Innovation, Sciences et
Développement économique Canada
Office de la Propriété Intellectuelle du Canada

Innovation, Science and
Economic Development Canada
Canadian Intellectual Property Office

CA 3216821 A1 2022/12/01

(21) 3 216 821

(12) DEMANDE DE BREVET CANADIEN
CANADIAN PATENT APPLICATION

(13) A1

(86) **Date de dépôt PCT/PCT Filing Date:** 2021/05/27
(87) **Date publication PCT/PCT Publication Date:** 2022/12/01
(85) **Entrée phase nationale/National Entry:** 2023/10/13
(86) **N° demande PCT/PCT Application No.:** US 2021/034569
(87) **N° publication PCT/PCT Publication No.:** 2022/250674

(51) **Cl.Int./Int.Cl.** ***E21B 47/01*** (2012.01),
E21B 47/017 (2012.01)

(71) **Demandeur/Applicant:**
VECTOR MAGNETICS LLC, US

(72) **Inventeurs/Inventors:**
GARCIA, MARIANO, US;
KUCKES, ARTHUR F., US;
THOMPSON, MORGAN, US

(74) **Agent:** TORYS LLP

(54) **Titre : ENSEMBLE DE FOND DE TROU AVEC FILTRE D'ISOLATION DE RESSORT**
(54) **Title: A DOWNHOLE ASSEMBLY WITH SPRING ISOLATION FILTER**

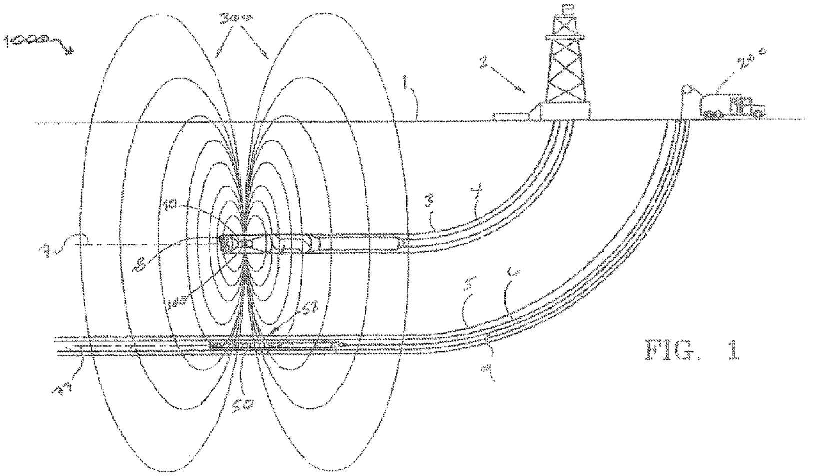


FIG. 1

(57) **Abrégé/Abstract:**

The present invention is directed to an apparatus for use on a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum. The apparatus has a housing assembly including a first end, a second end, and one or more protective enclosures configured to accommodate one or more devices. The housing assembly is configured to be rotationally registered to the structural member when coupled to the structural member, and is characterized by a predetermined housing mass. A spring arrangement is coupled between the structural member and the first end and/or coupled between the structural member and the second end in the operational state. The spring arrangement is characterized by a predetermined force-displacement relationship. The housing assembly and the spring arrangement form an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship. The predetermined spectral transfer function includes a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing member is substantially isolated from the stress wave energy.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
01 December 2022 (01.12.2022)

WIPO | PCT

(10) **International Publication Number**
WO 2022/250674 A1

(51) **International Patent Classification:**
E21B 47/01 (2012.01) *E21B 47/017* (2012.01)

(21) **International Application Number:**
PCT/US2021/034569

(22) **International Filing Date:**
27 May 2021 (27.05.2021)

(25) **Filing Language:** English

(26) **Publication Language:** English

(71) **Applicant: VECTOR MAGNETICS LLC** [US/US]; 236 Cherry Street, Ithaca, NY 14850 (US).

(72) **Inventors: GARCIA, Mariano**; 3 Stormy View Drive, Ithaca, NY 14850 (US). **KUCKES, Arthur, F.**; 318 Savage Farm Drive, Ithaca, NY 14850 (US). **THOMPSON, Morgan**; 3053 Dubois Road, Ithaca, NY 14850 (US).

