variation (i.e., seismic or acoustic) signal that propagates through the water in all directions. The pressure variation generated in the water by the air-gun is illustrated in Figure 5. Between highest pressure and the following lowest pressure, there is a peak pressure variation (P-P). The high-low cycle repeats, forming a bubble pulse train.
- 10 The time T between successive pulses is the bubble period, and it may be used as a measure of air-gun stability in operation.

**[0034]** In yet another embodiment, the shots used to obtain the far-field initial estimate are selected so that shapes of the primary pulses in the near-field measurements of the selected shots to be similar. The shape similarity may be

- 15 assessed using first derivatives of the shapes or may be established if corresponding samples of two near-field measurements (i.e., from two shots) are predominantly proportional (i.e., have the same ratio).

**[0035]** Method 300 then includes estimating water-bottom reflection portions at different depths,  $WB(d_i)$  at 330. These water-bottom reflection portions are estimated

- 20 using differences,  $diff_i$ , between the near-field measurements,  $sig_i$ , and the far-field initial estimate  $FF$ :

$$diff_i = sig_i - FF = \delta FF_i + WB(d_i) + \delta WB_i. \quad (3)$$

[0036] A water-bottom reflection portion corresponding to a specific depth,  $WB(d_i)$ , is estimated using a cluster of shots corresponding substantially to the specific depth  $d_i$ . Assuming that  $\delta FF_i$  is random, it cancels out when considering the cluster of shots. Accurate knowledge of the water-bottom depth throughout the surveyed area  
 5 (attainable via bathymetry) is not required since the clustered shots are in a small window around (substantially equal to)  $d_i$ . A reasonably good estimate of the water-bottom depth for the shots would suffice.

[0037] In one embodiment, step 330 may include filtering out  $\delta FF_i$  using various known method such as predictive convolution. For a shot  $\delta FF_i$  may be identified by  
 10 focusing in the time window where the far-field signature occurs (e.g., up to 0.75 ms in Figure 4). If in this time window the far-field initial estimate is removed, the remainder would be  $\delta FF_i$ . Another method for filtering out  $\delta FF_i$  may employ deconvolving  $WB(d_i)$ , leaving only a sparse Dirac-like response, and then convolving with  $WB(d_i)$ . After filtering out  $\delta FF_i$ , and removing  $FF$  and  $WB(d_i)$ , the remaining  $\delta WB$  may also be  
 15 removed shot by shot.

[0038] Once the water-bottom reflection portions are known, the signature of a signal penetrating the seafloor is deblended for each shot at 340. The deblended signature is:

$$sig_i' = sig_i - WB(d_i) = FF + \delta FF_i + \delta WB_i \approx sig_i^* \quad (4)$$

20 [0039] Figure 6 is a graph of amplitude versus time in which continuous line 610 is  $sig_i$ , dashed line 620 is  $WB(d_i)$  and dash-point line 630 is the difference between lines 610 and line 620, thus representing  $sig_i'$ .

[0040] The steps of method 300 may be performed iteratively to enhance the shot-by-shot result.

[0041] The signature of a signal penetrating the seafloor may then be used to apply designation to seismic data acquired with receivers after each of the shots to  
5 obtain shot-by-shot impulsive responses characterizing the formation under the seafloor in the shallow-water surveyed area. These shot-by-shot impulsive responses may be used to generate images of the formation which illustrate locations of interfaces between the formation's layers.

[0042] If the seismic source includes plural air-guns, the steps of method 300 are  
10 performed for each of the air-guns. The resulting signatures of the air-guns are combined in a source signature of the total signal penetrating the seafloor in the shallow water surveyed area. The source signature is used to apply designation to the seismic data to obtain the shot-by-shot impulsive responses usable to generate images of the investigated structure under the seafloor.

