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(74) Agent: SINGH, Karan; Schlumberger K.K., 2-2-1 Fuchinobe, Sagamihara-shi, Kanagawa-ken 229-0006 (JP).

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(71) Applicants (for all designated States except US):
SCHLUMBERGER TECHNOLOGY B.V. [NL/NL]; Parkstraat 83-89, NL-2514 JG The Hague (NL). SERVICES PETROLIERS SCHLUMBERGER [FR/FR]; 42, rue Saint-Dominique, F-7007 Paris (FR). SCHLUMBERGER SURENCO S.A. [PA/PA]; Calle Aquilino de la Guardia, 8, Panama City (PA). PETROLEUM RESEARCH AND DEVELOPMENT N.V. [NL/NL]; De Ruyterkade 62, Willemstad, Curacao (AN). SCHLUMBERGER CANADA LIMITED [CA/CA]; 525 - 3rd Avenue Southwest, Calgary, Alberta T2P OG4 (CA). SCHLUMBERGER OVERSEAS S.A. [PA/PA]; Calle Aquilino de la Guardia, 8, Panama City (PA). SCHLUMBERGER HOLDINGS LIMITED; Craigmuir Chambers, Road Town, Tortola (VG). SCHLUMBERGER OILFIELD ASSISTANCE LIMITED; Craigmuir Chambers, Road Town, Tortola (VG).

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(72) Inventor; and

(75) Inventor/Applicant (for US only): KAMATA, Masahiro

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(57) Abstract: Various techniques are described which may be used to facilitate and improve seismic exploration activities. For example, one aspect of the present invention is directed to a technique for enabling in-situ measurement of geophone response parameters. Another aspect of the present invention is directed to a technique for improving geophone calibration and for improving the accuracy of measurement of geophone response parameters. Yet another aspect of the present invention is directed to a technique for compensating geophone response output data in order to improve the accuracy of such data.



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IMPROVED GEOPHONE CALIBRATION TECHNIQUE

BACKGROUND OF THE INVENTION***FIELD OF THE INVENTION***

The present invention relates to geophones, devices for sensing vibrations in earth
5 formations. The invention may be applicable to other types of vibration transducers, either in
sensing or transmitting operation.

BACKGROUND

In seismic exploration, the vibrations in the earth resulting from a source of seismic
energy are sensed at discrete locations by sensors and the output of the sensors used to
10 determine the nature of the underground formations. The source of seismic energy can be
natural, such as earthquakes and other tectonic activity, subsidence, volcanic activity or the
like, or man-made such as acoustic noise from surface or underground operations, or from
deliberate operation of seismic sources at the surface or underground. Sensors fall into two
main categories; hydrophones which sense the pressure field resulting from a seismic source, or
15 geophones which sense vibration arising from a seismic source.

When the earth moves due to the seismic energy propagating either directly from the
source or via an underground reflector, the geophone, which can be located at the earth's
surface or on the wall of a borehole which penetrates the earth, moves in the direction of
propagation of the energy. If the axis of the geophone is aligned with the direction of motion,
20 however, the moving coils mounted on the springs inside the geophone stay in the same
position causing relative motion of the coils with respect to the housing. When the coils move
in the magnetic field, a voltage is induced in the coils which can be output as a signal. The
response of a geophone is frequency dependent.

In order to ensure proper working operation of a geophone, it is preferable to have the
25 geophone calibrated periodically or before each use. Typically, geophone manufacturers and
vendors do not perform any calibrations on their geophone units before the units are sold to
customers. Rather the manufacturers provide assurances that the specifications of geophone
units are within specified tolerance ranges at a specific temperature such as room temperature.
However, such tolerance guarantees are not a substitute for proper calibration of the geophone

units. Consequently, many purchasers of geophone units perform their own calibration tests on the purchased geophone units before deploying such units in the field.

However, conventional geophone calibration tests are often inadequate for assuring the desired precision of the geophone measurements typically demanded for many of today's seismic exploration activities. Accordingly, it will be appreciated that there exists a desire to improve upon conventional geophone calibration tests in order to improve the accuracy of seismic exploration measurements.

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SUMMARY OF THE INVENTION

Different embodiments of the present invention are directed to various methods, systems, and computer program products for calculating response parameters of a geophone configured for use in seismic exploration activities. At least one calibration test is performed on the geophone to determine values for a first portion of response parameters associated with the geophone. The first portion of response parameters may include, for example, open circuit sensitivity, damping factor, natural frequency, etc. Using information relating to the first portion of response parameters, a moving mass parameter value for the geophone may then be determined. According to one embodiment, the moving mass parameter value represents an amount of moving mass associated with the geophone.

Another aspect of the present invention is directed to a technique for modifying geophone response output information generated by a first geophone configured for use in seismic exploration activities. A transfer function for an ideal response of a second geophone is determined based upon information relating to a portion of response parameters associated with the second geophone. The portion of response parameters may include, for example, open circuit sensitivity, damping factor, natural frequency, etc. The geophone response output information generated by the first geophone may then be modified using the transfer function. According to a specific embodiment, another transfer function may be determined for the first geophone based upon information relating to a portion of response parameters associated with the first geophone. The geophone response output information generated by the first geophone may then be modified using the first and/or second transfer functions.

Yet another aspect of the present invention is directed to a technique for processing seismic exploration information generated from seismic exploration activities. A first portion of the seismic information includes geophone response output information generated by at least one geophone. A second portion of the seismic exploration information includes source signal information relating to at least one source signal used in performing the seismic exploration activities. A first portion of response parameter values associated with a first geophone is determined. In one embodiment, the first portion of response parameter values may be determined by performing at least one calibration test procedure on the geophone. Accuracy of the seismic exploration information may then be improved by modifying at least a portion of the seismic exploration information to compensate for one or more of the first portion of response parameter values.

Additional objects, features and advantages of the various aspects of the present invention will become apparent from the following description of its preferred embodiments, which description should be taken in conjunction with the accompanying drawings.

15 BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows an example of a conventional geophone 10.

Figure 2 shows a simplified electric circuit representation of the geophone of Figure 1.

Figures 3A and 3B provide examples of a step calibration test technique for measuring geophone response properties.

20 Figures 4A and 4B provide examples of an impulse calibration test technique for measuring geophone response properties.

Figure 5 provides an example of an impedance calibration test technique for measuring geophone response properties.

25 Figure 6 provides an example of a dynamic calibration test technique for measuring geophone response properties.

Figures 7A and 7B provide examples of a reciprocity calibration test technique for measuring geophone response properties.

Figure 8 shows an example of various equipment configurations which may be used for vibroseis prospecting.

30 Figure 9 shows an example of different signal paths which may flow between the various features and devices illustrated in Figure 8.

Figure 10A shows an example of an unfiltered sweep signal, which may vary in frequency (e.g., 5Hz to 50Hz) over a given time period.

Figure 10B shows an example of a simulated sweep signal after geophone filtration.

Figure 11 graphically illustrates an example of the correlation between an unfiltered (original) sweep signal 1102 and a geophone filtered sweep signal 1104.

Figure 12 shows a block diagram illustrating one embodiment of how the geophone response compensation technique of the present invention may be applied to an array of geophones which have been deployed for vibroseis prospecting operations.

Figure 13 shows a block diagram illustrating an alternate embodiment of how the geophone response compensation technique of the present invention may be applied to an array of geophones which have been deployed for vibroseis prospecting operations.

Figures 14 and 15 graphically illustrate differences between uncompensated geophone response signals and geophone response signals which have been compensated using the geophone response compensation technique of the present invention.

Figure 16 shows a schematic diagram 1600 which may be used for describing a specific embodiment of the impedance calibration test technique.

Figure 17 illustrates the real and imaginary parts of an impedance equation, as represented as a circle on a complex plane.

Figure 18 illustrates a network device 60 suitable for implementing various aspects of the geophone calibration and compensation techniques of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As described in greater detail below, the present invention provides various techniques which may be used to facilitate and improve seismic exploration activities. For example, one aspect of the present invention is directed to a technique for enabling in-situ measurement of geophone response parameters. Another aspect of the present invention is directed to a technique for improving geophone calibration and for improving the accuracy of measurement of geophone response parameters. Yet another aspect of the present invention is directed to a technique for compensating geophone response output data in order to improve the accuracy of such data.

In order to gain a better understanding the various techniques and features described in this application, a brief description of geophone measurement techniques will now be described.

A seismic survey measures seismic waves propagated through the earth to map structural images in the earth. Geophones are often used to detect seismic signals at various locations, such as, for example, down holes, ground surfaces and/or seabeds. An example of a conventional geophone is shown in Figure 1. The geophone 10 of Figure 1 includes moving coils 12, 13 mounted on a bobbin 14, a magnet 15, a pair of pole pieces 16, 18 with suspension springs 20, 22 and a housing 24 as shown in FIG. 1. The pole pieces 16, 18 and housing 24 are made of magnetically permeable material and form a magnetic field in which the moving coils 12, 13 are suspended. In the example of Figure 1, the moving coils 12, 13, bobbin 14, and suspension springs 20, 22 collectively form the effective moving mass portion (m) of the geophone. As used in this application, the term "geophone" includes conventional-type geophones such as that illustrated in Figure 1, as well as geophone accelerometer (GAC) devices which, for example, may be configured or designed to measure relatively wider acceleration ranges than conventional-type geophones.

As shown in the embodiment of Figure 1, the geophone 10 includes a moving mass of coil suspended in a magnetic flux by means of a spring or a pair of springs. The moving coil tries to stay in the same position while the housing of magnetic circuit is moved in response to external vibrations. Figure 2 shows a simplified illustration of the geophone of Figure 1.. As illustrated in Figure 2, a moving coil 202 generates a voltage e_g in response to external vibration. The coil has an associated DC resistance r . The geophone output is shorted by R to provide a desired damping factor.

The geophone response is usually defined by its associated response properties, such as, for example, its natural frequency, damping factor, sensitivity and DC resistance of coil at room temperature. An example of traditional geophone response properties may be expressed by the following equations (1)-(6). For purposes of illustration, it is assumed that the geophone responds to sinusoidal earth accelerations. Thus, for example, the earth accelerations expressed by

$$\alpha = a \sin(\omega t), \quad (1)$$

and the geophone response may be characterized by

$$e_g = A(\omega) \sin(\omega t - \varphi) \quad (2)$$

where

$$A(\omega) = \frac{a\omega S_0 \left(\frac{\omega}{\omega_0}\right)^2}{\sqrt{\left\{1 - \left(\frac{\omega}{\omega_0}\right)^2\right\}^2 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2}} \quad (3)$$

$$\tan \varphi = \frac{1 - \left(\frac{\omega}{\omega_0}\right)^2}{2\zeta \frac{\omega}{\omega_0}} \quad (4)$$

$$\zeta = \zeta_0 + \frac{S_0^2}{2(r+R)m\omega_0} \quad (5)$$

5 $S = S_0 \frac{R}{r+R} \quad (6)$

and where:

e_g corresponds to generated voltage,

S_0 corresponds to open circuit sensitivity,

S corresponds to total sensitivity,

10 ζ_0 corresponds to open circuit damping,

ζ corresponds to total damping,

ω_0 corresponds to natural frequency = $2\pi f_0$,

r corresponds to DC resistance,

S corresponds to shunt resistance,

15 m corresponds to effective moving mass.

VIBROSEIS

In the acquisition of seismic data, seismic waves are used to interpret subsurface geological formations. One type of geophysical prospecting technique is generally known as "vibroseis" prospecting or simply vibroseis. Vibroseis employs a seismic vibroseis source used to generate a controlled wavetrain that propagates through the earth or water to be detected by seismic detectors (e.g., geophones).

20

Figure 8 shows an example of various equipment configurations which may be used for vibroseis prospecting. As shown in the example of Figure 8, surface acquisition of seismic data

may be performed using a surface vibroseis source 812. Typically, surface vibroseis sources emit an energized wavefield over a selected time period known as sweep time. Seismic detectors (e.g., surface acquisition geophones 806a, downhole acquisition geophones 806b) detect earth movements during the sweep time period and during an additional time period commonly referred to as listen time. Typically, the energization takes the form of a sinusoidal wavefield of continuously varying frequency applied to the earth or a body of water during a sweep time lasting from about two to about 20 seconds or even more. For marine acquisition of seismic data, marine air gun seismic sources are generally used to generate the source signal, which typically includes a single pulse having multiple frequencies.

In seismic acquisitions which utilize a vibrator 812 such as that illustrated in Figure 8, a pilot sweep signal drives the vibrator, causing the vibrator to inject acoustic signals into the earth in accordance with the pilot sweep signal. The geophones (806a, 806b) on the earth surface and/or downhole pick up signals propagated through the earth as shown in Figure 8. The signals detected by the geophones are filtered by the geophone transfer function described by Equations (1) and (2) above. The recorded signals are then correlated with the pilot sweep signal(s) (802a, 802b) which are fed directly to the seismic recorders (e.g., surface seismic recorder 804a, downhole seismic recorder 804b).

Figure 9 shows an example of different signal paths which may flow between the various features and devices illustrated in Figure 8. For purposes of illustration, an example of a vibroseis cross-correlation technique will now be described by way of example with reference to Figures 9, 10A, 10B, and 11.

Figure 10A shows an example of an unfiltered sweep signal, which may vary in frequency (e.g., 5Hz to 50Hz) over a given time period. As illustrated in Figure 9, the unfiltered electronic sweep signal may be fed to vibrator 902 and cross-correlation unit 912. According to one implementation, the vibrator 902 uses the electronic sweep signal to produce corresponding seismic vibrations in the earth formation 904. These vibrations are detected by geophone 910, which produces a filtered output geophone response signal. Figure 10B shows an example of a simulated sweep signal after geophone filtration. In the example of Figure 10B, the signal is filtered by a 10Hz geophone with 70% damping.

The cross-correlation unit 912 comparison the unfiltered pilot sweep signal with the geophone filtered sweep signal. Figure 11 graphically illustrates an example of the correlation between the unfiltered (i.e., original or source) sweep signal 1102 and the geophone filtered

sweep signal 1104. As illustrated in Figure 11, the correlated results are no longer zero phase for various ranges of sweep signal frequencies, such as, for example, from 10Hz to 100Hz and from 5Hz to 50Hz.