(74) **Agent: PRICE, Frederick, J.m.** et al.; Bond, Schoeneck & King, PLLC, One Lincoln Center, Syracuse, NY 13202 (US).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, IT, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,

(54) **Title:** A DOWNHOLE ASSEMBLY WITH SPRING ISOLATION FILTER

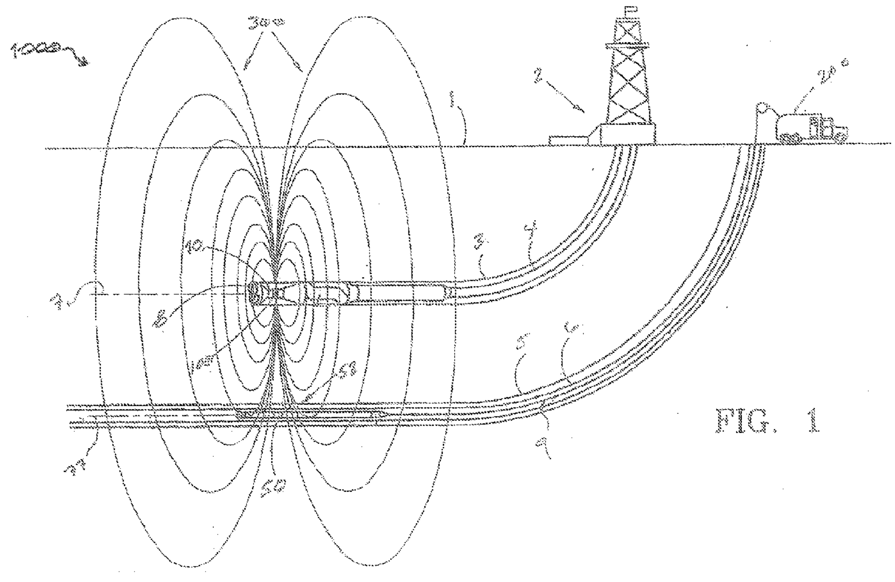


FIG. 1

(57) **Abstract:** The present invention is directed to an apparatus for use on a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum. The apparatus has a housing assembly including a first end, a second end, and one or more protective enclosures configured to accommodate one or more devices. The housing assembly is configured to be rotationally registered to the structural member when coupled to the structural member, and is characterized by a predetermined housing mass. A spring arrangement is coupled between the structural member and the first end and/or coupled between the structural member and the second end in the operational state. The spring arrangement is characterized by a predetermined force-displacement relationship. The housing assembly and the spring arrangement form an isolation filter characterized by a predetermined spectral transfer function, the predetermined

WO 2022/250674 A1

[Continued on next page]

UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report (Art. 21(3))*

spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship. The predetermined spectral transfer function includes a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing member is substantially isolated from the stress wave energy.

A DOWNHOLE ASSEMBLY WITH SPRING ISOLATION FILTER

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates generally to an apparatus and method for drilling boreholes, and particularly to a downhole assembly and method for generating rotating magnetic fields or sensing magnetic fields (or other such parameters) used for guiding directional drilling of a borehole.

2. Technical Background

[0002] In underground drilling operations such as oil and gas drilling operations, it is often desirable to precisely control the drilling path of a new borehole relative to a known location (which may be disposed within the pathway of an existing borehole). To do that, operators may precisely monitor the location of the drill bit forming the new borehole relative to the existing borehole. For example, when a group of wells are drilled from an offshore platform, it is often necessary to drill new wells spaced three meters or less from existing wells for 300 meters or more during the initial depth interval. Subsequently, the wells may be directionally deviated and drilled to targets which may be two kilometers or more away in lateral directions. In another example application, this procedure may be useful when twin horizontal wells are drilled for the steam-assisted gravity drainage (SAGD) of heavy oils. In this example, it may be necessary to drill one well directly above the other while maintaining a five meter (±2 meter) spacing over 500 meters of horizontal extension at depths of 500 or more meters. Moreover, the present invention may be employed in various types of underground drilling operations such as geothermal drilling, mining, hammer drilling and/or other such drilling operations; and the present invention should not be deemed to be limited to the aforementioned examples.

[0003] The monitoring system used to control the drilling operations can include a magnetic field sensor that is disposed in the existing borehole and a magnetic source that is disposed in the new borehole. Specifically, the magnetic source assembly may be disposed in a drill string proximate the drill bit/tool. The magnetic source generates rotating magnetic fields. The sensor apparatus typically includes a magnetometer assembly that is configured to measure the magnetic field radiating from the magnetic source assembly. The sensor apparatus precisely calculates the location of the source from the field measurements. In this way, the drilling of the new borehole may be precisely controlled to achieve a desired separation between the existing borehole and the new borehole.