[0043] An apparatus 700 capable of carrying out operations in accordance with  
15 the above-discussed methods is illustrated in Figure 7. Hardware, firmware, software or a combination thereof may be used to perform the various steps and operations described herein. Apparatus 700 may include server 701 having a central processor unit (CPU) 702 which may be coupled to a random access memory (RAM) 704 and to a  
20 read-only memory (ROM) 706. Memory 706 represents different types of storage media able to store executable codes. Thus memory 706 may be a programmable ROM (PROM), an erasable PROM (EPROM), etc. Central processor unit 702 includes

one or more processors and may be configured to communicate with various internal and external components via input/output (I/O) circuitry 708 and bussing 710 to provide control signals and the like. Server 701 may also include disk drives 712, CD-ROM drives 714, and other hardware employed for reading and/or storing data, such as a DVD, etc. In one embodiment, software for carrying out the above-discussed steps may be stored and distributed on a CD-ROM 716, removable media 718 or other form of media non-transitorily storing information. The removable media may be inserted into, and read by, devices such as the CD-ROM drive 714, disk drive 712, etc. Server 701 may be coupled to a display 720, which may be any type of known display or presentation screen, such as LCD, plasma displays, cathode ray tubes (CRT), etc. A user input interface 722 including one or more user interface mechanisms such as a mouse, keyboard, microphone, touch pad, touch screen, voice-recognition system, etc., may be provided. Server 701 may be part of a larger network configuration as in a global area network (GAN) such as the Internet 728.

**[0044]** CPU 702, which includes one or more processors, is configured (A) to obtain a far-field initial estimate from stacked time-aligned primary pulses in the near-field measurements; (B) to estimate water-bottom reflections at different depths using differences between the near-field measurements and the far-field initial estimate, with each one of the water-bottom reflections corresponding to a specific depth and being estimated using a cluster of shots among the plurality of shots, with shots in the cluster corresponding substantially to the specific depth; and (C) to deblend a signature of the

air-gun for each shot by subtracting one of the water-bottom reflections according to a water-bottom depth for the shot from the shot's near-field measurement.

**[0045]** Embodiments may be a computer program product which implements methods such as 300. Accordingly, the embodiments may take the form of an entirely  
5 hardware embodiment or a combination of hardware and software. The computer program product may be stored on a computer-readable storage medium having computer-readable instructions embodied in the medium. Any suitable computer-readable medium may be utilized, including hard disks, CD-ROMs, digital versatile discs (DVD), optical storage devices or magnetic storage devices such as floppy disk or  
10 magnetic tape. Other non-limiting examples of computer-readable media include flash-type memories or other known types of memories.

**[0046]** The disclosed exemplary embodiments provide methods and seismic data processing apparatus removing water-bottom effect from near-field measurements to obtain signature of a signal penetrating seafloor in a shallow water surveyed area. It  
15 should be understood that this description is not intended to limit the invention. On the contrary, the exemplary embodiments are intended to cover alternatives, modifications and equivalents, which are included in the spirit and scope of the invention as defined by the appended claims. Further, in the detailed description of the exemplary embodiments, numerous specific details are set forth in order to provide a  
20 comprehensive understanding of the claimed invention. However, one skilled in the art would understand that various embodiments may be practiced without such specific details.

[0047] Although the features and elements of the present exemplary embodiments are described in the embodiments in particular combinations, each feature or element can be used alone without the other features and elements of the embodiments or in various combinations with or without other features and elements disclosed herein.

[0048] This written description uses examples of the subject matter disclosed to enable any person skilled in the art to practice the same, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the subject matter is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims.

**WHAT IS CLAIMED IS:**

1. A seismic data processing method (300), comprising:

receiving (310) near-field measurements for a plurality of shots, the near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow water surveyed area;

obtaining (320) a far-field initial estimate from stacked primary pulses in the near-field measurements;

estimating (330) water-bottom reflection portions for different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific depth and being estimated using a cluster of shots among the plurality of shots, the shots in the cluster corresponding substantially to the specific depth; and

deblending (340) a signature of the air-gun for each shot among the plurality of shots, from the near-field measurement for the shot and using the one of the water-bottom reflection portions according to a water-bottom depth for the shot,

wherein the deblended signature is then used to process seismic data related to the shot, the seismic data being acquired with receivers.