GEOPHONE RESPONSE CHARACTERISTICS AND CALIBRATION

5 Geophone manufacturers typically supply geophones with nominal response properties at room temperature, and provide assurances that the response properties are within specified tolerance ranges. For example, a manufacturer may specify that the tolerance ranges at room temperature may be, for example, +/-5% for natural frequency, open circuit sensitivity, open circuit damping and DC resistance. However, tests performed by the present inventive entity
10 have shown that 5% errors in the geophone response properties can result in amplitude measurement errors of 15% or more.

In order to process seismic signals with sufficient high fidelity to be able to extract precise information, it is preferable to calibrate the geophone prior to use, and to compensate for geophone response properties by adjusting, for example, data produced from the geophone
15 response to take into account geophone calibration and/or response properties.

Traditionally, geophone calibration is accomplished by performing one or more tests on the geophone in order to determine the geophone's response properties, namely natural frequency, damping factor, sensitivity and DC resistance. Typically, the geophone's DC resistance (r) of the moving coil is measured using a multimeter. The natural frequency, damping factor, and sensitivity characteristics of the geophone may be measured using different
20 measurement or testing techniques such as, for example, step calibration test techniques, impulse calibration test techniques, impedance calibration test techniques or dynamic calibration test techniques. The sensitivity characteristics of the geophone may also be measured using a reciprocity calibration test technique. Each of these different measurement
25 techniques is described below.

Step Calibration Test Technique

An example of a step calibration test technique for measuring geophone response properties may be illustrated with reference to Figures 3A and 3B. Figure 3A shows a simplified schematic of a geophone 300. According to one embodiment of the step calibration
30 test technique, a voltage may be applied at E_0 to dislocate the moving coil 310 from its neutral position. The voltage applied at E_0 is then released (e.g., at time T_0), and the geophone

responds according to its natural vibration. The natural vibration is measured as the response signal from the output of the geophone. This is illustrated, for example, in Figure 3B of the drawings, which graphically illustrates the step test input voltage 352 (at E_0) and the geophone output signal 354. Using the step test, sensitivity, natural frequency and damping factor characteristics of the geophone may be calculated based on a given set of initial parameters, including the value of E_0 , the DC resistance of the moving coil, and the amount of moving mass of the geophone.

Impulse Calibration Test Technique

An example of an impulse calibration test technique for measuring geophone response properties may be illustrated with reference to Figures 4A and 4B. Figure 4A shows a simplified schematic of a geophone 400. According to one embodiment of the impulse calibration test technique an impulse test signal is input to the geophone at 402. An example of the impulse test signal is represented by signal line 452 of Figure 4B. Ranges for portions of the geophone response output signal 454 (e.g., a_1 , a_2 , T) are pre-calculated for sensitivity, damping and natural frequency based on stated tolerances of the geophone response properties. The impulse test signal may be applied at time T_0 , and the geophone response for a_1 , a_2 and T may then be measured to see if the geophone the response properties are within their stated tolerance ranges. Typically, the impulse calibration test technique is not used for calibrating the geophone, but rather is typically used to verify that the geophone response properties are within their stated tolerance ranges.

Impedance Calibration Test Technique

An example of an impedance calibration test technique for measuring geophone response properties may be illustrated with reference to Figure 5 of the drawings. According to one embodiment of the impedance calibration test technique, input signal(s) (e.g., sinusoidal signals) are applied at 504 and output voltages e_1 and e_2 are measured as shown in Figure 5. The impedance at the measurement frequency may be derived in accordance with the following equation:

$$Z = \frac{e_2}{i} = \frac{e_2 R}{e_1} \quad (7)$$

In Equation 7 above, the electric signal applied to the coil is represented by e_2 . The current which flows into the coil may be determined by e_1 and R .

The impedance of a geophone may be expressed as:

$$Z(\omega) = r + \frac{S_g^2}{m} \frac{j\omega}{(\omega^2 - \omega_0^2) + 2jD_0\omega_0\omega} \quad (8)$$

Calculation of impedance utilizes at least two measurements at the frequencies ω_1 and ω_2 .

The natural frequency (ω_0), damping factor (ζ_0) and sensitivity (S_0) may be calculated according to:

$$\omega_0 = \sqrt{\frac{(A \cdot \omega_1 - \omega_2)\omega_1\omega_2}{A \cdot \omega_2 - \omega_1}} \quad (9)$$

$$f_0 = \frac{1}{2\pi} \cdot \omega_0 \quad (10)$$

$$\zeta_0 = \frac{(\omega_0^2 - \omega_1^2)(\text{Re}(Z(\omega_1)) - R_c)}{2\omega_0\omega_1 \text{Im}(Z(\omega_1))} \quad (11)$$

$$S_g = \sqrt{\frac{m \text{Im}\{Z(\omega_1)\} \left\{ (\omega_0^2 - \omega_1^2)^2 + 4\zeta_0^2 \omega_0^2 \omega_1^2 \right\}}{(\omega_0^2 - \omega_1^2)\omega_1}} \quad (12)$$

where,

$$A = \frac{\frac{\text{Re}(Z(\omega_1)) - r}{\text{Im}(Z(\omega_1))}}{\frac{\text{Re}(Z(\omega_2)) - r}{\text{Im}(Z(\omega_2))}} \quad (13)$$

and where:

f_0 corresponds to natural frequency [Hz],

ζ_0 corresponds to open-circuit damping factor,

S_g corresponds to open-circuit sensitivity derived from nominal moving mass [V/m/s],

ω_1 corresponds to angular frequency of f_1 ,

ω_2 corresponds to angular frequency of f_2 ,
Re(Z) corresponds to impedance real part,
Im(Z) corresponds to impedance imaginary part,
 r corresponds to coil resistance [Ω],

5 m corresponds to geophone moving mass [kg].

It will be appreciated that calculation of the geophone response properties using the above-described impedance calibration test technique relies upon utilizing a known value for the amount of moving mass (m) of the geophone. Typically, this known value for m
10 corresponds to the nominal value of the moving mass which is provided by the manufacturer.

Dynamic Calibration Test Technique

An example of a dynamic calibration test technique for measuring geophone response properties may be illustrated with reference to Figure 6 of the drawings.

According to one embodiment of the dynamic calibration test technique, a calibrated
15 reference sensor 604 and one or more geophones 602 to be calibrated are positioned on top of a shaking device 606, as illustrated, for example, in Figure 6. The geophone(s) 602 and reference sensor 604 are then shaken (e.g., in a vertical direction of excitation) using shaking device 606. The geophone response properties may then be determined by comparing the geophone response output to the reference sensor output. For example, since the phase and amplitude
20 response are known from the reference sensor measurements, the natural frequency and damping factor of the subject geophone may be determined from the transfer function between the two.

It will be appreciated that the relative accuracy of the dynamic calibration test technique depends upon the accuracy of calibration of the reference sensor and the response of the
25 reference sensor. Typically, the reference sensor 604 is calibrated by a third party which is associated with some type of entity for measurement standards.

The embodiment of Figure 6 illustrates one implementation of the dynamic calibration test using a vertical configuration. According to an alternate implementation of the present invention, the dynamic calibration test may also be performed using a horizontal configuration.
30 In such an embodiment, the geophone(s), reference sensor and shaker device assembly may be positioned horizontally, and excitation applied in a horizontal direction.

According to at least one embodiment, the geophone(s), reference sensor and shaker device may be enclosed in a housing which, for example, may be made with iron, steel, and/or materials which help to prevent magnetic coupling between the shaker and the geophones.

According to a specific implementation of the dynamic calibration test technique, the reference sensor 604 may correspond to a reference geophone in which the moving mass of the reference geophone has been substantially accurately measured and/or determined. Various techniques for accurately measuring a geophone's moving mass are described in greater detail below.

Reciprocity Calibration Test Technique

10 An example of a reciprocity calibration test technique for measuring geophone response properties may be illustrated with reference to Figures 7A and 7B.

According to one embodiment, the reciprocity calibration test technique may be used to determine the sensitivity of multiple geophones in situations where no reference sensor is used.

For example, as shown in the embodiment of Figure 7A, three uncalibrated geophones (Ga, Gb, Gc) are mounted on a block 710. A sinusoidal electric signal e_0 is then input into one of the geophones (Ga), which causes excitation of the geophone Ga in the direction indicated. This excitation results in the shaking of block 710, and consequently results in the shaking of geophones Gb and Gc..

15 In open circuit conditions, the responses output signals of geophones Gb and Gc (namely e_{ab} and e_{ac}) may be expressed as a function of input signal voltage and geophone impedances as shown below:

$$e_{ab} = \frac{S_a e_0}{M_s \text{abs}\{Z_a(\omega)\}} \frac{\omega}{\sqrt{(\omega_a^2 - \omega^2)^2 + (2D_a \omega_a \omega)^2}} \frac{S_b \omega^2}{\sqrt{(\omega_b^2 - \omega^2)^2 + (2D_b \omega_b \omega)^2}} \quad (14)$$

$$e_{ac} = \frac{S_a e_0}{M_s \text{abs}\{Z_a(\omega)\}} \frac{\omega}{\sqrt{(\omega_a^2 - \omega^2)^2 + (2D_a \omega_a \omega)^2}} \frac{S_c \omega^2}{\sqrt{(\omega_c^2 - \omega^2)^2 + (2D_c \omega_c \omega)^2}}$$

where M is the mass of block with three geophones.

Another sinusoidal electric signal is then input into geophone Gb to thereby shake geophone Gc along with block 710 (as illustrated, for example, in Figure 7B).

The response of geophone Gc (e_{bc}) may then be expressed by:

$$e_{bc} = \frac{S_b e_0}{M_s \text{abs}\{Z_a(\omega)\}} \frac{\omega}{\sqrt{(\omega_b^2 - \omega^2)^2 + (2D_b \omega_b \omega)^2}} \frac{S_c \omega^2}{\sqrt{(\omega_c^2 - \omega^2)^2 + (2D_c \omega_c \omega)^2}} \quad (15)$$

The absolute sensitivities of three geophones may be determined by solving the equations below:

$$\begin{aligned}
 S_a &= \sqrt{\frac{e_{ab}e_{ac}}{e_{bc}e_0} M_s \frac{\{Z_a(\omega)\}^2 (\omega_a^2 - \omega^2)^2 + (2D_a \omega_a \omega)^2}{\{Z_b(\omega)\} \omega^3}} \\
 S_b &= \sqrt{\frac{e_{ab}e_{bc}}{e_{ac}e_0} M_s \{Z_b(\omega)\} \frac{(\omega_b^2 - \omega^2)^2 + (2D_b \omega_b \omega)^2}{\omega^3}} \\
 S_c &= \sqrt{\frac{e_{ac}e_{bc}}{e_{ab}e_0} M_s \{Z_b(\omega)\} \frac{(\omega_c^2 - \omega^2)^2 + (2D_c \omega_c \omega)^2}{\omega^3}}
 \end{aligned} \tag{16}$$

5

The embodiment of Figures 7A-7B illustrate one implementation of the reciprocity calibration test using a horizontal configuration. According to an alternate implementation of the present invention, the reciprocity calibration test may also be performed using a vertical configuration. In such an embodiment, the geophones may be positioned vertically, and excitation applied in a vertical direction.

10

Additional details relating to the reciprocity calibration test technique may be found in the reference "The Reciprocity Calibration of Piezoelectric Accelerometers," by Mark Harrison, A.O. Sykers, and Paul G. Marcotte, THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, Volume 24, Number 4, July, 1952, herein incorporated by reference in its entirety for all purposes.

15

A detailed description of various embodiments of the reciprocity calibration test technique for geophone calibration is described in U.S. patent No. 5,644,067 to Gabrielson, entitled "APPARATUS AND METHOD FOR CALIBRATION OF SENSING TRANSDUCERS", the entirety of which is incorporated herein by reference for all purposes.

20 ***OTHER FACTORS AFFECTING GEOPHONE CALIBRATION***

Research conducted by the present inventive entity has revealed that geophone response measurements are dependent not only upon its internal response properties, but also upon external factors such as, for example, temperature and tilt of the geophone. For example, the DC resistance (r) of the geophone is a function of temperature, and the geophone response is also a function of temperature. More specifically, by considering the electric circuit shown in Figure 2, the geophone's sensitivity may be affected by the change in coil resistance r as shown

25

by Equation 6 (above). The open circuit sensitivity may also be reduced by the temperature as shown, for example, in Figure 7. Temperature also affects the open circuit damping characteristics. Geophone response may also be affected by its tilt. Additionally, if a geophone is used under tilt, the displacement of the internal springs may change the geophone's natural
5 frequency.

Moving Mass Issues

In addition to the above-described factors which may affect geophone response measurements and/or response properties, it will be appreciated that many of the above-described geophone calibration and geophone response property test techniques are dependent
10 upon utilizing known values for various geophone properties in order to determine values for unknown geophone properties. For example, as described previously, at least a portion of the above-described geophone calibration test techniques and geophone response property test techniques rely upon using a pre-known value for the amount of moving mass (m) of the geophone. As described previously with respect to Figure 1, moving coils 12, 13, bobbin 14,
15 and suspension springs 20, 22 collectively form the moving mass portion (m) of the geophone 10. Typically, the value for m corresponds to the nominal value of the moving mass which is provided by the manufacturer. One technique which may be used by manufacturers for determining the geophone moving mass value is to compute the moving mass value by adding together estimated or average mass values of the each of the individual components (e.g.,
20 moving coil, bobbin, suspension springs) which collectively form the moving mass.

Because geophone manufacturers typically provide values for nominal geophone response properties, and provide assurances that the response properties are within specified tolerance ranges, it is common practice in the industry, when performing geophone calibration tests, to rely upon the nominal value of the moving mass which is provided by the manufacturer.
25 Moreover, precise calculation of the geophone moving mass value is extremely difficult to ascertain. One reason for this is that the moving mass is comprised of several different (and sensitive) components within the geophone which are typically inaccessible to the user. Another reason is that it is difficult to determine the precise portion of moving suspension spring mass which contributes to the geophone moving mass value.

Moreover, there has conventionally been no need or desire to perform independent
30 measurements of geophone moving mass values since, conventionally, there has been no recognition in the industry of the possibility that errors in geophone moving mass values may

significantly contribute to errors in geophone calibration and/or geophone response characteristics. As a result, there has been no motivation to one having ordinary skill in the relevant art to measure the geophone moving mass value to a degree of precision which is greater than that of the nominal value provided by the manufacturer.

