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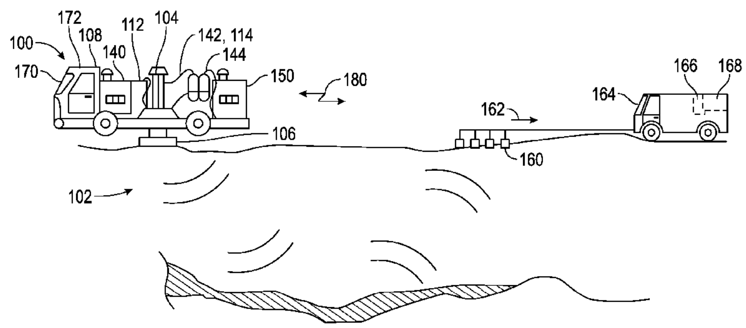

FIG. 1

(57) Abstract: A method of performing a seismic sweep determining a user-defined force at a frequency using user defined inputs; determining a maximum force at the frequency using sweep parameters; and using the maximum force to drive a seismic source if the user-defined force is greater than the maximum force.

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TITLE: METHOD OF SEISMIC VIBRATORY LIMITS CONTROL AT LOW FREQUENCIES

INVENTOR(S): PHILLIPS, Thomas; WEI, Zhouhong; and CHEN, Ruru

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0001] The present disclosure generally relates to seismic prospecting and in particular to methods and apparatus for generating seismic source signals with enhanced seismic frequency sweeps.

2. Description of the Related Art

[0002] In the oil and gas exploration industry, geophysical tools and techniques are commonly employed in order to identify a subterranean structure having potential hydrocarbon deposits. Many different techniques are used to generate a seismic signal.

[0003] Seismic vibratory energy sources have been used in the field many years. A seismic vibrator in its simplest form is merely a heavy vehicle that has the ability to shake the ground at a predetermined range of frequencies of about **2** to **100** Hz. The vibrator imparts a signal into the subsurface of the earth over a relatively long period of time, which allows for an energy level less than impulse generators such as dynamite.

[0004] The imparted energy, known as the seismic source signal or "pilot" signal, travels through the subsurface and reflects some of the energy from certain subsurface geological boundaries or layers. The reflected energy is then transmitted back to the earth's surface where it is recorded using an earth motion detector. The recorded data is processed to yield information about a location and physical properties of layers making up the subsurface.

[0005] The seismic vibrator source signal is typically a sweep signal, or simply sweep. Sweeps are sinusoidal vibrations in the **2**-**100** Hz range described above and having a duration on the order of **2** to **20** seconds depending on the terrain, the subsurface lithology, economic constraints and physical capabilities of the vibrator. The sinusoidal sweep can be increased in frequency overtime, which is called an "upsweep." The upsweep is the signal used typically in modern seismic exploration. Also, the sinusoidal sweep can be decreased in frequency overtime, which is called a "downsweep." The end products of the vibrator sweep are waves that propagate through the earth to return clues about the subsurface.

[0006] The present disclosure provides methods and devices for enhancing seismic sweeps.

SUMMARY OF THE DISCLOSURE

[0007] In aspects, the present disclosure provides methods, systems and products related to performing a seismic sweep. The sweep may be performed by determining a user-defined force at a frequency using user defined vibrator control inputs; determining a maximum force at the frequency using sweep parameters; and driving a seismic source at the frequency in dependence upon the maximum force if the user-defined force is greater than the maximum force at the frequency. Driving the seismic source at the frequency in dependence upon the maximum force may be carried out by driving the seismic source at an amplitude derived using the maximum force; or by scaling the maximum force and driving the seismic source at an amplitude derived using the scaled maximum force.

[0008] The user-defined force may be determined at a plurality of frequencies, and driving the seismic source may be carried out in dependence upon the maximum force at each frequency where the user-defined force is greater than the maximum force.

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[0009] System aspects may include at least one processor configured to control a seismic source. The system may also include a seismic source in communication with and configured to respond to one or more of the processor(s). The at least one processor may be configured to implement methods described herein. For example, the processor may be configured to determine a user-defined force at a frequency using user defined vibrator control inputs; determine a maximum force at the frequency using sweep parameters; and drive the seismic source at the frequency in dependence upon the maximum force if the user-defined force is greater than the maximum force at the frequency.