2. The method of claim 1, further comprising:

obtaining shot-by-shot impulsive responses of a formation under the seafloor in the shallow water surveyed area, from the seismic data using the deblended signatures; and

generating an image of the formation based on the shot-by-shot impulsive responses, the image illustrating interfaces between layers of the formation.

3. The method of claim 1, wherein the obtaining of the far-field initial estimate

5 includes:

selecting a subset of the plurality of shots, shots in the selected subset being expected to yield substantially a same signature; and

obtaining the far-field initial estimate from time-aligned primary pulses in the near-field measurements for the shots in the subset.

10

4. The method of claim 3, wherein the selecting is performed such that a bubble period of the air-gun has substantially a same value for the shots in the subset.

5. The method of claim 3, wherein the selecting is performed such that a

15 pressure in the air-gun shortly before being firing the shot has substantially a same value for the shots in the subset.

6. The method of claim 3, wherein the shots are selected so that shapes of the primary pulses in the near-field measurements of the selected shots to be similar.

20

7. The method of claim 1, further comprising:

after estimating the water-bottom reflections, filtering out shot-by-shot far-field variations.

8. The method of claim 7, wherein the shot-by-shot far-field variations are  
5 filtered out using predictive convolution.

9. The method of claim 1, wherein the deblending is performed iteratively.

10. The method of claim 1, wherein the seismic source includes plural air-  
10 guns and the receiving, the obtaining, the estimating and the deblending are performed for each of the air-guns, the method further comprising:

calculating a source signature of the signal penetrating the seafloor in the shallow water surveyed area, using the deblended signatures of the air-guns;

applying designature to the seismic data using the source signature for obtaining  
15 impulsive responses of a formation under the seafloor in the shallow water surveyed area; and

generating an image of the formation based on the shot-by-shot impulsive responses, the image illustrating interfaces between layers of the formation.

20 11. An apparatus (700) for processing seismic data, the apparatus comprising:

a user interface (708,714, 712) configured to receive or retrieve near-field measurements for a plurality of shots, the near-field measurements being recorded using a sensor (110) placed close to an air-gun (100) of a seismic source, during a seismic survey in a shallow water surveyed area; and

5 a data processing unit (702) including one or more processors, the data processing unit being configured:

to obtain a far-field initial estimate from stacked primary pulses in the near-field measurements;

10 to estimate water-bottom reflection portions at different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific depth and being estimated using a cluster of shots among the plurality of shots, the shots in the cluster corresponding substantially to the specific depth; and

15 to deblend a far-field signature of the air-gun for each shot among the plurality of shots, by subtracting the one of the water-bottom reflections according to a water-bottom depth for the shot,

wherein the deblended signature of the signal is then used to process seismic data acquired with receivers and related to the shot.

20

12. The apparatus of claim 11, wherein the data processing unit is further configured:

to obtain shot-by-shot impulsive responses of a formation under the seafloor in the shallow water surveyed area, from the seismic data using the far-field signatures; and

to generate an image of the formation based on the shot-by-shot impulsive responses, the image illustrating interfaces between layers of the formation.

13. The apparatus of claim 11, wherein the data processing unit is configured to obtain the far-field initial estimate by:

selecting a subset of the plurality of shots, shots in the selected subset being expected to have substantially a same source signature; and

obtaining the far-field initial estimate from time-aligned primary pulses in the near-field measurements for the shots in the subset.

14. The apparatus of claim 13, wherein the data processing unit is configured to select the shots such that a bubble period of the air-gun of the air-gun has substantially a same value for the shots in the subset.

15. The apparatus of claim 13, wherein the data processing unit is configured to select the shots such that a pressure in the air-gun shortly before firing the shot has substantially a same value for the shots in the subset.

16. The apparatus of claim 13, wherein the data processing unit is further configured to select the shots such that shapes of the primary pulses in the near-field measurements of the selected shots to be similar.

5 17. The apparatus of claim 11, wherein the data processing unit is configured to filter out the shot-by-shot far-field variations using predictive convolution.

18. The apparatus of claim 11, wherein the data processing unit is configured to deblend the far-field signature iteratively.