5 Contrary to conventional wisdom, however, the present inventive entity has discovered that errors in the geophones nominal moving mass values, may, in fact, significantly contribute to errors in geophone calibration and/or geophone response characteristics. Accordingly, one technique for improving geophone calibration measurements and/or geophone response compensation techniques is to perform an accurate measurement of the geophone moving mass
10 properties. According to at least one embodiment of the present invention, the amount of moving mass may be measured and used to determine and/or compensate for various geophone response characteristics. In one implementation, the measured amount of moving mass may be used to more accurately determine the geophone response properties (such as, for example, natural frequency, damping factor, sensitivity, etc.) using, for example, one or more of the
15 geophone response property test techniques.

 According to a specific embodiment of the present invention, one technique for improving geophone calibration measurements and/or geophone response compensation techniques is to determine the moving mass by measuring the mass of the moving coil, bobbin, and suspension springs before fabrication of a geophone, and stamp the determined moving
20 mass value on the geophone. In this way, the actual moving mass value for each geophone may be ascertained and used for subsequent operations. This technique differs from conventional techniques which use the manufacturer's estimated or nominal value of the moving mass. Moreover, by using a more precise moving mass value, greater precision of the geophone response parameters may also be obtained, for example, using the impedance method described
25 by Equations 9, 11, and 12.

 According to an alternate embodiment of the present invention, another technique which may be used for determining the amount of moving mass of a geophone is to calculate the geophone's moving mass value using at least a portion of the geophone's response parameter values which have been determined using one or more of the above-described
30 geophone response property test techniques. For example, according to one implementation, the moving mass value may be calculated using measured or calculated values for the

geophone's damping factor, natural frequency, and open circuit sensitivity, as described in the equations below:

$$m_0 = \frac{S_g^2 (\omega_0^2 - \omega_1^2) \omega_1}{\text{Im}(Z(\omega_1)) [(\omega_0^2 - \omega_1^2)^2 + 4\zeta_0^2 \omega_0^2 \omega_1^2]} \quad (17a)$$

or

$$5 \quad m_0 = m \left(\frac{S_g}{S_0} \right)^2 \quad (17b)$$

where:

m_0 corresponds to absolute moving mass

ζ_0 corresponds to open-circuit damping factor,

S_0 corresponds to open-circuit sensitivity,

10 S_g corresponds to open-circuit sensitivity ,

ω_1 corresponds to angular frequency of a first measurement,

$\text{Im}(Z)$ corresponds to impedance imaginary part,

ω_0 corresponds to natural frequency.

15 In one implementation, the geophone's open circuit sensitivity may be determined, for example, by measurement and/or by using the dynamic calibration test technique. The geophone's damping factor and natural frequency may be determined, for example, using the impedance calibration test technique. According to different embodiments, for measurements involving the dynamic calibration test technique, response parameter values for the reference
20 sensor or reference geophone may be obtained using a variety of different techniques, such as, for example, by (1) fabricating a reference geophone by measuring the moving mass, (e.g., by weighing the moving coil and recording the moving mass value before fabrication of the reference sensor), (2) using a reference sensor which conforms with a public measurement standard such as, for example, The National Research Laboratory of Metrology of Japan
25 (<http://www.nrlm.go.jp/english/>), (3) using the reciprocity calibration test technique, etc.

According to at least one implementation, the moving mass value is a constant which does not change with varying temperature or tilt of the geophone. Thus, once the moving mass is known, a geophone can be tested in-situ any time using one or more of the above-described techniques. Additionally, it will be appreciated that the technique of the present invention

allows for improved accuracy of geophone calibration, which may be performed in-situ or before field employment.

Geophone Response Compensation

It will be appreciated that the technique of the present invention may be used to more precisely quantify the geophone response parameters, such as, for example, sensitivity, damping, and/or natural frequency. For example, by using a more precise, calculated moving mass value, the impedance test may be used to more precisely quantify the geophone response parameters, such as, for example, open circuit sensitivity, open circuit damping, and/or natural frequency. Consequently, the improved accuracy of the geophone response parameters not only allows the geophone to be calibrated with greater precision, but also allows for greater accuracy of geophone response compensation techniques.

According to various embodiments of the present invention, a variety of different geophone response compensation techniques may be used to achieve greater accuracy of the geophone response characteristics and/or measurements. For example, in at least one implementation, geophone response parameters values (which, for example, may be determined during geophone calibration) are used to compensate and/or transform the geophone response output signal(s) in a manner which provides greater accuracy and/or better approximates ideal geophone response characteristics. According to different embodiments, such ideal geophone response characteristics may include, for example, geophone response signals which exhibit zero phase characteristics, geophone response signals which exhibit symmetry characteristics, etc.

According to a specific embodiment of the present invention, a transfer function may be used to transform geophone response output signal(s) in a manner which better approximates ideal geophone response characteristics. In one implementation, the transfer function may be derived using information relating to the geophone response parameter values. Since the transfer function of an ideal geophone response is also known (e.g., for a geophone with the following properties: natural frequency = 10 Hz, open circuit sensitivity = 30 V/m/s, open circuit damping = 0.4, DC resistance = 375 ohm, effective moving mass = 10 gram), it is then possible to transfer or transform the geophone's response signals to the ideal geophone response. An example transformation may be implemented using the following equation:

$$Sig_n = ifft \left\{ fft(Sig_m) * \frac{H(f_n, \zeta_n, S_n, DRC_n)}{H(f_m, \zeta_m, S_m, DRC_m)} \right\} \quad (18)$$

where:

H corresponds to transfer function of a geophone,

f_n corresponds to nominal natural frequency (e.g., 10Hz),

ζ_n corresponds to nominal damping factor (e.g., 0.7),

5 S_n corresponds to nominal sensitivity,

DCR_n corresponds to nominal DC resistance (DCR) at which nominal response parameters are specified,

f_m corresponds to measured natural frequency in working environment,

ζ_m corresponds to measured damping factor in working environment,

10 S_m corresponds to measured damping factor in working environment,

DCR_m corresponds to measured DCR at which a geophone measures seismic signals,

Sig_n corresponds to compensated signal,

Sig_m corresponds to measured signal in working condition.

15 According to different embodiments, the geophone response compensation technique of the present invention may be applied to individual geophones as well as an array of geophones. For example, in one implementation, the geophone response compensation technique of the present invention may be applied to an array of geophones using, for example, the moving mass value which represents the average moving mass value of the geophone array. Moreover, even
 20 in situations where it is determined that selected geophones are out of tolerance, the geophone response compensation technique of the present invention may be used to compensate the output data from the out of tolerance geophones in order to transform such data into a valid, usable data.

Geophone Response Compensation for Vibroseis

25 Figure 11 graphically illustrates that vibroseis correlation with geophone output response signals is not zero phase. However, in accordance with at least one embodiment of the present invention, at least one geophone transfer function may be applied to the digitized pilot signal sweep in order to achieve geophone response compensation for vibroseis measurements. This is illustrated, for example, in Figures 12-15 of the drawings.

30 Figure 12 shows a block diagram illustrating one embodiment of how the geophone response compensation technique of the present invention may be applied to an array of geophones which have been deployed for vibroseis prospecting operations. In this example, it

is assumed that an average or nominal geophone response transfer function is applied to the pilot signal to produce a modified pilot signal which may then be correlated with one or more geophone response output signals. In the example illustrated in Figure 12, geophone compensation operations may be implemented at the geophone compensation block 1202 by applying, for example, the following equation:

$$Sig_n = \text{ifft} \{ \text{fft} (Sig_m) * H(f_n, \zeta_n, S_n, DCR_n) \} \quad (19)$$

where:

H corresponds to transfer function of a geophone,

f_n corresponds to nominal natural frequency (e.g., 10Hz),

10 ζ_n corresponds to nominal damping factor (e.g., 0.7),

S_n corresponds to nominal sensitivity,

DCR_n corresponds to nominal DC resistance (DCR) at which nominal response parameters are specified,

ζ_m corresponds to measured damping factor in working environment,

15 Sig_n corresponds to compensated signal,

Sig_m corresponds to measured signal in working condition.

Figure 13 shows a block diagram illustrating an alternate embodiment of how the geophone response compensation technique of the present invention may be applied to an array of geophones which have been deployed for vibroseis prospecting operations. According to a specific implementation, individual geophone response compensation functions may be applied to corresponding geophones in the array of geophones (e.g., 1304a-c). In the example illustrated in Figure 13, the vibroseis pilot signal is correlated with geophone response output signals to thereby generate a plurality of correlated output signals. The correlated output signals may then be modified, for example, by implementing compensation or correction operations. According to one implementation, correction a respective correlated output signals may be implemented at each of the geophone correction blocks 1302a-c by applying, for example, Equation (18).

In each of the embodiments illustrated in Figures 12 and 13, it is also possible to apply compensation filters obtained from an in-situ test for all or selected geophone signals.

Figures 14 and 15 graphically illustrate differences between uncompensated geophone response signals and geophone response signals which have been compensated using the

geophone response compensation technique of the present invention. In the example of Figure 14, signal 1402 represents a correlated geophone response signal (corresponding to a pilot sweep frequency range of 10-100Hz) for which geophone response compensation has not been performed. Signal 1404 represents a correlated geophone response signal (corresponding to a pilot sweep frequency range of 10-100Hz) for which geophone response compensation has been performed. As illustrated in Figure 14, signal 1404 better approximates ideal geophone response characteristics than signal 1402.

In the example of Figure 15, signal 1502 represents a correlated geophone response signal (corresponding to a pilot sweep frequency range of 5-50 Hz) for which geophone response compensation has not been performed. Signal 1504 represents a correlated geophone response signal (corresponding to a pilot sweep frequency range of 5-50 Hz) for which geophone response compensation has been performed. As illustrated in Figure 15, signal 1504 better approximates ideal geophone response characteristics than signal 1502.

It will be appreciated that the technique of the present invention may be used to minimize the phase of correlated geophone the response signals. Moreover, using the geophone response compensation technique of the present invention, true zero phase may be obtained for correlated geophone response signals.

Determining Geophone Response Parameters

The following section provides a more detailed discussion of various techniques which may be used for obtaining and curved accuracy in the measurement of geophone response parameters.

As described previously, the measured values of many geophone response parameters (such as, for example, natural frequency, damping factor, sensitivity, DC resistance, etc.) are dependent upon external factors such as, for example, temperature and tilt of the geophone. By measuring the DC resistance (DCR) at working conditions, it is possible to determine the actual or real-time temperature of a geophone. Once the real-time temperature of the geophone has been determined, the values of other response parameters (e.g., damping factor, sensitivity and natural frequency) of the geophone may then be accurately calculated for the actual working temperature of the geophone.

For example, for standard copper magnetic wire, the DCR may be expressed as a function of temperature as according to:

$$R_m = R_{25} \left(1 + \frac{C_r}{100} \cdot (T - 25) \right) \quad (\text{A0})$$

where $C_r = (0.393 \text{ \%})/^\circ\text{C}$.

In the impedance calibration test technique for performing geophone calibration, the DCR is typically measured by a multimeter. The calibration test technique may then be used to calculate natural frequency, open circuit damping and sensitivity. However, the present inventive entity has determined that independent DCR measurement (obtained, for example, by multimeter testing) may result in the calculation of multiple possible values for damping factor and sensitivity. Accordingly, in at least one embodiment, the DCR value may be calculated or measured using the impedance calibration test technique. The discussion below briefly describes how four geophone response parameters are calibrated by injecting signals at two different frequencies. More specifically, according to a specific embodiment, values for four unknown geophone response parameters, namely, DCR (r), natural frequency (ω_0), damping factor (ζ_0), and sensitivity (S_0) may be determined by solving four impedance equations derived from two impedance measurements using two different frequencies ω_1 and ω_2 .

Figure 16 shows a schematic diagram 1600 which may be used for describing a specific embodiment of the impedance calibration test technique. As illustrated in Figure 16, current (i) flows into the moving coil portion 1602 which is suspended in a magnetic flux B (not shown). The force F acting on the moving coil may be expressed as $F = Bli$, where B is the magnetic flux density, l is the effective wire length of the moving coil in the magnetic flux B , and i is the current.

The equation of motion for the moving coil may be expressed as:

$$m \frac{d^2 \xi}{dt^2} + \mu \frac{d\xi}{dt} + k\xi = Bli \quad (\text{A1})$$

where ξ is the relative position of the moving coil inside the geophone. The first term in the left hand side of Equation (A1) represents the inertial force, the second term represents the frictional force proportional to the velocity, and the last term represents the spring force. The summation of these three forces balances to the force due to the electric current.

The moving coil generates an electric signal e_g proportional to the velocity of the motion relative to the magnetic field, which may be expressed as:

$$e_g = Bl \frac{d\xi}{dt} \quad (\text{A2})$$

Equation (A1) may be rewritten in terms of e_g as:

$$\frac{d^2 e_g}{dt^2} + 2\zeta_0 \omega_0 \frac{de_g}{dt} + \omega_0^2 e_g = -\frac{S_0^2}{m} \frac{di}{dt} \quad (\text{A3})$$

where:

$$\omega_0 = \sqrt{\frac{k}{m}}$$

$$5 \quad \zeta = \frac{\mu}{2m\omega_0}$$

$$S_0 = Bl$$

Since the geophone output signal may be expressed as:

$$e_0 = e_g + ri \quad (\text{A4})$$

10 Equation (A3) may be rewritten in terms of the geophone output signal as:

$$\frac{d^2 e_0}{dt^2} + 2\zeta_0 \omega_0 \frac{de_0}{dt} + \omega_0^2 e_0 = -r \left(\frac{d^2 i}{dt^2} + 2\zeta_0 \omega_0 \frac{di}{dt} + \omega_0^2 i \right) - \frac{S_0^2}{m} \frac{di}{dt} \quad (\text{A5})$$

Laplace transformation of Equation (A5) yields geophone impedance as:

$$Z(s) = -\frac{E_0(s)}{I(s)} = r + \frac{S_0^2}{m} \frac{s}{s^2 + 2\zeta_0 \omega_0 s + \omega_0^2} \quad (\text{A6})$$

Equation (A6) may be rewritten as:

$$15 \quad Z(j\omega) = r + \frac{S_0}{m\omega_0} \frac{j \left(\frac{\omega}{\omega_0} \right)}{\left\{ 1 - \left(\frac{\omega}{\omega_0} \right)^2 \right\} + 2j\zeta_0 \left(\frac{\omega}{\omega_0} \right)} \quad (\text{A7})$$

Real and imaginary parts of impedance may be calculated according to:

$$\text{Re}(Z) = r + \frac{S_0}{m\omega_0} \frac{2\zeta_0 \left(\frac{\omega}{\omega_0} \right)^2}{\left\{ 1 - \left(\frac{\omega}{\omega_0} \right)^2 \right\} + \left(2\zeta_0 \frac{\omega}{\omega_0} \right)^2} \quad (\text{A8})$$

$$\text{Im}(Z) = r + \frac{S_0}{m\omega_0} \frac{1 - \left(\frac{\omega}{\omega_0}\right)^2}{\left\{1 - \left(\frac{\omega}{\omega_0}\right)^2\right\}^2 + \left(2\zeta_0 \frac{\omega}{\omega_0}\right)^2} \quad (\text{A9})$$

The real and imaginary parts of the impedance equation may be represented as a circle on a complex plane, as shown, for example, in Figure 17 of the drawings.