[0010] A machine-readable medium product aspect may have instructions thereon, that when executed by at least one processor, cause the processor to perform a method described herein. For example the instructions may be for a method for performing a seismic sweep in an earth formation, comprising determining a user-defined force for a seismic source at a frequency using user defined vibrator control inputs; determining a maximum force at the Frequency using sweep parameters; and determining a signal for driving the seismic source, the signal driving the source in dependence upon the maximum force if the user-defined force is greater than the maximum force at the frequency. The product may include further instructions for driving a seismic source according to the signal.

[0010a] According to one aspect of the present application, there is provided a method of performing a seismic sweep, comprising:

determining a user-defined seismic sweep signal over a plurality of frequencies using user defined vibrator control inputs;

determining a maximum force of a seismic source at each frequency of the seismic sweep signal using sweep parameters derived from the user-defined seismic sweep signal; and

driving the seismic source according to the seismic sweep signal in dependence upon the maximum force and at an amplitude modulated to the maximum force if a force of the seismic sweep signal is greater than the maximum force at a frequency of the seismic sweep signal.

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[0010b] According to another aspect of the present application, there is provided a system for performing a seismic sweep in an earth formation, comprising:

a seismic source comprising at least one processor, wherein the at least one processor is configured to:

determine user-defined seismic sweep signal over a plurality of frequencies using user defined vibrator control inputs;

determine a maximum force the seismic source at each frequency of the seismic sweep signal using sweep parameters derived from the user-defined seismic sweep signal; and

drive the seismic source according to the seismic sweep signal in dependence upon the maximum force and at an amplitude modulated to the maximum force if a force of the seismic sweep signal is greater than the maximum force at a frequency of the seismic sweep signal.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] For detailed understanding of the present disclosure, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

[0012] **FIG. 1** illustrates a typical seismic data acquisition operation utilizing aspects of the present disclosure;

[0013] **FIG. 2** is a schematic representation of functional features of a vibratory seismic source such as the source of **FIG. 1**;

[0014] **FIG. 3** illustrates a method for generating a composite force profile envelope in accordance with one embodiment of the present disclosure;

[0015] **FIG. 4** illustrates a force profile envelope generated using an equation for maximum reaction mass displacement in accordance with one embodiment of the present disclosure; and

[0016] **FIG. 5** illustrates a force curve having an amplitude reduced in accordance with one embodiment of the present disclosure.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0017] As will be appreciated from the discussion below, aspects of the present disclosure provide methods of limiting a drive level at each frequency of a frequency sweep using calculated force limits. When driven at low frequencies, the maximum force that can be generated by a seismic source is limited by the reaction mass weight and the maximum distance the reaction mass can travel. If the vibrator control electronics attempt to drive the reaction mass to produce more force, the distance in which the reaction mass can travel will exceed the physical limits and can cause damage to the vibrator. Methods and devices according to the present disclosure may improve the sweep performance and sweep quality (peak and average phase, force, and distortion) by preventing the reaction mass from hitting the stops and thereby creating spikes in phase and distortion.

[0018] **FIG. 1** depicts a geophysical survey layout that may use target seismic frequency sweeps developed in accordance with embodiments of the present disclosure. A seismic source **100** is positioned at a predetermined location in an area of exploration and coupled to the earth. In the embodiment shown the seismic source **100** is a truck-carried vibratory seismic source. The vibratory seismic source **100** may be a single axis source imparting, for example, only compression P-waves into the earth. Those skilled in the art would recognize that a multi-axis vibratory source capable of imparting both P and S waves into the earth can be configured according to the present disclosure described in detail herein below without additional illustration or description. Therefore, the present disclosure will focus on a single axis seismic source for brevity and without limiting the scope of the disclosure.

[0019] The seismic source **100** includes a truck **170** having a cab **172** housing a controller **108**. The seismic source includes a hydraulic subsystem **140** used to move a reaction mass **104**. As will be described in more detail in reference to **FIG. 2**, the moving reaction mass **104** acts upon a base plate **106** to impart a seismic source signal **102** into the earth. The signal **102** travels through the earth, reflects at discontinuities and formations, and travels toward the earth's surface.