[0004] One issue that may be associated with a magnetic source assembly or a sensor assembly relates to their sensitivity to stress waves. Briefly stated, the drilling process may generate stress waves and vibrational forces which propagate along the drill string to the magnetic source or sensor assembly. The stress waves may cause the magnetic source assembly or the sensor assembly to fail.

[0005] Another issue relates to the thermal energy generated from various sources. Those skilled in the drilling/mining arts will appreciate that a drill bit may become relatively hot during mining and drilling operations. Magnetic materials may lose their magnetic remanence if temperatures exceed the temperature rating of the magnetic material.

[0006] Another issue relates to rotationally registering the magnetic source assembly or the sensor assembly to the drill bit. Rotational registration allows the monitoring system to determine the orientation of the drill bit, as well the location of the drill bit, to more effectively control the drilling process.

SUMMARY OF THE INVENTION

[0007] The present invention substantially addresses the needs described above by providing an apparatus and method configured to substantially isolate a downhole assembly from the stress waves experienced during drilling operations. The present invention includes cooling means that direct thermal energy away from the apparatus. The present invention is also configured to rotationally register a downhole assembly to a drill bit to thus provide drill bit orientation data during the drilling control operation.

[0008] One aspect of the present invention is directed to an apparatus for use on a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state. The stress wave energy is characterized by an operational frequency spectrum. The apparatus comprises a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device. The housing assembly is configured to be rotationally registered to the structural member when coupled to the structural member. The housing assembly is characterized by a predetermined housing mass. A spring arrangement is coupled between the structural member and the first end and/or coupled between the structural member and the second end in the operational state. The spring arrangement is characterized by a predetermined force-displacement relationship. The housing assembly and the spring arrangement form an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship. The predetermined spectral transfer function includes a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing member is substantially isolated from the stress wave energy.

[0009] In one embodiment, the spring arrangement includes at least one first spring element coupled between the first end and the structural member in the operational state, and wherein the spring arrangement includes at least one second spring element coupled between the second end and the structural member in the operational state.

[0010] In one version of the embodiment, the housing assembly is substantially cylindrical, and wherein the at least one first spring element and the at least one second spring element have an outer diameter substantially equal to an outer diameter of the housing assembly.

[0011] In one version of the embodiment, the at least one first spring element includes a plurality of first spring elements coupled in parallel between the first end and the structural member in the operational state, and the at least one second spring element includes a plurality of second spring elements coupled in parallel between the second end and the structural member in the operational state.

[0012] In one version of the embodiment, the plurality of first spring elements includes four spring elements or the plurality of second spring elements includes four spring elements.

[0013] In another embodiment, the spring arrangement includes at least one compression spring, the at least one compression spring being configured to oppose compression along the longitudinal axis.

[0014] In another embodiment, the at least one device includes at least one sensor device or at least one magnetic source element.

[0015] In one version of the embodiment, the at least one sensor device includes at least one accelerometer, at least one magnetometer, a gyro sensor, at least one environmental sensor, a piezoelectric transducer, or a battery device.

[0016] In one version of the embodiment, the at least one protective enclosure includes at least one set of pockets orientated in a plane perpendicular to the longitudinal axis, and wherein each pocket of the at least one set of pockets is configured to accommodate a magnetic source element.

[0017] In another embodiment, the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies substantially greater than the natural resonant frequency, and wherein the stress wave energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum, and wherein the attenuation factor increases as the frequency f increases.

[0018] In another embodiment, the housing assembly is substantially cylindrical having an inner diameter and an outer diameter respectively defining an interior housing surface and an exterior housing surface; and wherein the housing assembly includes a first housing portion coupled to a second housing portion, each of the first housing portion and the second housing portion having a substantially semicircular cross-section so that the housing assembly has a substantially circular cross-section when the first housing portion is coupled to the second housing portion; and wherein a key channel arrangement is formed in the interior housing surface where the first housing portion coupled to the second housing portion, the key channel arrangement being configured to mate with a portion of the structural member to effect rotational registration.

[0019] In one version of the embodiment, the at least one protective enclosure includes a plurality of pockets formed in the interior housing surface or the exterior housing surface, each pocket of the plurality of pockets being configured to accommodate a magnetic source device; or wherein the at least one protective enclosure is formed in the exterior housing surface and configured to accommodate a sensor assembly.