The square sum of Equations (A8) and (A9) yields an expression:

$$5 \quad \left\{ \text{Re}(Z) - r - \frac{S_0^2}{4\zeta_0\omega_0 m} \right\}^2 + \{\text{Im}(Z)\}^2 = \left(\frac{S_0^2}{4\zeta_0\omega_0 m} \right)^2 \quad (\text{A10})$$

Equation (A10) may be represented by the circle in Figure 17 with radius a defined as:

$$a^2 = \{\text{Re}(Z) - c\}^2 + \{\text{Im}(Z)\}^2 \quad (\text{A11})$$

The center c of the circle is given by:

$$c = r + \frac{S_0^2}{4\zeta_0\omega_0 m} \quad (\text{A12})$$

10 Computation for geophone parameters may be expressed by:

$$Z = -\frac{e_0}{i} = R \frac{e_0}{e_R} \quad (\text{A13})$$

Measurement of impedance at two frequencies, ω_1 and ω_2 , gives four equations for real and imaginary parts of two impedances, as illustrated, for example, by Equations (A14) – (A17):

$$15 \quad \text{Re}(Z_1) = r + \frac{S_0^2}{m\omega_0} \frac{2\zeta_0 \left(\frac{\omega_1}{\omega_0}\right)^2}{\left\{1 - \left(\frac{\omega_1}{\omega_0}\right)^2\right\}^2 + \left(2\zeta_0 \frac{\omega_1}{\omega_0}\right)^2} \quad (\text{A14})$$

$$\text{Re}(Z_2) = r + \frac{S_0^2}{m\omega_0} \frac{2\zeta_0 \left(\frac{\omega_2}{\omega_0}\right)^2}{\left\{1 - \left(\frac{\omega_2}{\omega_0}\right)^2\right\}^2 + \left(2\zeta_0 \frac{\omega_2}{\omega_0}\right)^2} \quad (\text{A15})$$

$$\text{Im}(Z_1) = \frac{S_0^2}{m\omega_0} \frac{\left\{1 - \left(\frac{\omega_1}{\omega_0}\right)^2\right\} \left(\frac{\omega_1}{\omega_0}\right)}{\left\{1 - \left(\frac{\omega_1}{\omega_0}\right)^2\right\}^2 + \left(2\zeta_0 \frac{\omega_1}{\omega_0}\right)^2} \quad (\text{A16})$$

$$\text{Im}(Z_2) = \frac{S_0^2}{m\omega_0} \frac{\left\{1 - \left(\frac{\omega_2}{\omega_0}\right)^2\right\} \left(\frac{\omega_2}{\omega_0}\right)}{\left\{1 - \left(\frac{\omega_2}{\omega_0}\right)^2\right\}^2 + \left(2\zeta_0 \frac{\omega_2}{\omega_0}\right)^2} \quad (\text{A17})$$

From these four equations, it is possible to derive four geophone parameters, r , ζ_0 , ω_0 ,
5 and S_0 .

Inserting Z_1 and Z_2 into Equation (A11) gives the center and radius of the impedance
circle.

$$c = \frac{\text{Im}(Z_1)^2 - \text{Im}(Z_2)^2 + \text{Re}(Z_1)^2 - \text{Re}(Z_2)^2}{2\{\text{Re}(Z_1) - \text{Re}(Z_2)\}} \quad (\text{A18})$$

$$a = \sqrt{\text{Im}(Z_1)^2 + \{c - \text{Re}(Z_1)\}^2} \quad (\text{A19})$$

10 The DC resistance r may then be calculated according to:

$$r = c - a \quad (\text{A20})$$

From the four impedance Equations (A14)-(A17), ζ_0 , ω_0 , and S_0 may be determined
according to:

$$\omega_0 = \sqrt{\frac{(A\omega_1 - \omega_2)\omega_1\omega_2}{(A\omega_2 - \omega_1)}} \quad (\text{A21})$$

15 where:

$$A = \frac{\text{Re}(Z_1) - r}{\text{Re}(Z_2) - r} \cdot \frac{\text{Im}(Z_1)}{\text{Im}(Z_2)} \quad (\text{A22})$$

$$\zeta_0 = \frac{(\omega_0^2 - \omega_1^2)\{\text{Re}(Z_1) - r\}}{2\omega_0\omega_1\{\text{Im}(Z_1) - r\}} \quad (\text{A23})$$

$$S_0 = \sqrt{\frac{m\text{Im}(Z_1)\{(\omega_0^2 - \omega_1^2)\}^2 + 4\zeta_0^2\omega_0^2\omega_1^2}{(\omega_0^2 - \omega_1^2)\omega_1}} \quad (\text{A24})$$

It should be noted that ζ_0 , and S_0 may also be found as:

$$\zeta_0 = \frac{(\omega_0^2 - \omega_2^2)\{\text{Re}(Z_2) - r\}}{2\omega_0\omega_2\{\text{Im}(Z_2) - r\}} \quad (\text{A25})$$

$$S_0 = \sqrt{\frac{m\text{Im}(Z_2)\{(\omega_0^2 - \omega_2^2)\}^2 + 4\zeta_0^2\omega_0^2\omega_2^2}{(\omega_0^2 - \omega_2^2)\omega_2}} \quad (\text{A26})$$

The values for ζ_0 , and S_0 calculated from Equations (A13) and (A24) agree with the amounts calculated from Equations (A25) and (A26) as long as r is calculated from Equations (A18), (A19), and (A20). However, if r is measured by using a separate instrument, such as a
5 multimeter, for example, then the values for ζ_0 , and S_0 may not agree.

Other Embodiments

Generally, the geophone calibration and compensation techniques of the present invention may be implemented on software and/or hardware. For example, they can be
10 implemented in an operating system kernel, in a separate user process, in a library package bound into network applications, on a specially constructed machine, or on a network interface card. In a specific embodiment of this invention, the technique of the present invention is implemented in software such as an operating system or in an application running on an operating system.

15 A software or software/hardware hybrid implementation of the geophone calibration and compensation techniques of this invention may be implemented on a general-purpose programmable machine selectively activated or reconfigured by a computer program stored in memory. Such programmable machine may be implemented on a general-purpose network host machine such as a personal computer or workstation. Further, the invention may be at
20 least partially implemented on a card (e.g., an interface card) for a network device or a general-purpose computing device.

Referring now to Figure 18, a network device 60 suitable for implementing various aspects of the geophone calibration and compensation techniques of the present invention includes a master central processing unit (CPU) 62, interfaces 68, and a bus 67 (e.g., a PCI
25 bus). When acting under the control of appropriate software or firmware, the CPU 62 may be responsible for implementing specific functions associated with the functions of a desired network device. For example, when configured as a general-purpose computing device, the CPU 62 may be responsible for data processing, media management, I/O communication, calculating the geophone response parameter values, performing geophone response

compensation operations, etc. The CPU 62 preferably accomplishes all these functions under the control of software including an operating system (e.g. Windows NT), and any appropriate applications software.

5 CPU 62 may include one or more processors 63 such as a processor from the Motorola or Intel family of microprocessors, or the MIPS family of microprocessors. In an alternative embodiment, processor 63 is specially designed hardware for controlling the operations of network device 60. In a specific embodiment, a memory 61 (such as non-volatile RAM and/or ROM) also forms part of CPU 62. However, there are many different ways in which memory could be coupled to the system. Memory block 61 may be used for a variety of purposes such as, for example, caching and/or storing data, programming instructions, etc.

10 The interfaces 68 are typically provided as interface cards (sometimes referred to as "line cards"). Generally, they control the sending and receiving of data packets over the network and sometimes support other peripherals used with the network device 60, such as, for example, display devices 70 and/or printing devices 72. It will be appreciated that the various geophone calibration and compensation techniques of the present invention may generate data or other information to be presented for display on electronic display devices and/or non-electronic display devices (such as, for example, printed for display on paper).

15 Examples of other types of interfaces that may be provided are Ethernet interfaces, frame relay interfaces, cable interfaces, DSL interfaces, token ring interfaces, and the like. In addition, various very high-speed interfaces may be provided such as fast Ethernet interfaces, Gigabit Ethernet interfaces, ATM interfaces, HSSI interfaces, POS interfaces, FDDI interfaces and the like. Generally, these interfaces may include ports appropriate for communication with the appropriate media. In some cases, they may also include an independent processor and, in some instances, volatile RAM. The independent processors may be used, for example, to handle data processing tasks, display tasks, communication tasks, media control tasks, etc.

20 Although the system shown in Figure 18 illustrates one specific network device of the present invention, it is by no means the only network device architecture on which the present invention can be implemented. For example, an architecture having a single processor that handles communications as well as routing computations, etc. is often used. Further, other types of interfaces and media could also be used with the network device.

25 Regardless of network device's configuration, it may employ one or more memories or memory modules (such as, for example, memory block 65) configured to store data, program

instructions for the general-purpose network operations and/or other information relating to the functionality of the geophone calibration and compensation techniques described herein. The program instructions may control the operation of an operating system and/or one or more applications, for example. The memory or memories may also be configured to store data structures, seismic logging information, geophone response parameter information, vibroseis prospecting information, and/or other specific non-program information described herein.

Because such information and program instructions may be employed to implement the systems/methods described herein, the present invention relates to machine readable media that include program instructions, state information, etc. for performing various operations described herein. Examples of machine-readable media include, but are not limited to, magnetic media such as hard disks, floppy disks, and magnetic tape; optical media such as CD-ROM disks; magneto-optical media such as floptical disks; and hardware devices that are specially configured to store and perform program instructions, such as read-only memory devices (ROM) and random access memory (RAM). The invention may also be embodied in a carrier wave traveling over an appropriate medium such as airwaves, optical lines, electric lines, etc. Examples of program instructions include both machine code, such as produced by a compiler, and files containing higher level code that may be executed by the computer using an interpreter.

Although several preferred embodiments of this invention have been described in detail herein with reference to the accompanying drawings, it is to be understood that the invention is not limited to these precise embodiments, and that various changes and modifications may be effected therein by one skilled in the art without departing from the scope of spirit of the invention as defined in the appended claims.

25

IT IS CLAIMED

1. A method for calculating response parameters of a geophone configured or designed for use in seismic exploration activities, the method comprising:

performing at least one calibration test on the geophone to determine values for a first
5 portion of response parameters associated with the geophone;

determining, using information relating to the first portion of response parameters, a
moving mass parameter value for the geophone; and

wherein the moving mass parameter value represents an amount of moving mass
associated with the geophone.

10

2. The method of claim 1 wherein the first portion of response parameters includes
at least one response parameter selected from a group consisting of: open circuit sensitivity,
damping factor and natural frequency.

15

3. The method of claim 1 wherein the first portion of response parameters includes
open circuit sensitivity, damping factor and natural frequency.

20

4. The method of claim 1 wherein the moving mass of the geophone includes:
at least one moving coil;
a bobbin; and
at least one suspension spring.

25

5. The method of claim 1 further comprising performing an impedance calibration
test on the geophone to determine values for at least one of the first portion of response
parameters.

30

6. The method of claim 1 further comprising performing a dynamic calibration test
on the geophone to determine values for at least one of the first portion of response parameters.

30

7. The method of claim 1 further comprising performing a reciprocity calibration
test on the geophone to determine values for at least one of the first portion of response
parameters.

8. The method of claim 1 further comprising calculating the moving mass parameter (m) value according to:

$$m = \frac{S_g^2 (\omega_0^2 - \omega_1^2) \omega_1}{\text{Im}(Z(\omega_1)) \left[(\omega_0^2 - \omega_1^2)^2 + 4\zeta_0^2 \omega_0^2 \omega_1^2 \right]};$$

5 where:

m_0 corresponds to absolute moving mass

ζ_0 corresponds to open-circuit damping factor,

S_0 corresponds to open-circuit sensitivity,

S_g corresponds to open-circuit sensitivity,

10 ω_1 corresponds to angular frequency of a first measurement,

$\text{Im}(Z)$ corresponds to impedance imaginary part, and

ω_0 corresponds to natural frequency.

9. The method of claim 1 further comprising calculating the moving mass parameter (m) value according to:

$$m_0 = m \left(\frac{S_g}{S_0} \right)^2$$

where:

m_0 corresponds to absolute moving mass

S_0 corresponds to open-circuit sensitivity, and

20 S_g corresponds to open-circuit sensitivity.

10. The method of claim 1 further comprising:

determining an open circuit sensitivity value for the geophone;

determining a damping factor value for the geophone;

25 determining a natural frequency value for the geophone; and

calculating the moving mass parameter value using the open circuit sensitivity value, damping factor value and natural frequency value.

11. The method of claim 1 further comprising:

30 measuring a DC resistance value of the geophone at working conditions;

determining, using the measured DC resistance value, a current temperature value of the geophone; and

calculating at least a portion of the geophone response parameters using the current temperature value.

5

12. The method of claim 11 further comprising:

calculating an open circuit sensitivity value for the geophone using the current temperature value;

10 calculating a damping factor value for the geophone using the current temperature value; and

calculating a natural frequency value for the geophone using the current temperature value.

13. A method for modifying geophone response output information generated by a first geophone configured or designed for use in seismic exploration activities, the method comprising:

15 determining a second transfer function for an ideal response of a second geophone based upon information relating to a second portion of response parameters associated with the second geophone, wherein the second portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

20 modifying geophone response output information generated by the first geophone using the second transfer function.

25 14. The method of claim 13 further comprising:

determining a first transfer function for the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

30 modifying geophone response output information generated by the first geophone using the first and second transfer functions.

15. The method of claim 13 wherein the first geophone has associated therewith a moving mass parameter value, the method further comprising using the moving mass parameter value to adjust values relating to the first portion of response parameters.

5 16. The method of claim 13 wherein the first geophone has associated therewith a moving mass parameter value, the method further comprising using the moving mass parameter value to modifying the first geophone response output information generated by the first geophone.