10

19. The apparatus of claim 11, wherein the seismic source includes plural air-guns, the near-field measurements include measurements using sensors placed close to each of the air-guns, and the data processing unit is configured to obtain far-field initial estimates, to estimate water-bottom reflections and to deblend far-field signatures  
15 for each of the air-guns,

the data processing unit being further configured

to calculate a source signature of the signal penetrating the seafloor in the shallow water surveyed area using the far-field signatures of the air-guns;

to apply designature to the seismic data using the source signature for obtaining  
20 impulsive responses of a formation under the seafloor in the shallow water surveyed area; and

to generate an image of the formation based on the shot-by-shot impulsive responses, the image illustrating interfaces between layers of the formation.

20. A computer readable medium (706) non-transitorily storing executable  
5 codes which when executed on a computer make the computer perform a seismic data processing method (300) comprising:

receiving (310) near-field measurements for a plurality of shots, the near-field measurements being recorded using a sensor placed close to an air-gun of a seismic source, during a seismic survey in a shallow water surveyed area;

10 obtaining (320) a far-field initial estimate from stacked primary pulses in the near-field measurements;

estimating (330) water-bottom reflection portions for different depths using differences between the near-field measurements and the far-field initial estimate, each one of the water-bottom reflection portions corresponding to a specific depth and being  
15 estimated using a cluster of shots among the plurality of shots, shots in the cluster corresponding substantially to the specific depth; and

deblending (340) a signature of the air-gun for each shot among the plurality of shots, from the near-field measurement for the shot and using the one of the water-bottom reflection portions according to a water-bottom depth for the shot,

20 wherein the deblended signature is then used to process seismic data related to the shot, the seismic data being acquired with receivers.