[0020] In one version of the embodiment, the magnetic source device is selected from a group of magnetic source devices including a permanent magnet and an electromagnet.

[0021] In one version of the embodiment, a protective cover is disposed over the housing assembly in the operational state, the protective cover substantially configured to conform to the exterior housing surface.

[0022] In one version of the embodiment, the protective cover is disposed over the spring arrangement in the operational state.

[0023] In another embodiment, the predetermined force-displacement relationship includes a constant spring rate or a variable spring rate.

[0024] Another aspect of the present invention is directed to an assembly comprising a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum. An apparatus is coupled and rotationally registered to the structural member, the apparatus comprises a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device, the housing assembly being characterized by a predetermined housing mass. A spring arrangement is coupled between the structural member and the first end and/or coupled between the structural member and the second end, the spring arrangement being characterized by a predetermined force-displacement relationship. The housing assembly and the spring arrangement form an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship. The predetermined spectral transfer function includes a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing member is substantially isolated from the stress wave energy.

[0025] In an embodiment, the spring arrangement includes at least one first spring element coupled between the first end and the structural member, and at least one second spring element coupled between the second end and the structural member.

[0026] In one version of the embodiment, the at least one first spring element and the at least one second spring element have an outer diameter substantially equal to an outer diameter of the housing assembly.

[0027] In one version of the embodiment, the at least one first spring element includes a plurality of first spring elements coupled in parallel between the first end and the structural member, and wherein the at least one second spring element includes a plurality of second spring elements coupled in parallel between the second end and the structural member.

[0028] In one version of the embodiment, the plurality of first spring elements includes four spring elements and/or wherein the plurality of second spring elements includes four spring elements.

[0029] In one version of the embodiment, the structural member is a drill rod or a drill rod attachment including a central fluid channel configured to conduct a pressurized fluid along the longitudinal axis in the operational state, the structural member including a plurality of fluid openings in a region where the structural member is coupled to the housing assembly, the pressurized fluid including a gas or a liquid.

[0030] In another embodiment, the structural member includes a carrying region, a first shoulder member being disposed at a first end portion of the carrying region and a second shoulder member being disposed at a second end portion of the carrying region, wherein the housing assembly is coupled to the carrying region between the first shoulder member and the second shoulder member, and wherein the spring arrangement includes at least one first spring element coupled between the first end and the first shoulder member, and at least one second spring element coupled between the second end and the second shoulder member.

[0031] In one version of the embodiment, the structural member further comprises a box portion disposed at a first end of the structural member, a pin portion disposed at a second end of the structural member, and a carrying region being disposed between the box portion and the pin portion, the box portion being configured to accommodate a drive element of a drill string and the pin portion being configured to accommodate a tool bit or a drill bit.

[0032] In another embodiment, the spring arrangement includes at least one first spring element and at least one second spring element, and wherein the structural member further comprises a first collar member and a second collar member, and wherein the at least one first spring element is coupled between the first end and the first collar member, and wherein the at least one second spring element is coupled between the second collar member and the second end.

[0033] In one version of the embodiment, the first collar member includes a first registration feature configured to rotationally register the at least one first spring element to an orientation feature on the structural member, and/or wherein the second collar member includes a second registration feature configured to rotationally register the at least one second spring element to an orientation feature on the structural member.

[0034] In another embodiment, the at least one device includes at least one sensor device or at least one magnetic source element.

[0035] In one version of the embodiment, the at least one sensor device includes at least one accelerometer, at least one magnetometer module, a gyro sensor, at least one environmental sensor, a piezoelectric transducer, or a battery device.

[0036] In one version of the embodiment, the at least one protective enclosure includes at least one set of pockets orientated in a plane perpendicular to the longitudinal axis, and wherein each pocket of the at least one set of pockets is configured to accommodate a magnetic source element.

[0037] In another embodiment, the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies substantially greater than the natural resonant frequency, wherein the stress wave energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum and wherein the attenuation factor increases as the frequency f increases.

[0038] In another embodiment, the predetermined force-displacement relationship includes a constant spring rate or a variable spring rate.

[0039] Another aspect of the present invention is directed to a method comprising: providing a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum; providing a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device, the housing assembly being characterized by a predetermined housing mass; providing a spring arrangement, the spring arrangement being characterized by a predetermined force-displacement relationship, the housing assembly and the spring arrangement forming an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship, the predetermined spectral transfer function including a passband having frequencies that are substantially outside the operational frequency spectrum; coupling the housing assembly to the structural member such that the housing assembly is rotationally registered to the structural member; coupling the spring arrangement between the structural member and the first end and/or between the structural member and the second end; and entering an operational state wherein stress wave energy propagates along the structural member, the stress wave energy being substantially attenuated by the isolation filter so that the housing member is substantially isolated from the stress wave energy.