10 17. The method of claim 15 further comprising calculating the moving mass parameter value using geophone response parameter information relating to open circuit sensitivity, damping factor and natural frequency.

15 18. The method of claim 15 wherein the moving mass parameter value corresponds to a nominal moving mass value.

20 19. The method of claim 13 wherein the first geophone response output information includes a first geophone response output signal, the method further comprising modifying the first geophone response output signal to produce a modified geophone response output signal according to:

$$Sig_n = \text{ifft} \left\{ \text{fft}(Sig_m) * \frac{H(f_n, \zeta_n, S_n, DRC_n)}{H(f_m, \zeta_m, S_m, DRC_m)} \right\}$$

where:

H corresponds to transfer function of a geophone,

f_n corresponds to nominal natural frequency,

25 ζ_n corresponds to nominal damping factor,

S_n corresponds to nominal sensitivity,

DCR_n corresponds to nominal DC resistance at which nominal response parameters are specified,

f_m corresponds to a natural frequency value associated with the first geophone,

30 ζ_m corresponds to measured damping factor in working environment,

S_m corresponds to a damping factor value associated with the first geophone,

DCR_m corresponds to a DC resistance value associated with the first geophone,

Sig_n corresponds to the modified geophone response output signal,

Sig_m corresponds to the first geophone response output signal.

5 20. The method of claim 13 further comprising:

determining that the first geophone is out of tolerance, wherein the geophone response output information generated by the first geophone is invalid as being significantly inaccurate;

modifying the geophone response output information to produce modified geophone response output information which is valid as being significantly accurate.

10

21. The method of claim 13 further comprising:

measuring a DC resistance value of the first geophone at working conditions;

determining, using the measured DC resistance value, a current temperature value of the first geophone; and

15 calculating at least a portion of the first geophone response parameters using the current temperature value.

22. The method of claim 21 further comprising:

20 calculating an open circuit sensitivity value for the first geophone using the current temperature value;

calculating a damping factor value for the first geophone using the current temperature value; and

calculating a natural frequency value for the first geophone using the current temperature value.

25

23. The method of claim 13 wherein the geophone response output information is generated by at least one geophone during vibroseis prospecting operations, the method further comprising modifying the geophone response output information using geophone calibration information generated during calibration testing of the at least one geophone.

30

24. A method for processing seismic exploration information generated from seismic exploration activities, wherein a first portion of seismic exploration information

includes geophone response output information generated by at least one geophone, wherein a second portion of the seismic exploration information includes source signal information relating to at least one source signal used in performing the seismic exploration activities, the method comprising:

5 determining a first portion of response parameter values associated with a first geophone; and

 improving accuracy of the seismic exploration information by modifying at least a portion of the seismic exploration information to compensate for at least one of the first portion of response parameter values.

10

25. The method of claim 24 further comprising performing at least one calibration test on the at least one geophone to determine values for the first portion of response parameters.

15

26. The method of claim 24 further comprising:

 generating modified source signal information by modifying the source signal information using at least one of the first portion of response parameters values; and

 generating correlated output signal information using the modified source signal information and the geophone response output information.

20

27. The method of claim 24 wherein the first portion of response parameter values includes an open circuit sensitivity value, a damping factor value and a natural frequency value.

25

28. The method of claim 24 wherein the first portion of response parameter values includes a moving mass parameter value, the method further comprising:

 generating modified source signal information by modifying the source signal information using the moving mass parameter value; and

 generating correlated output signal information using the modified source signal information and the geophone response output information.

30

29. The method of claim 24 further comprising:

generating correlated output signal information using the source signal information and the geophone response output information; and

generating modified correlated output signal information by modifying the correlated output signal using at least one of the first portion of response parameters values.

5

30. The method of claim 29 wherein the first portion of response parameter values includes an open circuit sensitivity value, a damping factor value and a natural frequency value.

31. The method of claim 29 wherein the first portion of response parameter values includes a moving mass parameter value, the method further comprising:

10

generating correlated output signal information using the source signal information and the geophone response output information; and

generating modified correlated output signal information by modifying the correlated output signal using the moving mass parameter value.

15

32. The method of claim 24 further comprising:

determining a first transfer function for an ideal response of the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

20

modifying source signal information using the first transfer function.

33. The method of claim 24 further comprising:

25

determining a first transfer function for an ideal response of the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

30

modifying geophone response output information using the first transfer function.

34. The method of claim 24 further comprising:

determining a first transfer function for an ideal response of the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and
5 natural frequency;

generating correlated output signal information using the source signal information and the geophone response output information; and

modifying the correlated output signal information using the first transfer function.

10 35. The method of claim 24 wherein the source signal information includes pilot sweep signal information relating to vibroseis prospecting operations.

36. The method of claim 24 further comprising:

measuring a DC resistance value of the first geophone at working conditions;

15 determining, using the measured DC resistance value, a current temperature value of the first geophone; and

calculating at least a portion of first geophone response parameters using the current temperature value.

20 37. The method of claim 36 further comprising:

calculating an open circuit sensitivity value for the first geophone using the current temperature value;

calculating a damping factor value for the first geophone using the current temperature value; and

25 calculating a natural frequency value for the first geophone using the current temperature value.

38. The method of claim 24 wherein the seismic exploration activity includes vibroseis prospecting operations, and wherein the seismic exploration information includes
30 correlated output signal information generated using the geophone response output information and source signal information, the method further comprising modifying the correlated output signal to minimize phase characteristics associated with the correlated output signal.

39. The method of claim 24 wherein the seismic exploration activity includes vibroseis prospecting operations, and wherein the seismic exploration information includes correlated output signal information generated using the geophone response output information and source signal information, the method further comprising modifying the correlated output signal to increase symmetry characteristics associated with the correlated output signal.

40. A system for calculating response parameters of a geophone configured or designed for use in seismic exploration activities, the system comprising:

10 at least one processor;
at least one interface; and
memory;

the system being configured or designed to perform at least one calibration test on the geophone to determine values for a first portion of response parameters associated with the

15 geophone;

the system being further configured or designed to determine, using information relating to the first portion of response parameters, a moving mass parameter value for the geophone;

wherein the moving mass parameter value represents an amount of moving mass associated with the geophone.

20 41. The system of claim 40 wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency.

25 42. The system of claim 40 wherein the moving mass of the geophone includes:
at least one moving coil;
a bobbin; and
at least one suspension spring.

30 43. The system of claim 40 being further configured or designed to perform an impedance calibration test on the geophone to determine values for at least one of the first portion of response parameters.

44. The system of claim 40 being further configured or designed to perform a dynamic calibration test on the geophone to determine values for at least one of the first portion of response parameters.

5

45. The system of claim 40 being further configured or designed to perform a reciprocity calibration test on the geophone to determine values for at least one of the first portion of response parameters.

10

46. The system of claim 40 being further configured or designed to:
determine an open circuit sensitivity value for the geophone;
determine a damping factor value for the geophone;
determine a natural frequency value for the geophone; and
calculate the moving mass parameter value using the open circuit sensitivity value,
15 damping factor value and natural frequency value.

20

47. The system of claim 40 being further configured or designed to:
measure a DC resistance value of the geophone at working conditions;
determine, using the measured DC resistance value, a current temperature value of the
geophone; and
calculate at least a portion of the geophone response parameters using the current
temperature value.

25

48. The system of claim 47 being further configured or designed to:
calculate an open circuit sensitivity value for the geophone using the current
temperature value;
calculate a damping factor value for the geophone using the current temperature value;
and
calculate a natural frequency value for the geophone using the current temperature value.

30

49. A system for modifying geophone response output information generated by a first geophone configured or designed for use in seismic exploration activities, the system comprising:

at least one processor;

5 at least one interface; and

memory;

the system being configured or designed to determine a second transfer function for an ideal response of a second geophone based upon information relating to a second portion of response parameters associated with the second geophone, wherein the second portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

10 the system being further configured or designed to modify geophone response output information generated by the first geophone using the second transfer function.

15 50. The system of claim 49 being further configured or designed to:

determine a first transfer function for the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

20 modify geophone response output information generated by the first geophone using the first and second transfer functions.

25 51. The system of claim 49 wherein the first geophone has associated therewith a moving mass parameter value, the system being further configured or designed to use the moving mass parameter value to adjust values relating to the first portion of response parameters.

30 52. The system of claim 49 wherein the first geophone has associated therewith a moving mass parameter value, the system being further configured or designed to use the moving mass parameter value to modify the first geophone response output information generated by the first geophone.

53. The system of claim 51 being further configured or designed to calculate the moving mass parameter value using geophone response parameter information relating to open circuit sensitivity, damping factor and natural frequency.

5 54. The system of claim 51 wherein the moving mass parameter value corresponds to a nominal moving mass value.

55. The system of claim 49 being further configured or designed to:
determine that the first geophone is out of tolerance, wherein the geophone response
10 output information generated by the first geophone is invalid as being significantly inaccurate;
modify the geophone response output information to produce modified geophone
response output information which is valid as being significantly accurate.

56. The system of claim 49 being further configured or designed to:
15 measure a DC resistance value of the first geophone at working conditions;
determine, using the measured DC resistance value, a current temperature value of the
first geophone; and
calculate at least a portion of the first geophone response parameters using the current
temperature value.

20 57. The system of claim 56 being further configured or designed to:
calculate an open circuit sensitivity value for the first geophone using the current
temperature value;
calculate a damping factor value for the first geophone using the current temperature
25 value; and
calculate a natural frequency value for the first geophone using the current temperature
value.

58. The system of claim 49 wherein the geophone response output information is
30 generated by at least one geophone during vibroseis prospecting operations, the system being
further configured or designed to modify the geophone response output information using

geophone calibration information generated during calibration testing of the at least one geophone.

5 59. A system for processing seismic exploration information generated from seismic exploration activities, wherein a first portion of seismic information includes geophone response output information generated by at least one geophone, wherein a second portion of the seismic exploration information includes source signal information relating to at least one source signal used in performing the seismic exploration activities, the system comprising:

at least one processor;

10 at least one interface; and

memory;

the system being configured or designed to determine a first portion of response parameter values associated with a first geophone; and

15 the system being further configured or designed to improve accuracy of the seismic exploration information by modifying at least a portion of the seismic exploration information to compensate for at least one of the first portion of response parameter values.

20 60. The system of claim 59 being further configured or designed to perform at least one calibration test on the at least one geophone to determine values for the first portion of response parameters.

61. The system of claim 59 being further configured or designed to:

generate modified source signal information by modifying the source signal information using at least one of the first portion of response parameters values; and

25 generate correlated output signal information using the modified source signal information and the geophone response output information.

30 62. The system of claim 59 wherein the first portion of response parameter values includes an open circuit sensitivity value, a damping factor value and a natural frequency value.

63. The system of claim 59 wherein the first portion of response parameter values includes a moving mass parameter value, the system being further configured or designed to:

generate modified source signal information by modifying the source signal information using the moving mass parameter value; and

generate correlated output signal information using the modified source signal information and the geophone response output information.

5

64. The system of claim 59 being further configured or designed to:

generate correlated output signal information using the source signal information and the geophone response output information; and

10 generate modified correlated output signal information by modifying the correlated output signal using at least one of the first portion of response parameters values.

65. The system of claim 64 wherein the first portion of response parameter values includes an open circuit sensitivity value, a damping factor value and a natural frequency value.

15 66. The system of claim 64 wherein the first portion of response parameter values includes a moving mass parameter value, the system being further configured or designed to:

generate correlated output signal information using the source signal information and the geophone response output information; and

20 generate modified correlated output signal information by modifying the correlated output signal using the moving mass parameter value.

67. The system of claim 59 being further configured or designed to:

25 determine a first transfer function for an ideal response of the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

modify at least one of source signal information and geophone response output information using the first transfer function.

30

68. The system of claim 59 being further configured or designed to:

determine a first transfer function for an ideal response of the first geophone based upon information relating to a first portion of response parameters associated with the first geophone, wherein the first portion of response parameters includes open circuit sensitivity, damping factor and natural frequency;

- 5 generate correlated output signal information using the source signal information and the geophone response output information; and
modify the correlated output signal information using the first transfer function.

69. The system of claim 59 wherein the source signal information includes pilot
10 sweep signal information relating to vibroseis prospecting operations.

70. The system of claim 59 being further configured or designed to:
measure a DC resistance value of the first geophone at working conditions;
determine, using the measured DC resistance value, a current temperature value of the
15 first geophone; and
calculate at least a portion of first geophone response parameters using the current temperature value.

71. The system of claim 70 being further configured or designed to:
20 calculate an open circuit sensitivity value for the first geophone using the current temperature value;
calculate a damping factor value for the first geophone using the current temperature value; and
calculate a natural frequency value for the first geophone using the current temperature
25 value.

72. The system of claim 59 wherein the seismic exploration activity includes vibroseis prospecting operations, and wherein the seismic exploration information includes correlated output signal information generated using the geophone response output information
30 and source signal information, the system being further configured or designed to modify the correlated output signal to at least one of minimize phase characteristics and increase symmetry characteristics associated with the correlated output signal.

73. A system for calculating response parameters of a geophone configured or designed for use in seismic exploration activities, the system comprising:

means for performing at least one calibration test on the geophone to determine values
5 for a first portion of response parameters associated with the geophone; and

means for determining, using information relating to the first portion of response parameters, a moving mass parameter value for the geophone;

wherein the moving mass parameter value represents an amount of moving mass associated with the geophone.

10

74. A system for modifying geophone response output information generated by a first geophone configured or designed for use in seismic exploration activities, the system comprising:

means for determining a second transfer function for an ideal response of a second
15 geophone based upon information relating to a second portion of response parameters associated with the second geophone, wherein the second portion of response parameters includes at least one response parameter selected from a group consisting of: open circuit sensitivity, damping factor and natural frequency; and

means for modifying geophone response output information generated by the first
20 geophone using the second transfer function.

75. A system for processing seismic exploration information generated from seismic exploration activities, wherein a first portion of seismic information includes geophone response output information generated by at least one geophone, wherein a second portion of
25 the seismic exploration information includes source signal information relating to at least one source signal used in performing the seismic exploration activities, the system comprising:

means for determining a first portion of response parameter values associated with a first geophone; and

means for improving accuracy of the seismic exploration information by modifying at
30 least a portion of the seismic exploration information to compensate for at least one of the first portion of response parameter values.