[0020] A plurality of sensors **160** are coupled to the earth in an array spaced apart from the seismic source **100**. The sensors **160** detect the reflected source signal **102**, and electrical signals **162**, which may be digital and/or analog, are transmitted from the array of sensors **160** to a recording station (not shown) typically housed in a truck. The recording station includes a seismic recorder **168** and may also include a correlation processor, which also receives an electrical signal **180** indicative of the actual source signal **102** imparted into the earth.

[0021] Still referring to **FIG. 1**, the seismic source **100** comprises several subsystems having system components used in generating the seismic signal **102**. The system **100** includes a hydraulic pump subsystem **140** having hydraulic lines **142** carrying hydraulic fluid **114** to a servo valve assembly **112**. A cooler **150** is typically present to cool the hydraulic subsystem. Low frequency accumulators **144** mounted on the truck are relatively large, e.g. about ten gallons or more, and serve to dampen low frequency noise, e.g. about **25** Hz or less, caused by operation of the hydraulic system.

[0022] **FIG. 2** schematically illustrates a seismic signal generating system **100** substantially as described above and shown in **FIG. 1** for imparting a sinusoidal seismic signal **102** into the earth. Reference numerals are aligned with the like components of **FIG. 1**. The base plate **106** is coupled via static weight to the earth. The reaction mass **104** is movably coupled to the base plate **106** such that controlled movement of the reaction mass **104** via the hydraulic subsystem **140** vibrates the base plate **106** at a desired amplitude and frequency or sweep to generate the signal **102**. The controller **108** includes a processor **110** for controlling the system **100**. The controller is electrically coupled to the servo valve assembly **112**. The servo valve assembly **112** includes a servo motor **120**, a pilot valve **122** and a main stage valve **124**.

[0023] The servo valve assembly **112** controls fluid movement in the hydraulic subsystem **140**, which provides a force for moving the reaction mass **104**. An electrical signal **116** having characteristics of the desired sweep signal is transmitted from the controller **108** to the servo motor, which operates the pilot valve **122**. The pilot valve **122** is coupled to the main stage valve **124** and includes a hydraulic coupling for transferring hydraulic pressure to operate the main stage valve. When operated, the main stage valve pressurizes and depressurizes hydraulic passages (not shown) to move the reaction mass **104** according to the controller signal.

[0024] In aspects of the disclosure the seismic signal **102** is created by regulating the flow of the pressurized hydraulic fluid **114** against the reaction mass **104**, forcing the reaction mass **104** to reciprocate vertically rapidly and repeatedly. Acoustic characteristics of this vibration are controlled by regulating the flow of the hydraulic fluid **114** to adjust the speed and force of the reaction mass **104**.

[0025] Referring now to **Fig. 3**, there is shown one method **200** for controlling vibratory limits of seismic source **100** (**Fig. 1**). At step **202**, a user may input entries into the vibrator control electronics. These entries may include reaction mass weight and usable reaction mass stroke limits. These entries may be processed to generate amplitudes for operating the seismic source **100** (**Fig. 1**). At step **204**, an information processor (e.g., a microprocessor) associated with the vibrator control electronics may determine the force at each sample based on the sweep parameters such as sweep length, start taper, end taper, drive level, peak output force, hold down weight, start frequency, end frequency, and sweep type. This determination may be output as an “envelope” defining the maximum force at each sample frequency. At step **206**, the force associated with the user entries is compared with the force determined at step **204** for each frequency. Specifically, if the force associated with the user entries exceeds the force determined at a particular frequency, then the value determined at step **204** will be applied to over-ride the amplitude of the user’s entries at that particular frequency. At step **208**, the seismic source **100** (**Fig. 1**) is driven using the selected amplitude.