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Fig. 1

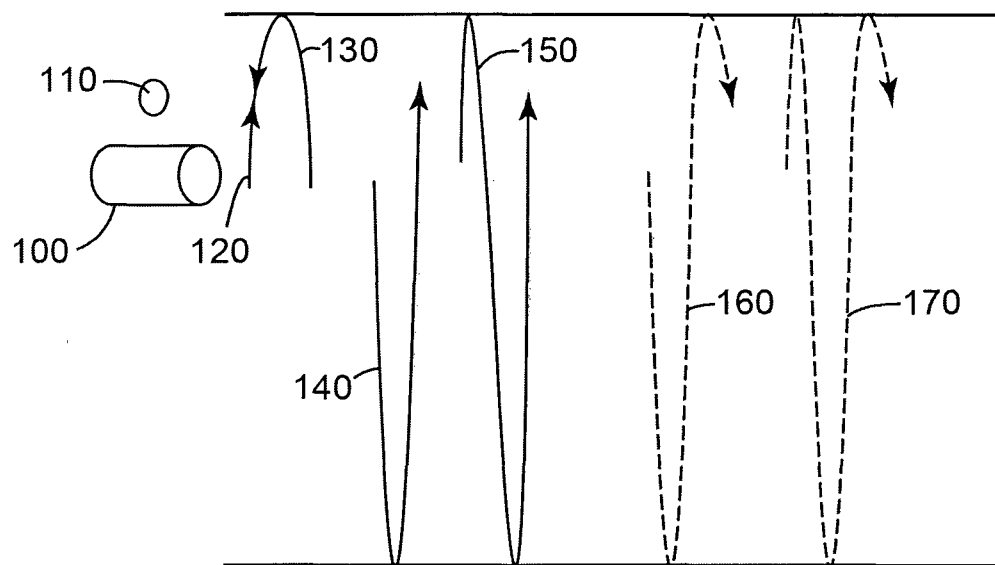
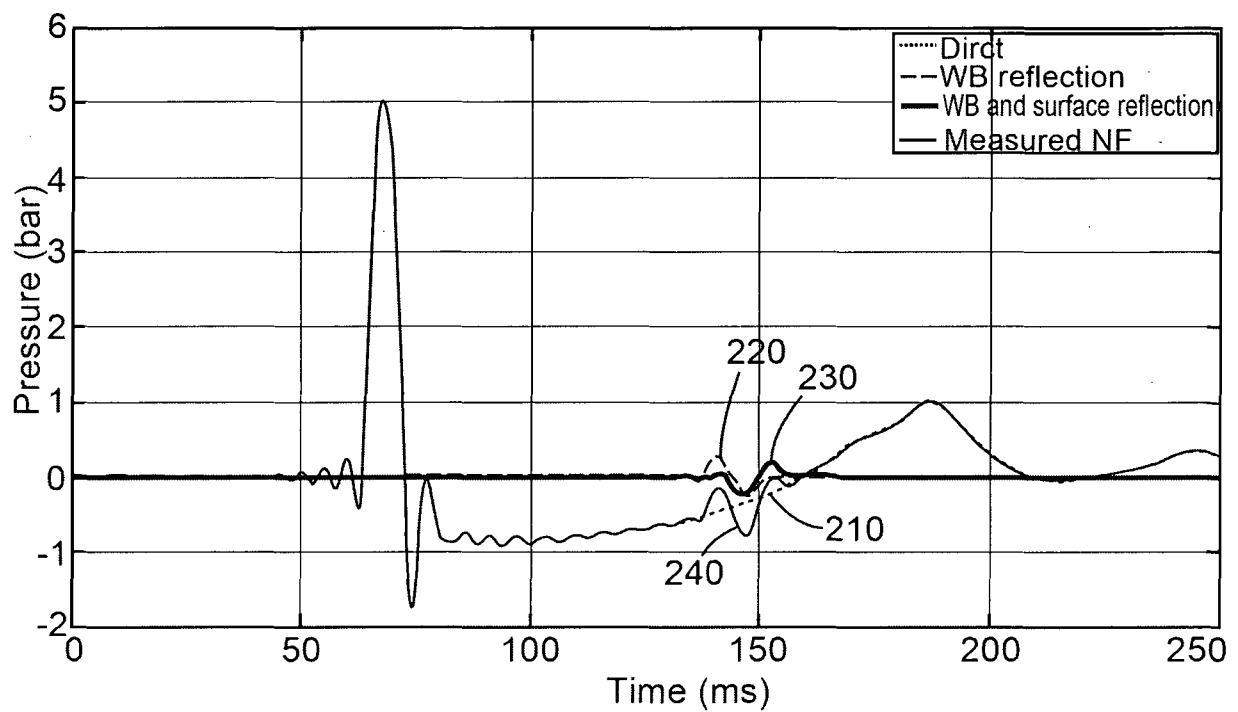