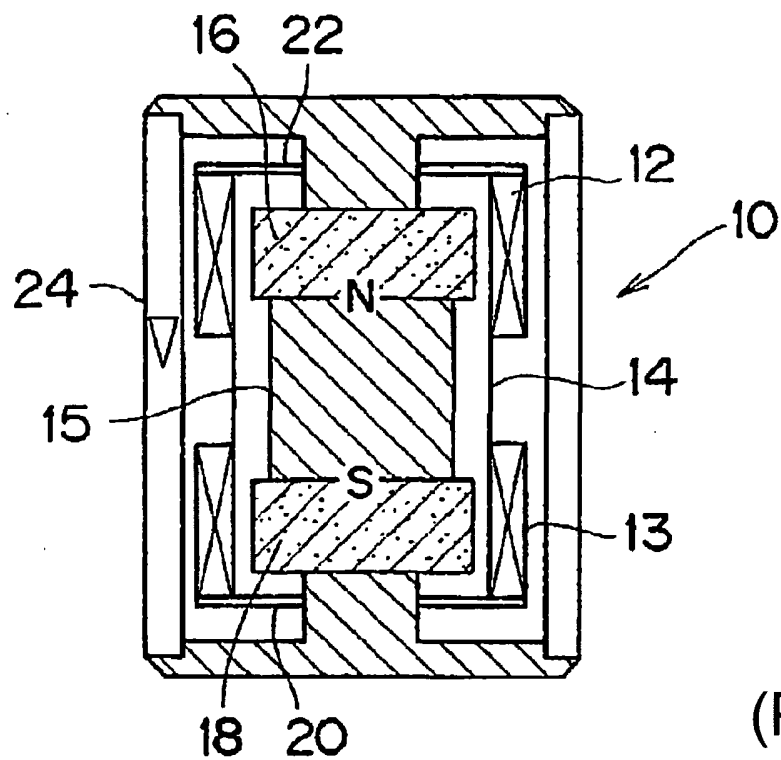


Fig. 1
(Prior Art)

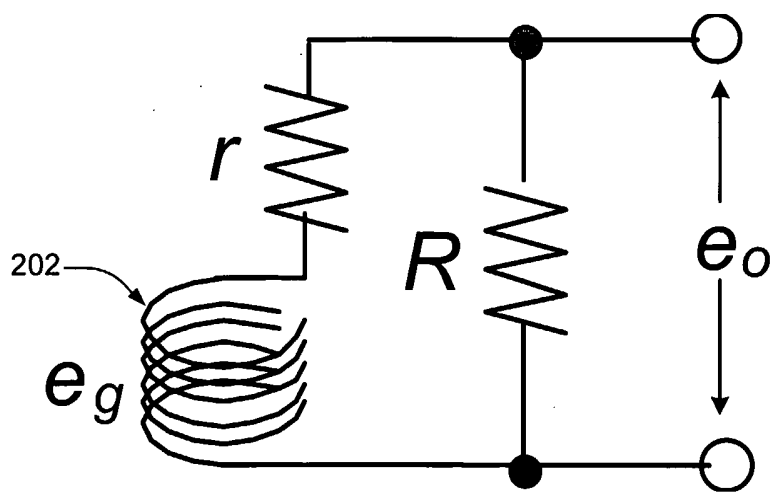
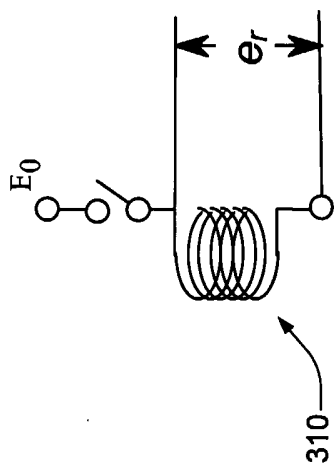
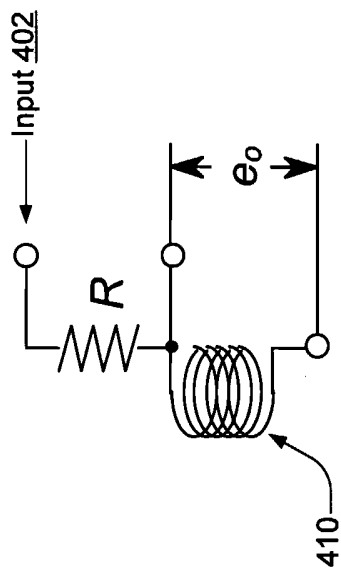


Fig. 2

200



300 Fig. 3A



400 Fig. 4A

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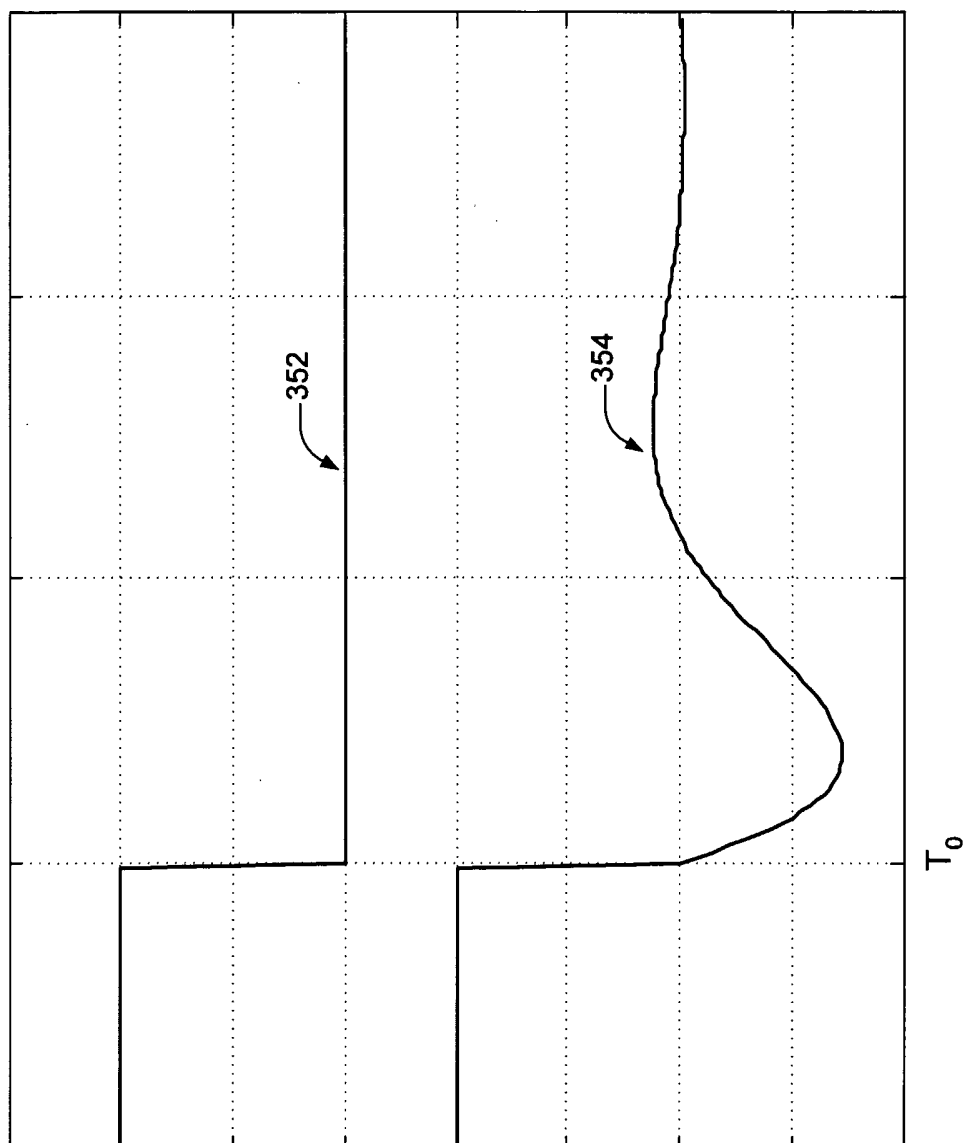


Fig. 3B

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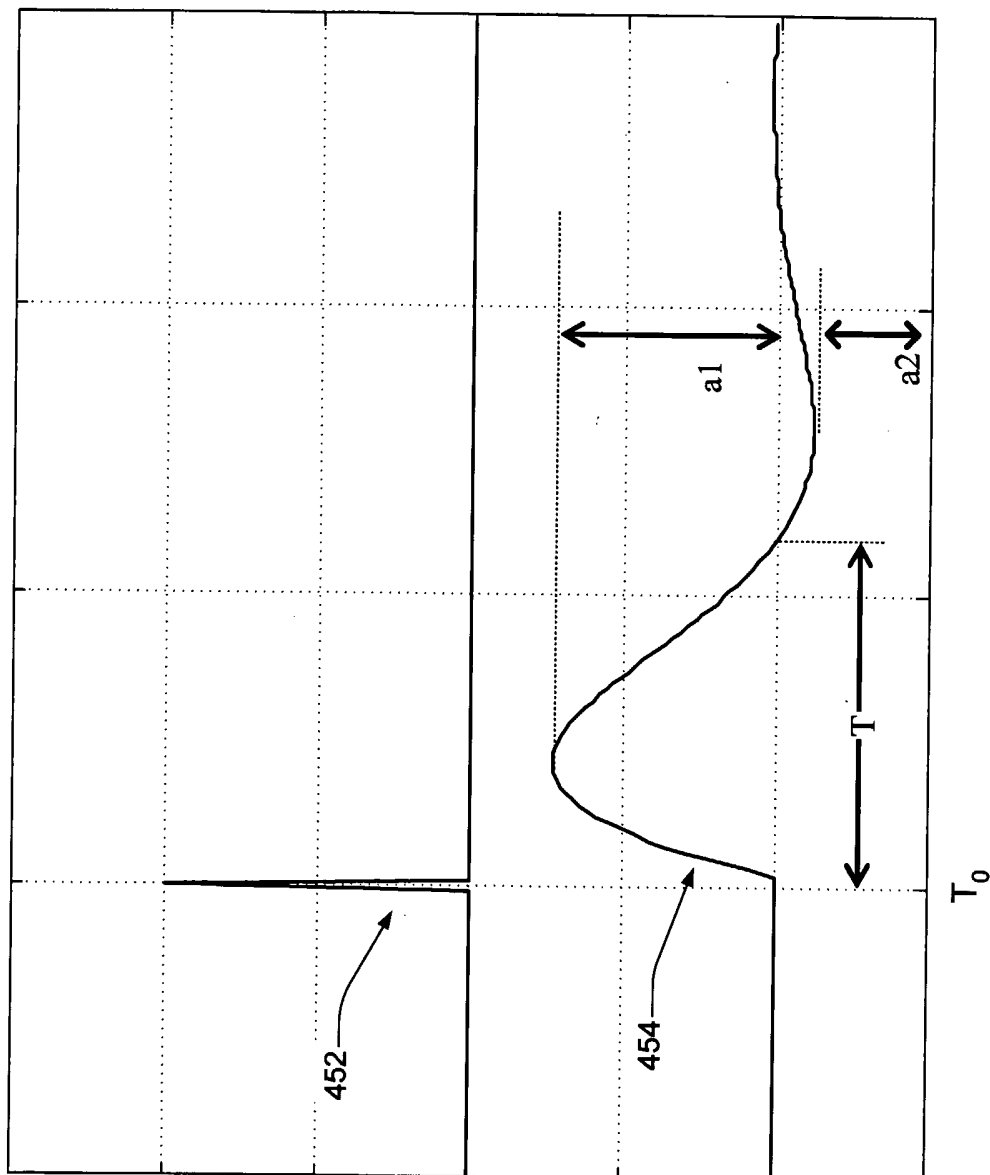


Fig. 4B

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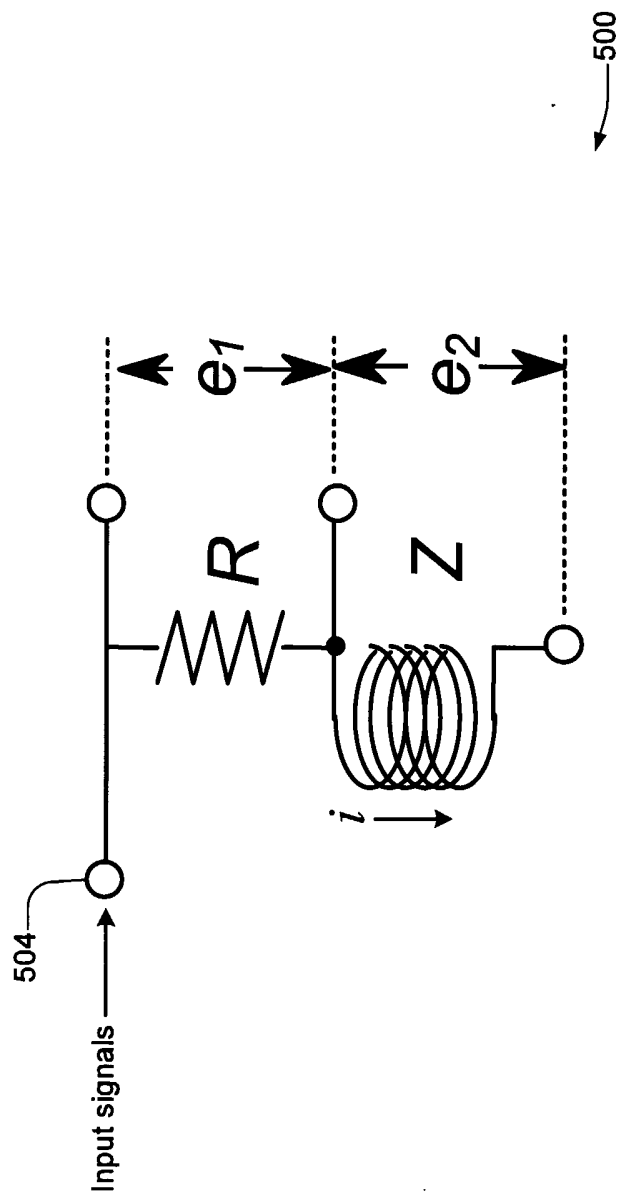