[0026] In another embodiment, the **Fig. 3** method may be used in connection with a software application that allows a user to enter the sweep and vibrator parameters and produces a file or samples of the sweep that are later transmitted to the vibrator control electronics manually, via radio communication (VHF, WiFi, UHF, etc.), or hard wire (USB, Ethernet, RS232, etc.). The sweep and vibrator parameters may be entered into the vibrator control electronics manually, via radio communication (VHF, WiFi, UHF, etc.), or hard wire (USB, Ethernet, RS232, etc.).

[0027] The envelope determined at step **204** may be developed using a variety of mathematical models and equations by using experimental / empirical values. In one non-limiting example the equations below may be used to estimate the maximum drive level at each frequency of the frequency sweep.

Displacement Limiting Equations:

$F = m \times a$ (Newton's 2^{nd} Law)

$Y = A \times \sin(\omega \times t)$ (Sinusoidal Displacement)

$\dot{Y} = \mathrm{A} \times \omega \times \cos(\omega \times t)$ (Sinusoidal Velocity)

$\ddot{Y} = -A \times \omega^2 \times \sin(\omega \times t)$ (Sinusoidal Acceleration)

$$F = m \times [-A \times \omega^2 \times \sin(\omega \times t)]$$

To find the maximum fundamental peak force at low frequencies:

$Max[\sin(\omega \times t)] = 1$, $a_{max} = |-A \times \omega^2| = A \times \omega^2$

$$F = m \times A \times \omega^2$$

m is the mass of the reaction mass, m_{RM}

A is the peak amplitude of displacement of reaction mass

$A = \frac{S_{RM}}{2}$, S_{RM} is the usable stroke

$\omega = 2 \times \pi \times f$, f is frequency

$$\boldsymbol{F = m_{RM} \times \frac{S_{RM}}{2} \times (2 \times \pi \times f)^2}$$

[0028] Referring now to **Fig. 4**, there is shown a graph **220** for illustrating the **Fig. 3** method. The graph **220** shows frequency versus force for an exemplary sweep. Line **226** is a force associated with user defined inputs as determined at step **202**. Line **222** is a maximum theoretical force associated determined at step **204**. Line **224** is a line obtained by scaling the line **222** (e.g., 90%). This scaling may be used to introduce a margin of safety to narrow the operating envelope. As can be seen, at the lower frequency region **228**, the line **226** exceeds the maximum value of both lines **222** and **224**. The region **228** is demarked at the points where either lines **222** or **224** intersect line **226**. Thus, the force values of line **222** or line **224** (if a safety margin is desired) are to drive the seismic source **100** in the region **228**. Once outside the region 248, the user defined inputs are used to drive the seismic source **100**.

[0029] Referring now to **Fig. 5**, there is shown a curve **260** illustrating user defined amplitudes and a curve **260** that that has been modified using the Fig. 3 method. As should be appreciated, the frequency remains unchanged, but the amplitude has been reduced.

[0030] Portions of the present disclosure pertaining to “software aspects” of the disclosure are used herein. These aspects include detailed description and claims in terms of logic, software or software implemented aspects typically encoded on a variety of media including, but not limited to, computer-readable media, machine-readable media, program storage media, or computer program product. Such media may be handled, read, sensed and/or interpreted by an information processing device. Those skilled in the art will appreciate that such media may take various forms such as cards, tapes, magnetic disks (e.g., floppy disk or hard drive) and optical disks (e.g., compact disk read only memory ("CD-ROM") or digital versatile (or video) disc ("DVD")). Any embodiment disclosed herein is for illustration only and not by way of limiting the scope of the disclosure or claims.

[0031] The term “information processing device,” “processor,” “computer,” or “controller” as used herein includes, but is not limited to, any device that transmits, receives, manipulates, converts, calculates, modulates, transposes, carries, stores or otherwise utilizes information. In several non-limiting aspects of the disclosure, an information processing device includes a computer that executes programmed instructions for performing various methods.

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CLAIMS:

1. A method of performing a seismic sweep, comprising:

determining a user-defined seismic sweep signal over a plurality of frequencies using user defined vibrator control inputs;

determining a maximum force of a seismic source at each frequency of the seismic sweep signal using sweep parameters derived from the user-defined seismic sweep signal; and

driving the seismic source according to the seismic sweep signal in dependence upon the maximum force and at an amplitude modulated to the maximum force if a force of the seismic sweep signal is greater than the maximum force at a frequency of the seismic sweep signal.