[0040] In another embodiment, the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies substantially greater than the natural resonant frequency, wherein the stress wave energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum and wherein the attenuation factor increases as the frequency f increases.

[0041] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0042] It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein. It should also be appreciated that terminology explicitly employed herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

[0043] The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0044] In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

[0045] Figure 1 is a cross-sectional view of a pair of horizontal, spaced wells in accordance with one application of the present invention;

[0046] Figure 2 is a cross-sectional view of a pair of horizontal, spaced boreholes in accordance with another application of the present invention;

[0047] Figure 3 is a diagrammatic depiction of a downhole assembly in accordance with an embodiment of the present invention;

[0048] Figure 4 is a detail view of a carriage apparatus of the downhole assembly depicted in Figure 3;

[0049] Figure 5 is a diagrammatic depiction of a drill rod structure of the downhole apparatus depicted in Figure 3 with the carriage apparatus removed;

[0050] Figure 6 is a detail view of carrying portion of the drill rod depicted in Figure 5;

[0051] Figure 7 is an isometric view of the carriage apparatus (with cover) depicted at Figure 3;

[0052] Figure 8 is an isometric view of a carriage housing portion of the carriage apparatus depicted at Figure 7;

[0053] Figure 9 is an isometric view of a carriage housing in accordance with an alternate embodiment;

[0054] Figure 10 is a detail view of a portion of the carriage housing depicted at Figure 9;

[0055] Figures 11A – 11C are cross-sectional views of the carriage housing depicted at Figure 9;

[0056] Figure 12 is a diagrammatic depiction of stress wave propagation in a top-hammer rock drilling operation;

[0057] Figures 13 A-B are charts showing an idealized stress wave surface velocity and surface acceleration resulting from the hammer blow depicted at Figure 12;

[0058] Figure 13 C-D are charts showing the idealized stress wave surface velocity and surface acceleration depicted at Figure 12 with reflections;

[0059] Figure 13 E-F are charts showing the stress wave surface velocity and surface acceleration signals depicted at Figures 13 C-D for multiple (e.g., ten) top hammer blows;

[0060] Figure 14 is a diagrammatic depiction of a spring mass isolation filter in accordance with the present invention;

[0061] Figure 15A is a chart showing an FFT of the surface accelerations depicted in Figure 13F;

[0062] Figure 15B is a chart showing a transfer function for the spring mass isolation filter depicted at Figure 14 and implemented by the carriage apparatus depicted throughout;

[0063] Figure 15C is a chart showing the output of the spring mass isolation filter when subject to the excitations shown at Fig. 15A;

[0064] Figure 16 is a diagrammatic depiction of a downhole assembly in accordance with an alternate embodiment of the present invention;

[0065] Figure 17 diagrammatic depiction of a downhole assembly in accordance with another alternate embodiment of the present invention;

[0066] Figures 18A – 18D are detail views of a clamp keying arrangement employed at Figs. 16-17;

[0067] Figure 19 is a detail view of the carriage apparatus employing the clamping arrangement depicted at Fig. 18D;

[0068] Figure 20 is a cross-sectional view of the carriage apparatus employing the clamping arrangement depicted at Fig. 18D;

[0069] Figure 21 is a diagrammatic depiction of a downhole assembly in accordance with yet another alternate embodiment of the present invention;

[0070] Figure 22 is a detail view of a carriage apparatus of the downhole assembly depicted in Figure 21;

[0071] Figure 23 is a detail view of a portion of the carriage apparatus depicted in Figure 21;

[0072] Figure 24 is a detail view of a carriage cover in accordance with another alternate embodiment of the present invention;

[0073] Figure 25 is a cross-sectional view of the carriage apparatus depicted in Figure 24;

[0074] Figure 26 is a detail view of a portion of the carriage apparatus in accordance with yet another alternate embodiment of the present invention;

[0075] Figure 27 is a diagrammatic depiction of a downhole assembly in accordance with yet another alternate embodiment of the present invention;

[0076] Figure 28 is a detail view of a carriage apparatus of the downhole assembly depicted in Figure 27;

[0077] Figure 29 is a diagrammatic depiction of the sensor assembly depicted at Figures 27 - 28;