Fig. 5

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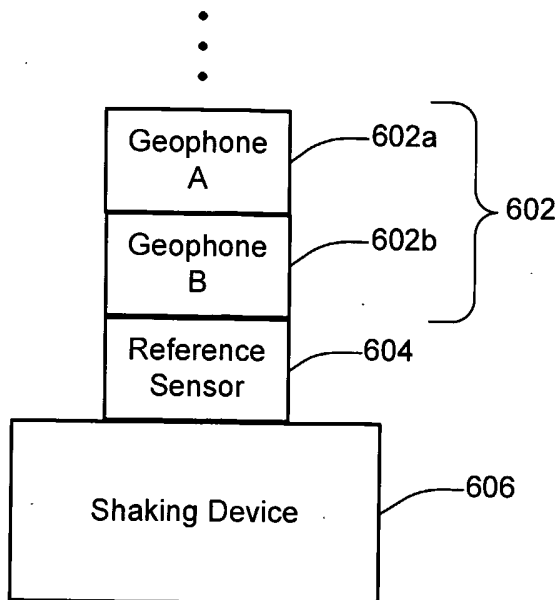


Fig. 6

← 600

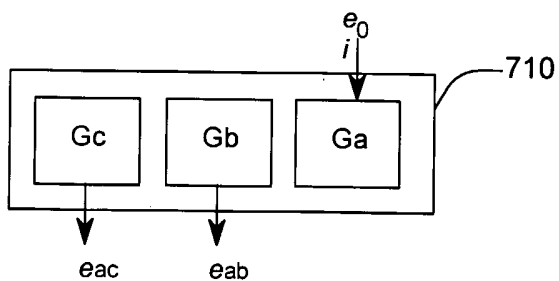


Fig. 7A

← 700

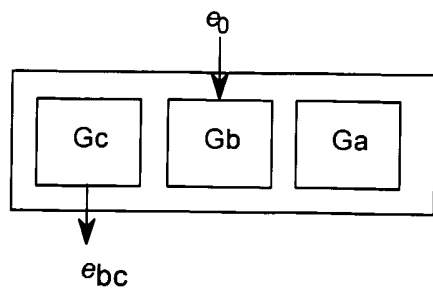


Fig. 7B

← 750

7114

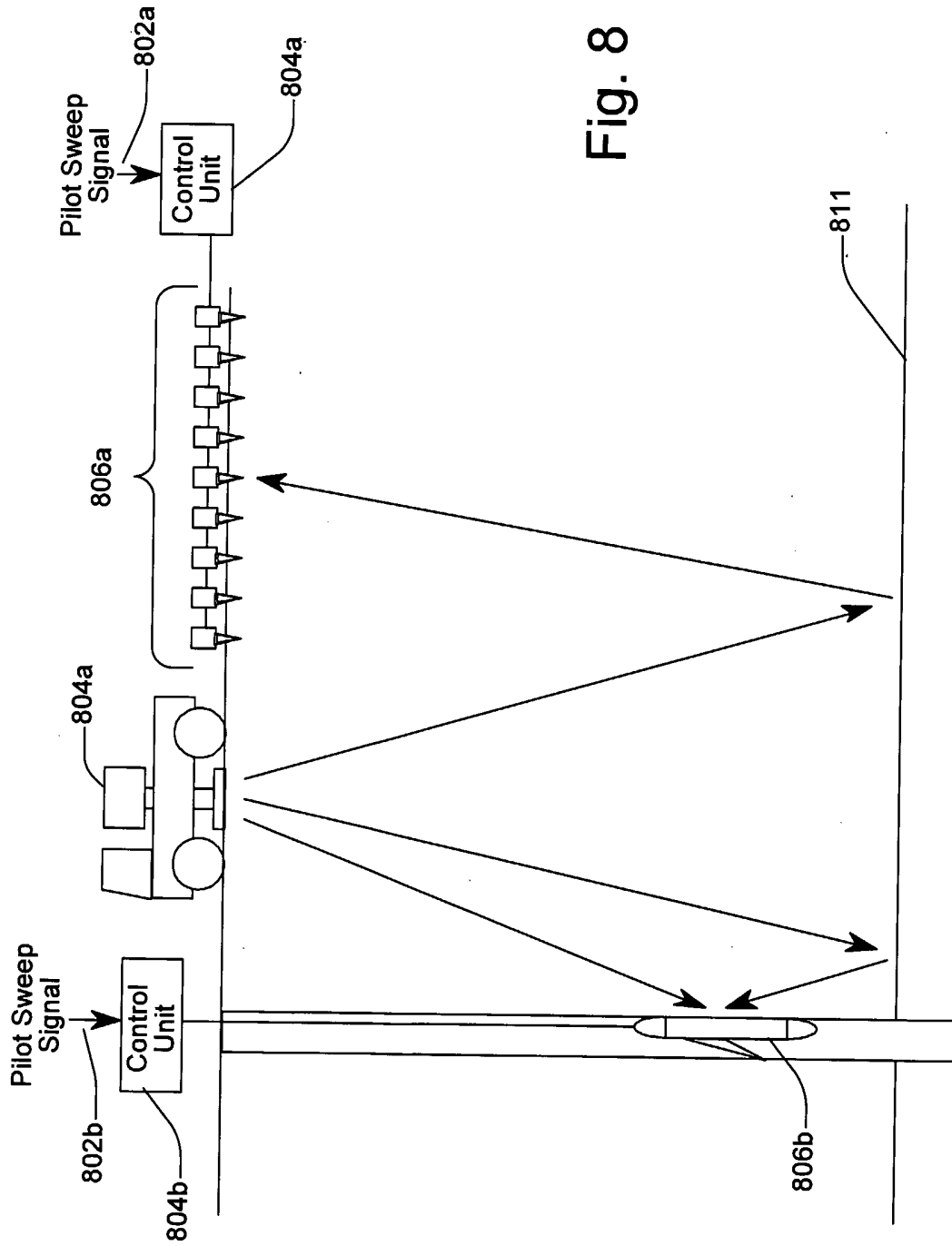


Fig. 8

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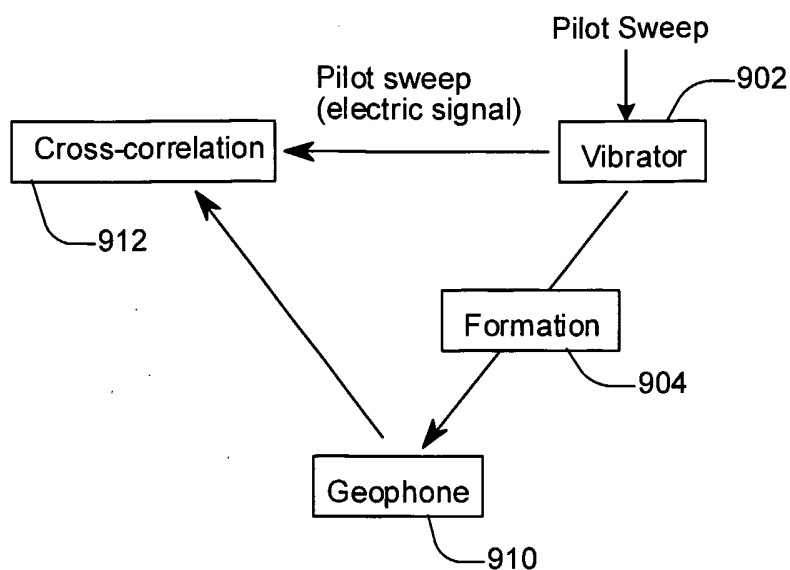


Fig. 9

900

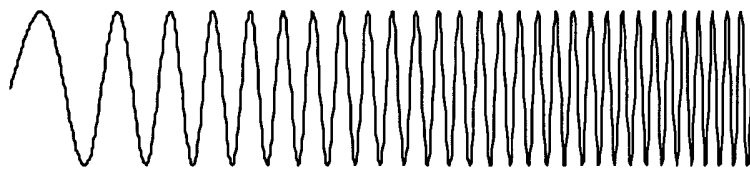


Fig. 10A

1000

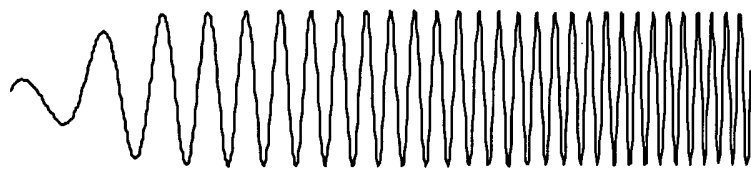


Fig. 10B

1050

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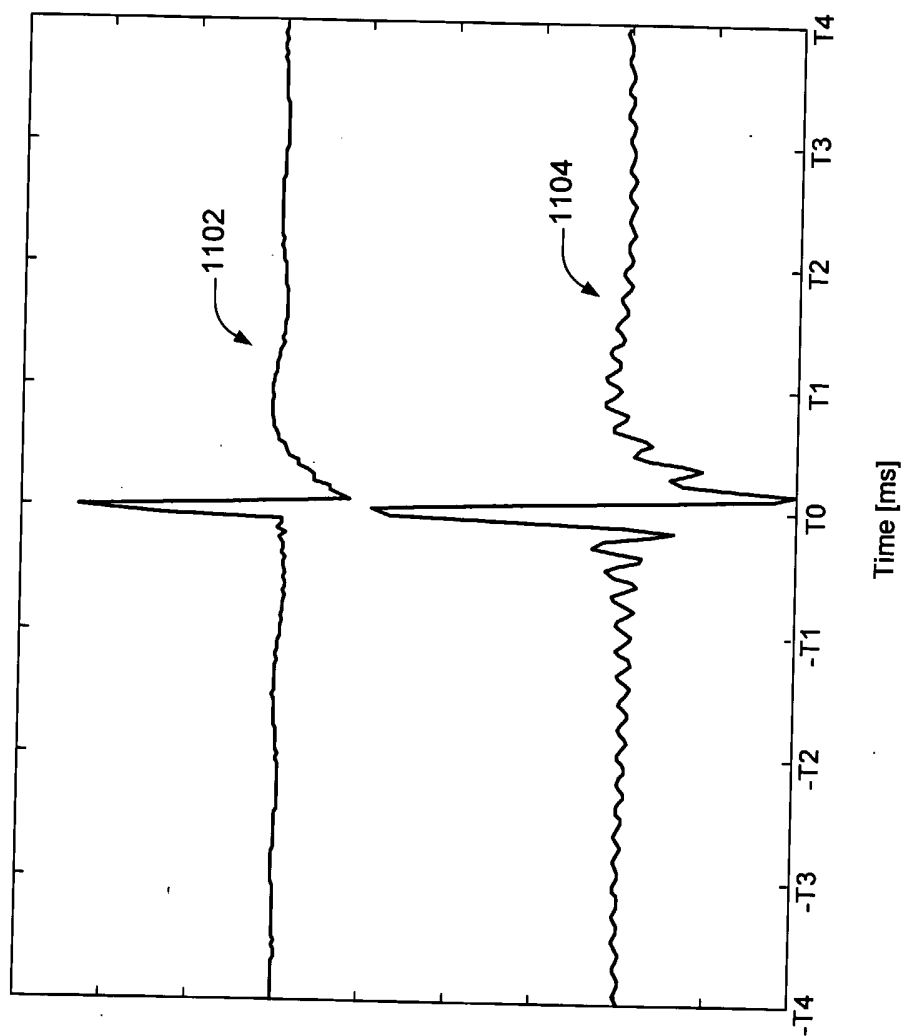