2. The method of claim 1, further comprising determining a scaled maximum force at each frequency of the seismic sweep signal by scaling the maximum force by a pre-determined factor; and wherein driving the seismic source according to the seismic sweep signal comprises driving the seismic source at an amplitude modulated to the scaled maximum force if the force of the seismic sweep signal is greater than the scaled maximum force at the frequency of the seismic sweep signal.

3. The method of claim 1, wherein the sweep parameters include at least one of: (i) sweep length, (ii) start taper, (iii) end taper, (iv) drive level, (v) peak output force, (vi) hold down weight, (vii) start frequency, (viii) end frequency, and (ix) sweep type.

4. A system for performing a seismic sweep in an earth formation, comprising:

a seismic source comprising at least one processor, wherein the at least one processor is configured to:

determine a user-defined seismic sweep signal over a plurality of frequencies using user defined vibrator control inputs;

determine a maximum force of the seismic source at each frequency of the seismic sweep signal using sweep parameters derived from the user-defined seismic sweep signal; and

drive the seismic source according to the seismic sweep signal in dependence upon the maximum force and at an amplitude modulated to the maximum force if a force of the

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seismic sweep signal is greater than the maximum force at a frequency of the seismic sweep signal.

5. The system of claim 4, wherein the at least one processor is further configured to:

determine a scaled maximum force at each frequency of the seismic sweep signal by scaling the maximum force by a pre-determined factor; and

wherein driving the seismic source according to the seismic sweep signal comprises driving the seismic source at an amplitude modulated to the scaled maximum force if the force of the seismic sweep signal is greater than the scaled maximum force at the frequency of the seismic sweep signal.

6. The system of claim 4, wherein the sweep parameters include at least one of: (i) sweep length, (ii) start taper, (iii) end taper, (iv) drive level, (v) peak output force, (vi) hold down weight, (vii) start frequency, (viii) end frequency, and (ix) sweep type.

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Patent Attorneys for the Applicant/Nominated Person

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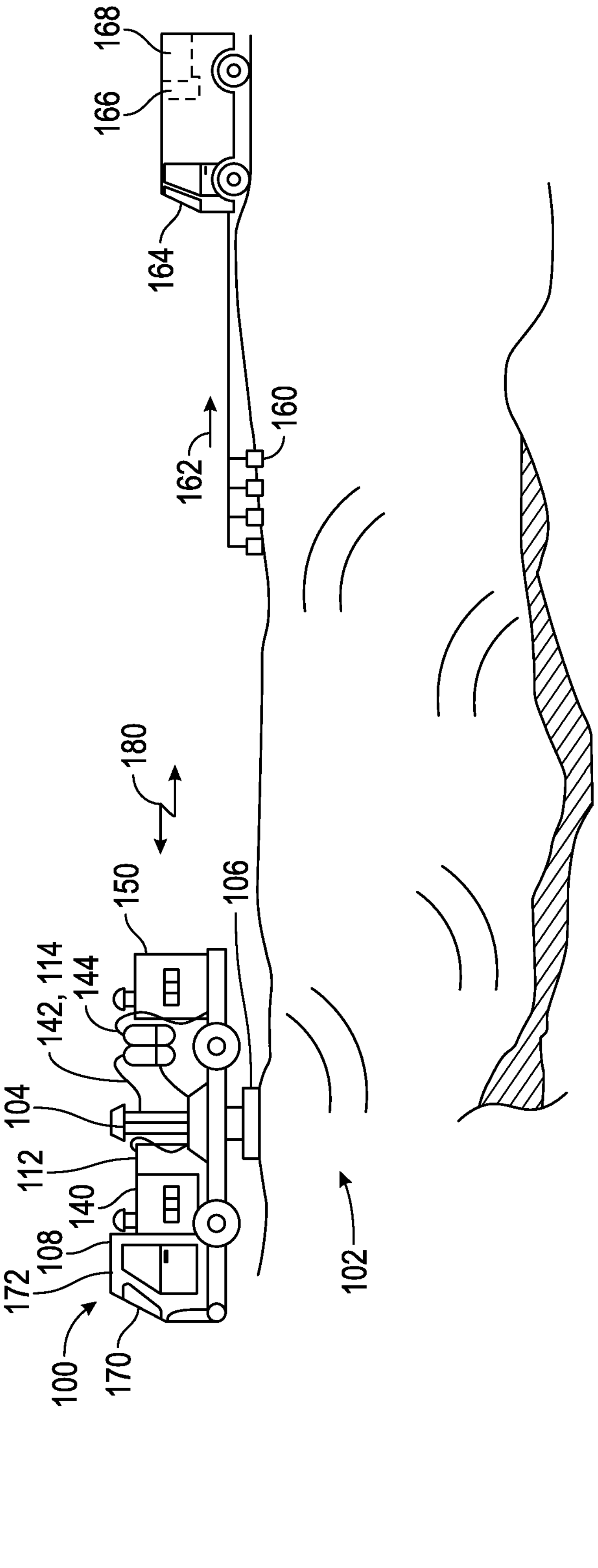
168
166
164
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180
150
142, 114
144
106
104
112
140
108
172
100
170
102