Fig. 2



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Fig. 3

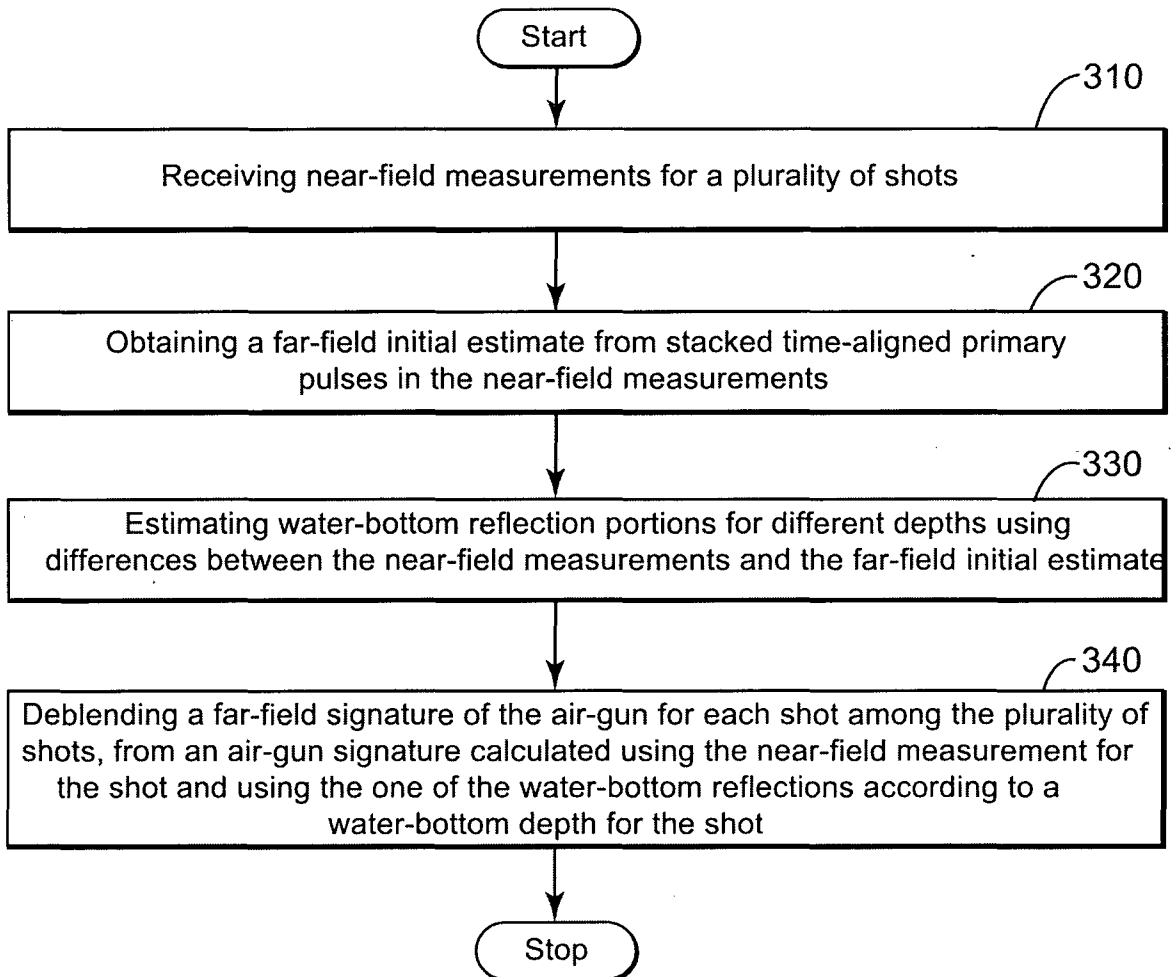