Fig. 11

1100

10/14

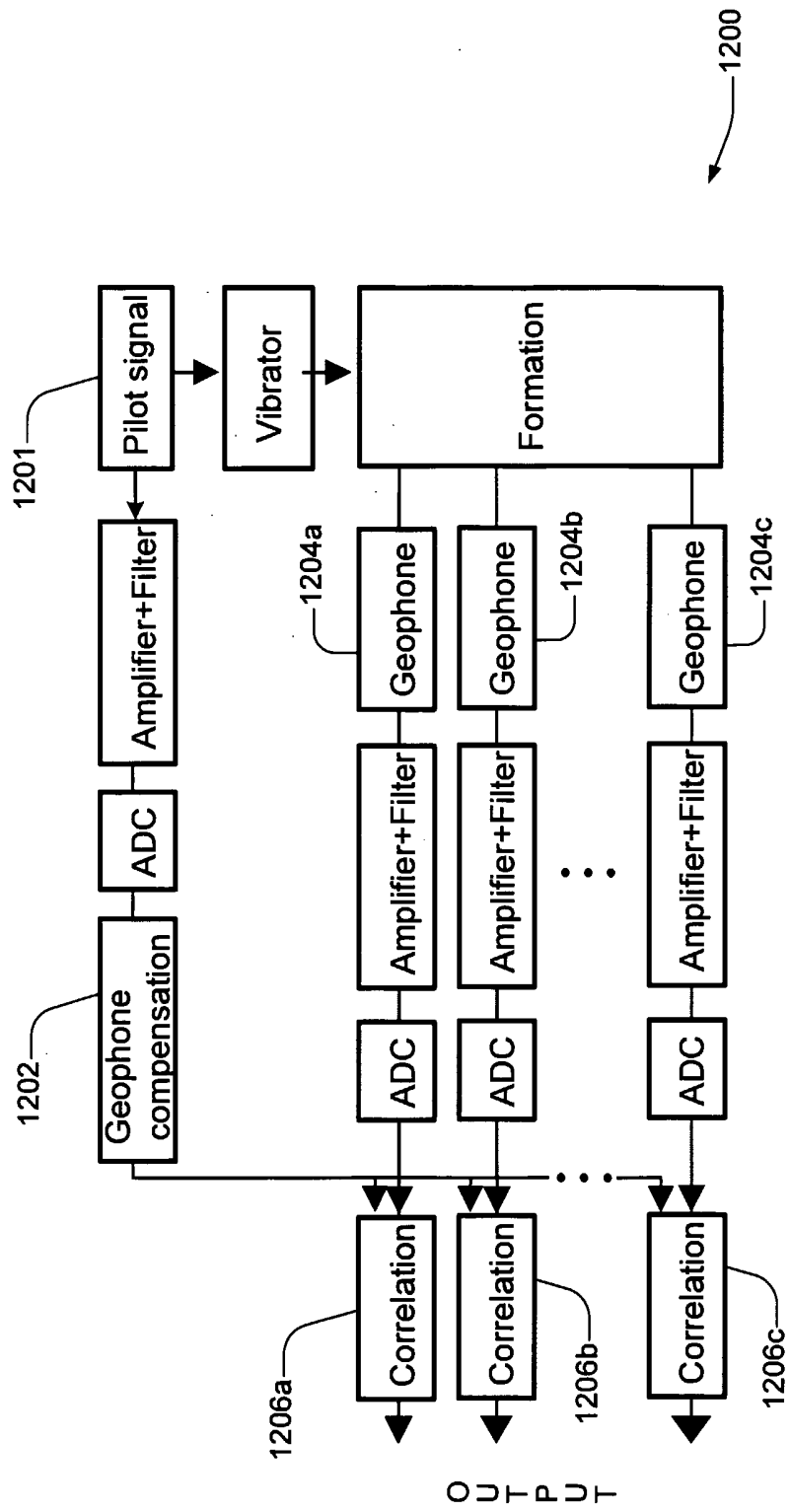
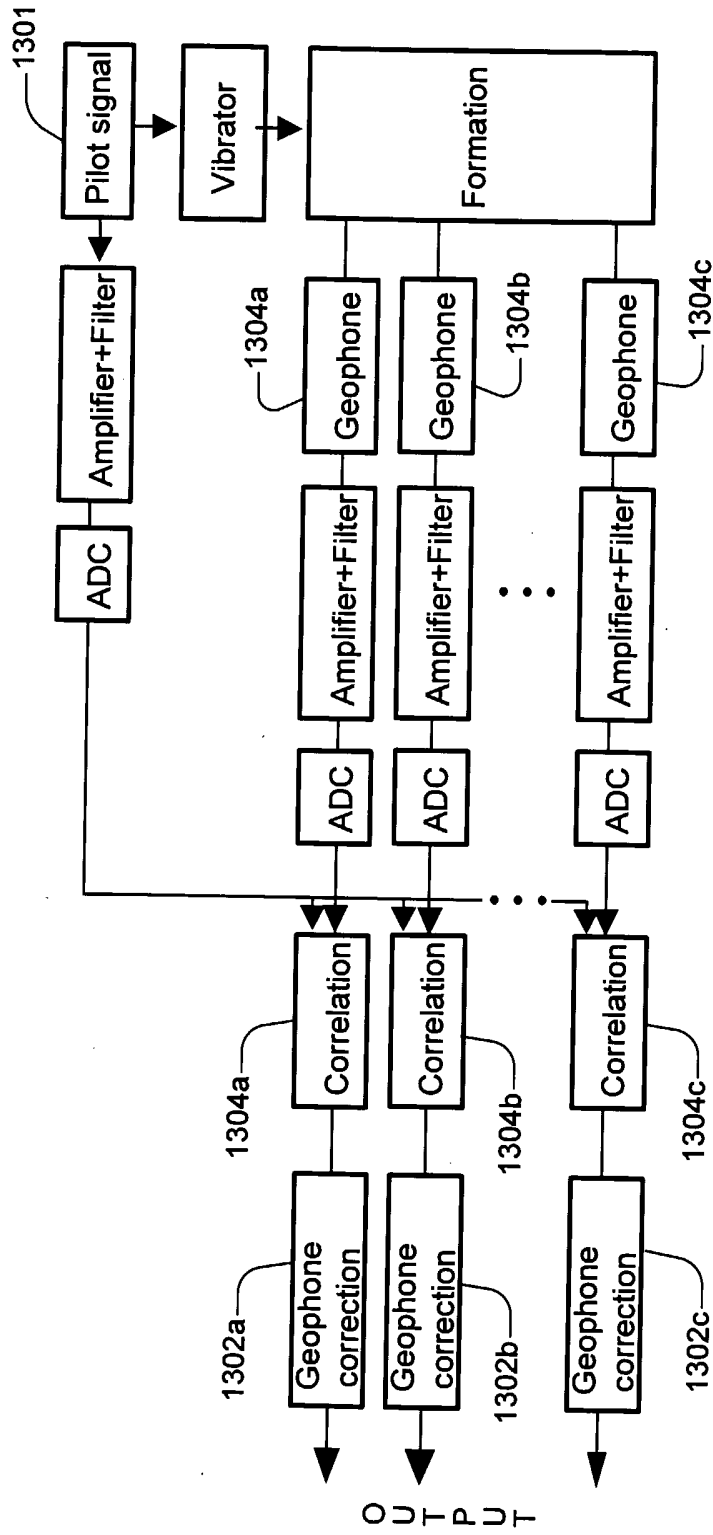


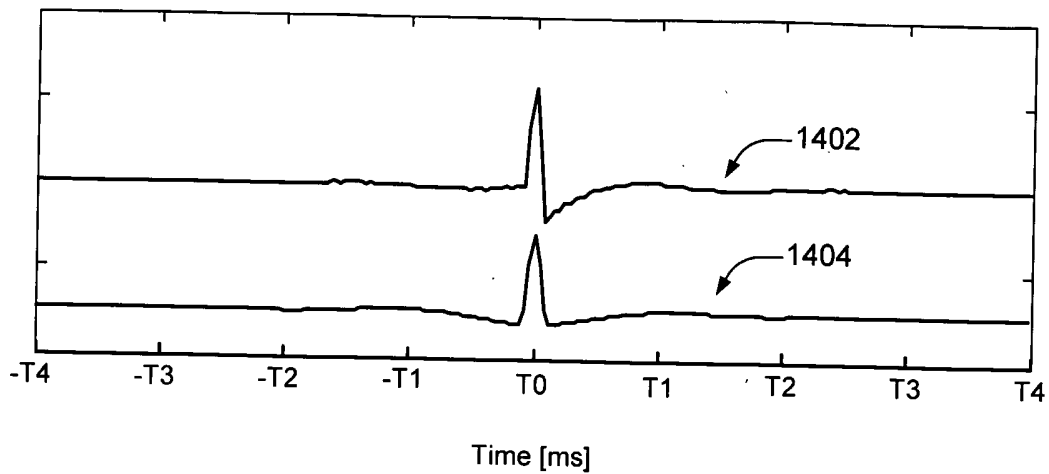
Fig. 12

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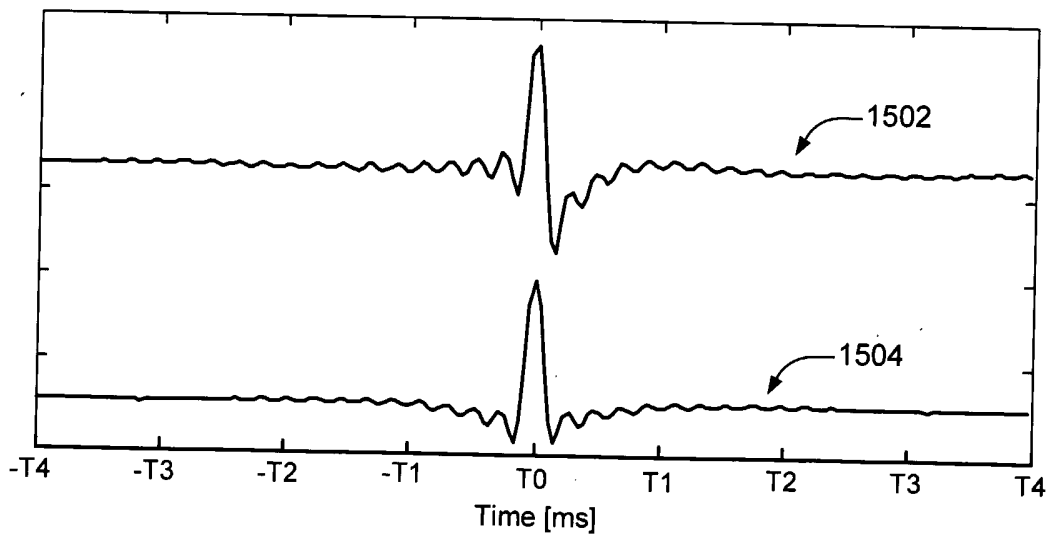


1300 Fig. 13

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1400 Fig. 14



1500 Fig. 15

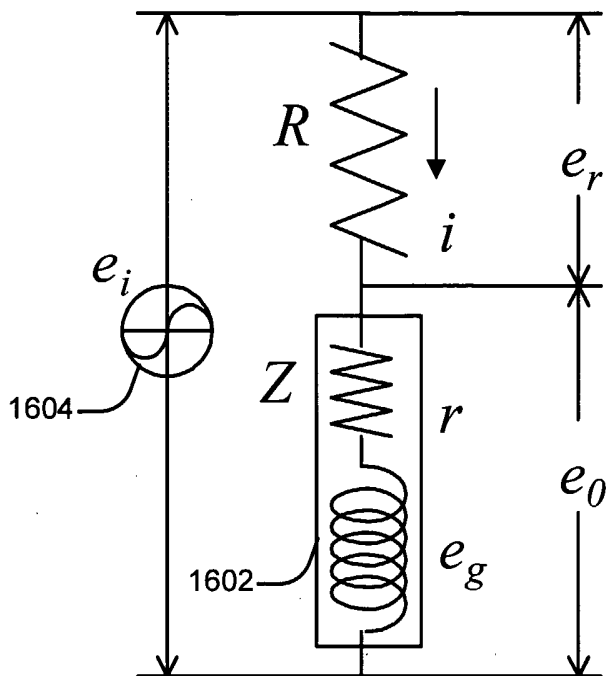
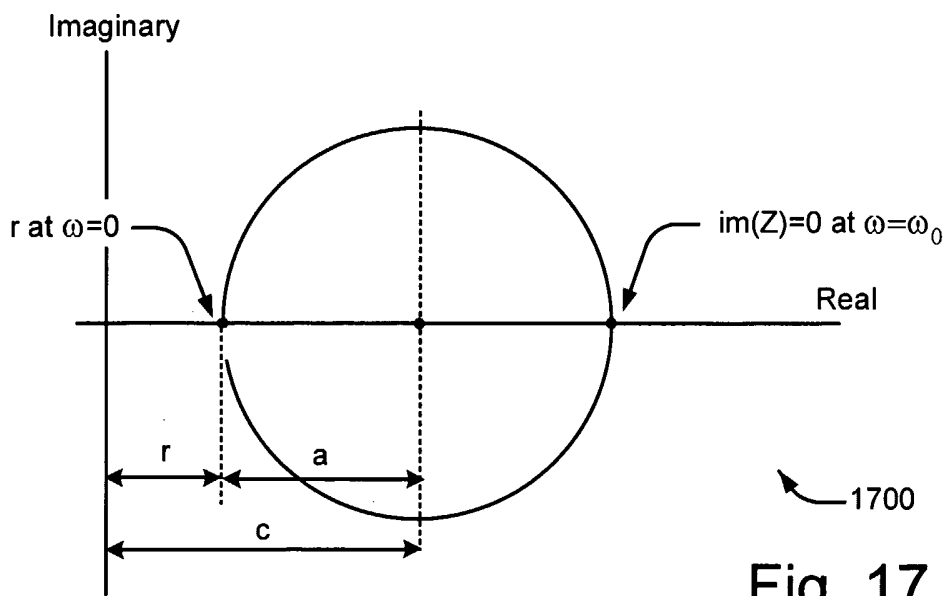


Fig. 16

1600



1700

Fig. 17

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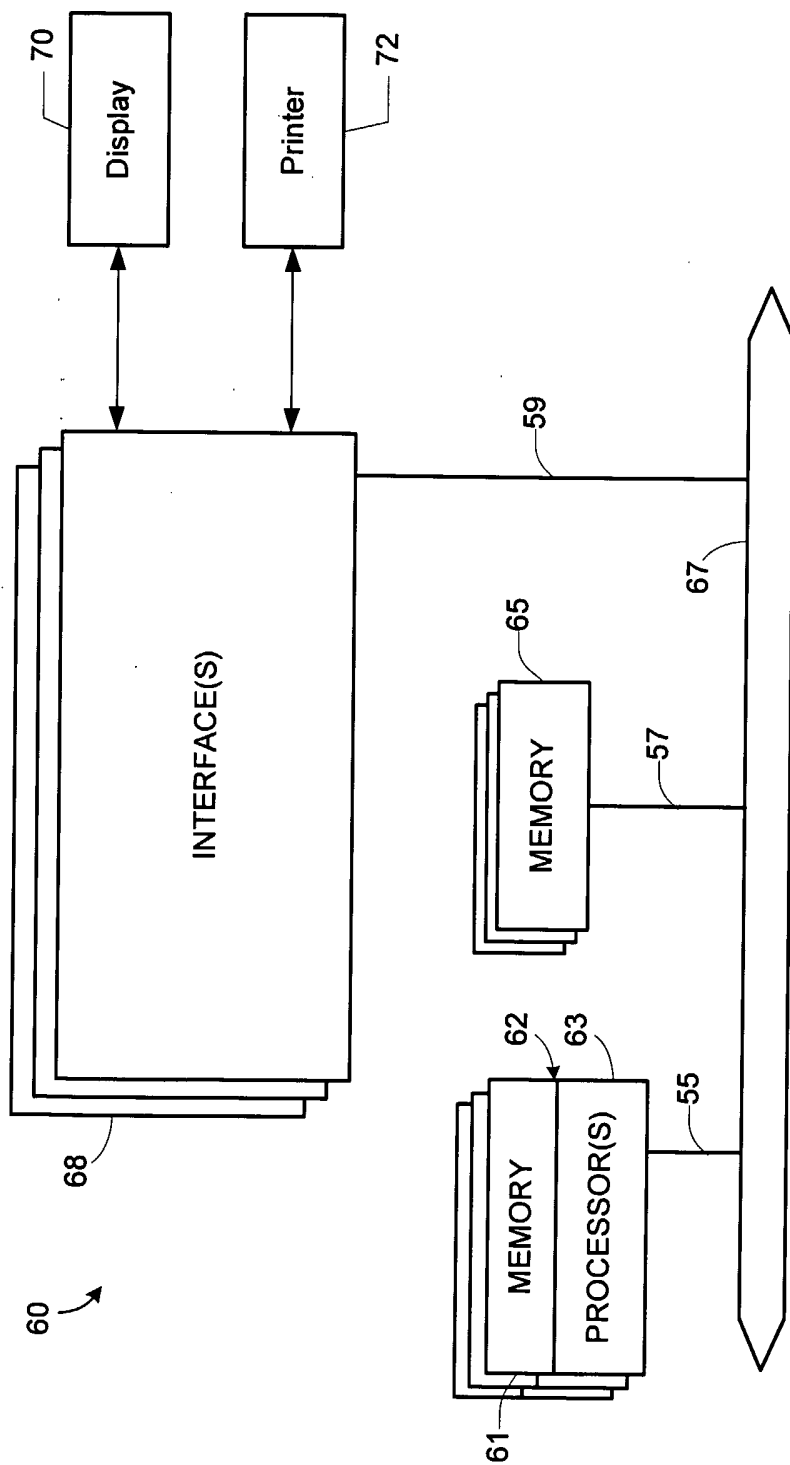


Figure 18