FIG. 1

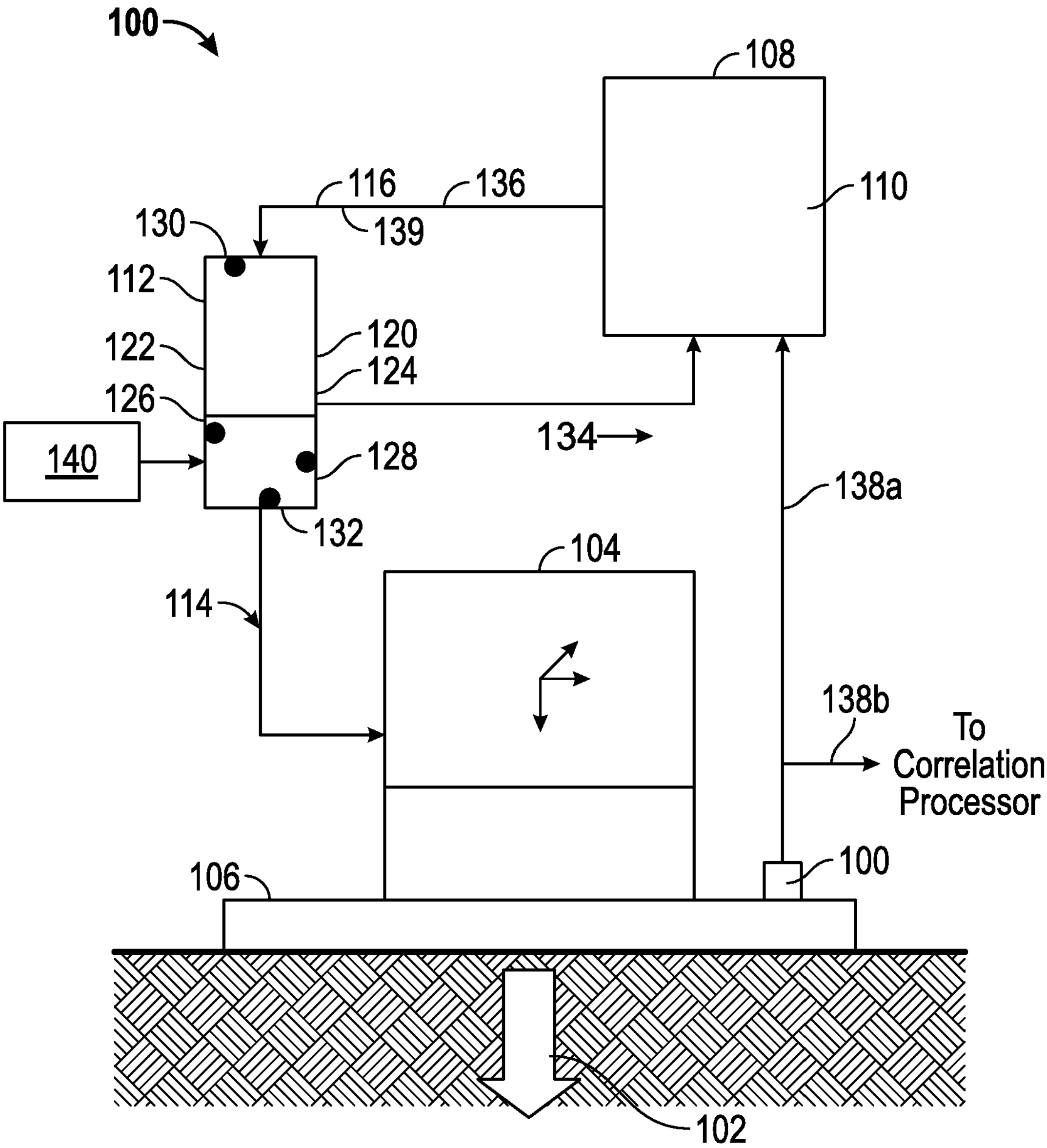
100
108
116
136
110
130
139
112
120
122
124
126
140
134
128
138a
132
104
114
138b
To Correlation Processor
100
106
102