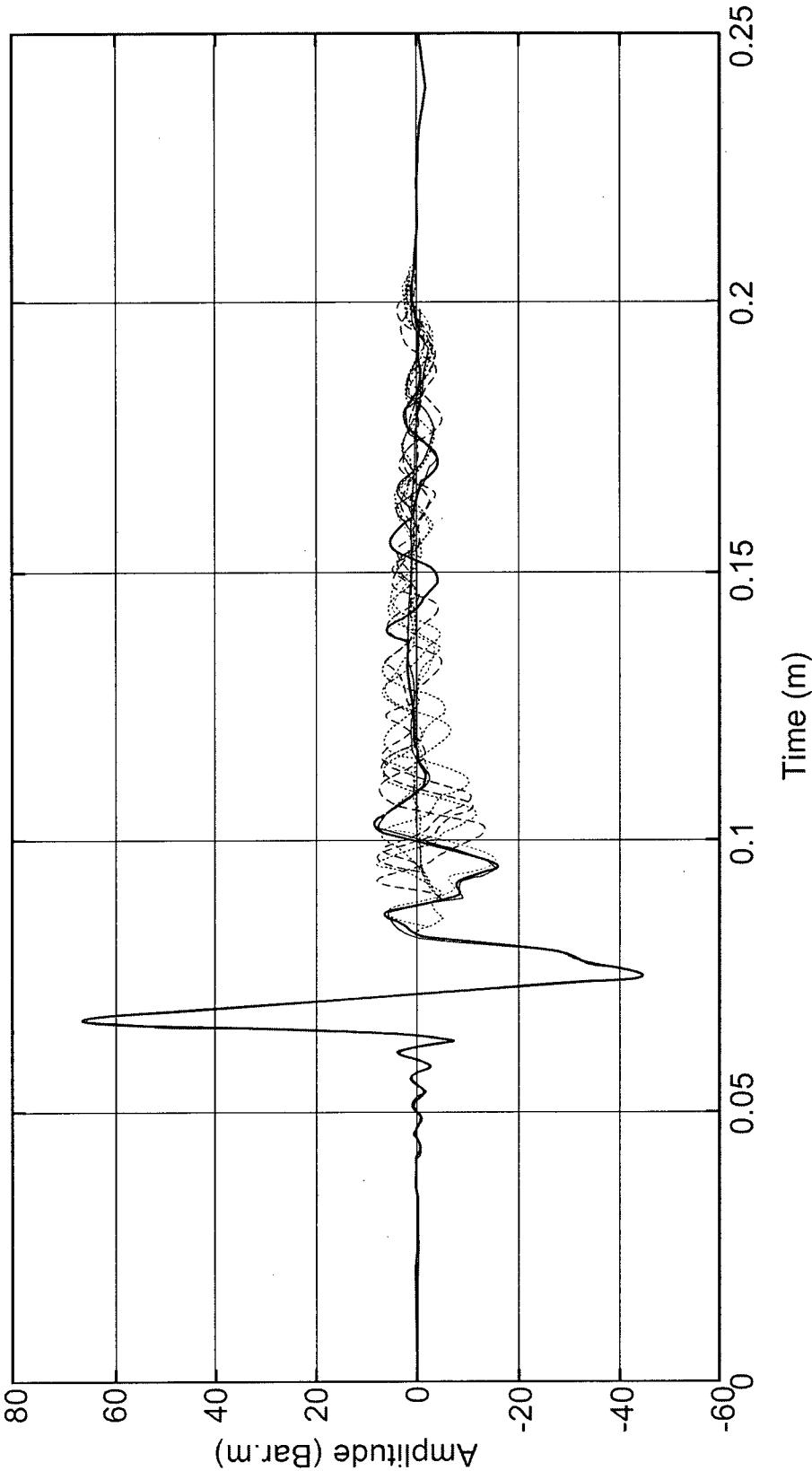
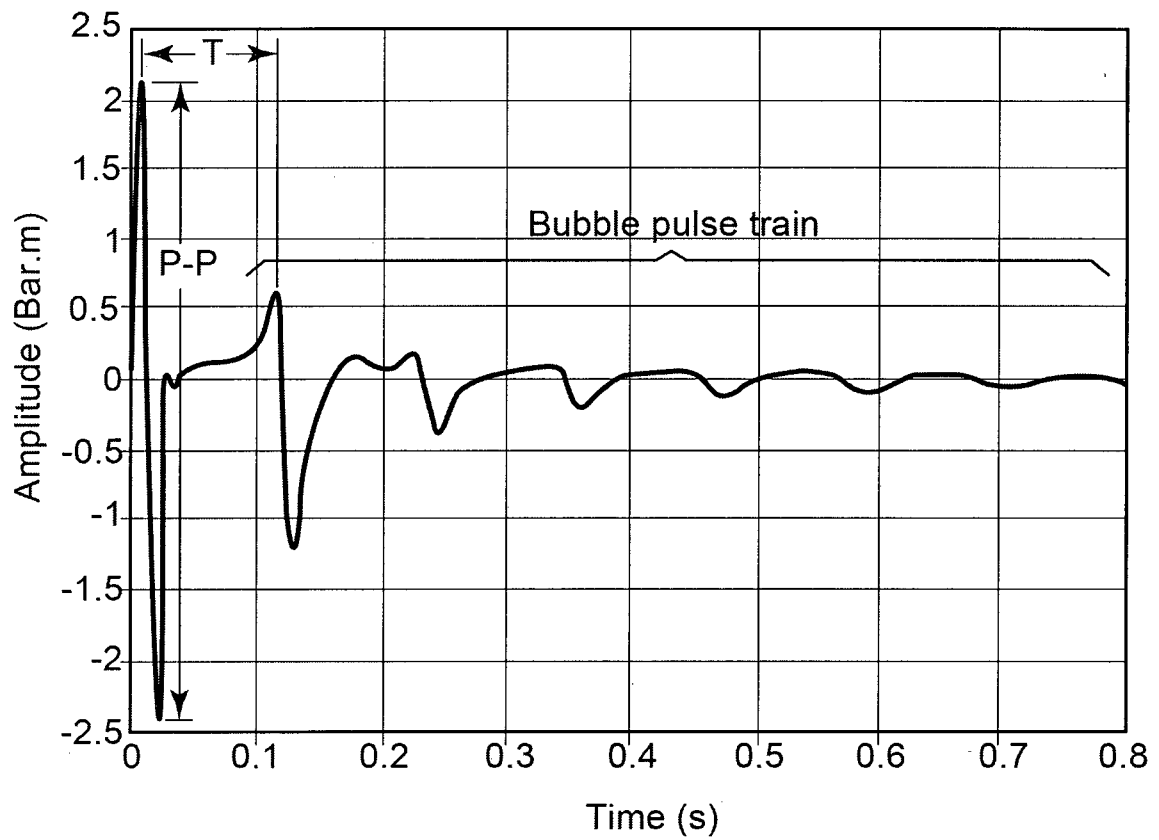
300

Fig. 4



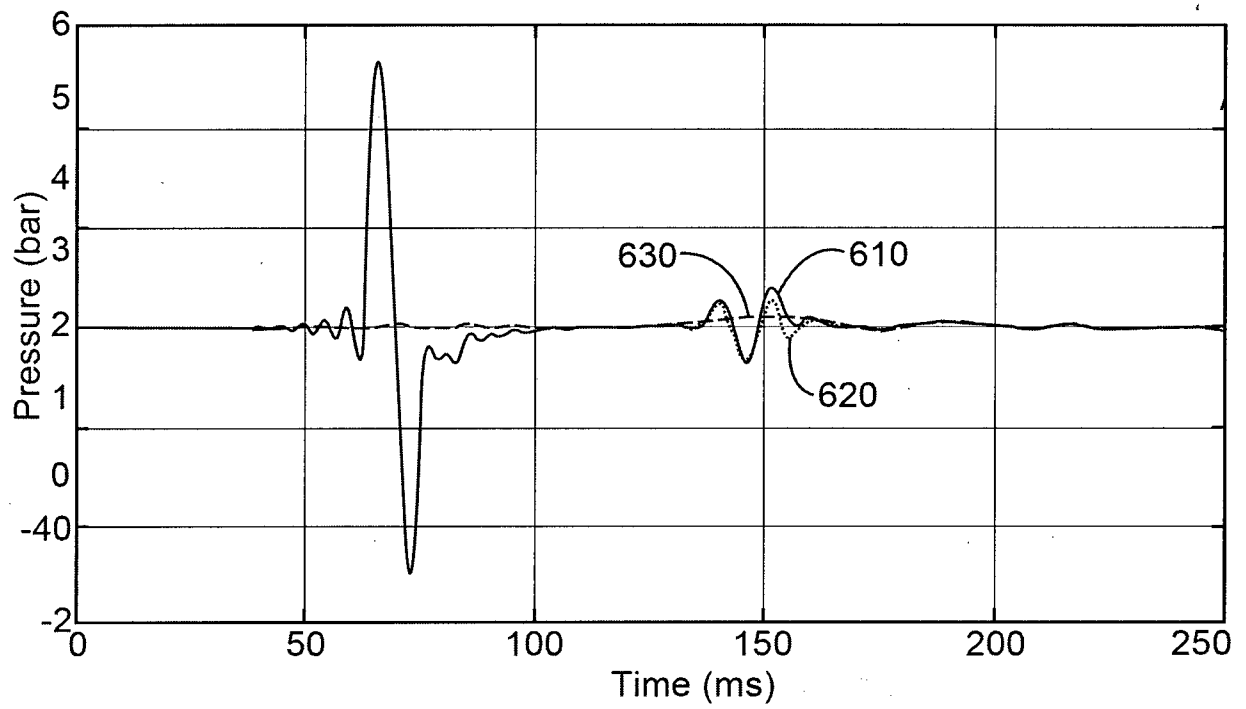
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Fig. 5



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Fig. 6



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Fig. 7