FIG. 2

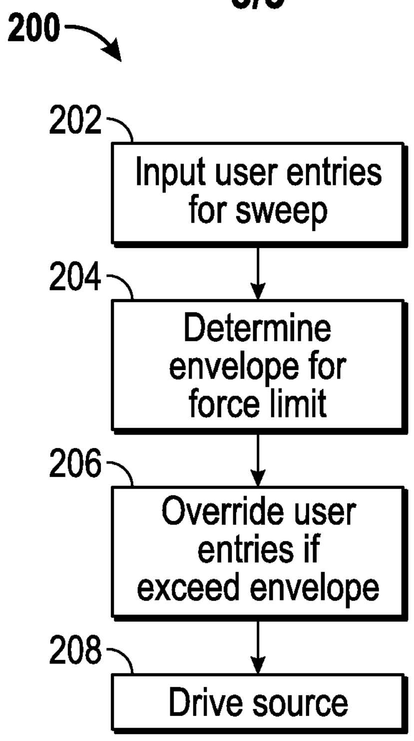

FIG. 3

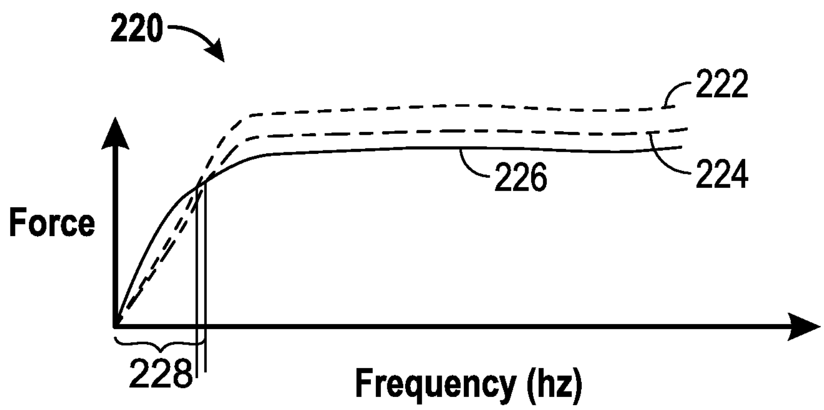

FIG. 4

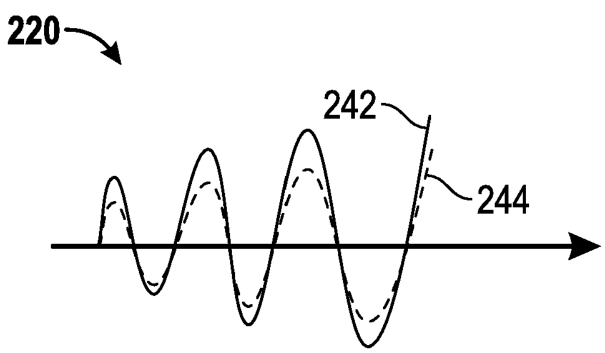

FIG. 5