[0078] Figure 30 is a diagrammatic depiction of a downhole assembly in accordance with yet another alternate embodiment of the present invention;

[0079] Figure 31 is a diagrammatic depiction of the downhole assembly shown in Figure 30 with a protective cover;

[0080] Figure 32 is an isometric view of a downhole assembly in accordance with yet another alternate embodiment of the present invention;

[0081] Figure 33 is an isometric view of the drill rod structure depicted in Figure 32 with the carriage apparatus removed;

[0082] Figure 34 is a cross-sectional view of the carriage housing depicted in Figure 32;

[0083] Figure 35 is a detail view of a collar assembly depicted at Figure 32;

[0084] Figure 36 is a detail view of a collar assembly depicted at Figure 32 in accordance with an alternate embodiment of the present invention; and

[0085] Figures 37 and 38 are detail views of the spring elements depicted at Figure 32.

DETAILED DESCRIPTION

[0086] Reference will now be made in detail to the present embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. An exemplary embodiment of the downhole assembly of the present invention is shown in Figure 1, and is designated generally throughout by reference numeral 10.

[0087] As depicted in Figure 1, a cross-sectional view of a measurement system 1000 featuring a magnetic source apparatus 10 and a magnetic field measurement sensor 50 is disclosed. The measurement system 100 is shown in the context of a pair of horizontal, spaced wells in accordance with an application of the present invention. This view illustrates a method and apparatus for guiding the directional drilling of a second borehole 3 relative to a first (previously drilled) borehole 5 such that the new borehole 3 is separated from the existing borehole 5 by a predetermined distance along their respective paths. The new borehole 3 contains a drill string 4 that carries or includes the downhole apparatus 10 equipped with the spring mass isolation filter. The drill assembly includes a drill bit 8 which is driven by suitable motors in a conventional manner, to rotate about a longitudinal axis of rotation and/or to reciprocate (axially hammer) along the longitudinal axis. The drill bit 8 may be steerable to control the drilling direction in response to control signals provided by a control station 2 located at the surface 1 (of the Earth). The magnetic source apparatus 10 includes a plurality of magnet elements 100 that generate an elliptically polarized rotating magnetic field 300 that is centered at the magnetic source apparatus 10 in the new borehole 3. The magnetic source apparatus 10 includes a magnetic field source 100, which may be implemented using a permanent bar magnet 100 that is typically mounted in a non-magnetic portion of the assembly (not shown in this view) located at the distal end of the drill string behind the rotating drill bit 8. (The term “non-magnetic” material refers to a material that has a magnetic permeability that is comparable to air or a vacuum). The magnets 100 have north-south axes that are perpendicular to the longitudinal axis 7 of the drill bit 8. Because assembly 100 rotates (and/or reciprocates) about the longitudinal axis 7 with the drill bit 8, the elliptically polarized magnetic field 300 is an alternating magnetic field at observation point 52 (which is radially spaced from the magnets 100).

[0088] The existing borehole 5 is illustrative of a horizontal well of the type which may be used for steam assisted gravity drainage of heavy oil (SADG). Of course, the present invention may be employed in any type of drilling application (and/or in any orientation) such as oil and gas drilling operations, geothermal, hammer drilling, top-hammer drilling, mining and/or other such drilling operations. In the example depicted in Figure 1, the drill bit 8 is controlled so that the borehole 3 is drilled directly above borehole 5 and is spaced above it by a predetermined, substantially constant distance. Control of the drill bit 8 is carried out in response to measurements made in the target borehole 5 by a magnetic field sensor 50. The measuring tool 50 is lowered into the borehole 5 through a casing by means of a suitable wireline 9, with the location, or depth, of the measuring tool being controlled from the earth's surface in conventional manner from an equipment truck 200. In one embodiment, the spring mass isolation filter of the present invention is embodied within the magnetic field sensor 50.

[0089] Again, the magnetic field sensor 50 is located at an observation point 52 and may incorporate a plurality of fluxgate magnetometers having their axes of maximum sensitivity intersecting each other at one or more observation points and substantially at right angles to each other. In one embodiment, the sensor may include two magnetometers; in another embodiment, there may be three magnetometers. If a gradient measurement is required, there may be six magnetometers in the sensor 50. The magnetometers measure the amplitude and the phase of two perpendicular components of the magnetic field 300. The measuring tool 50 may also include additional sensors such as earth's field sensors, inclinometers, and/or a gyroscope (depending on the application).

[0090] As embodied herein and depicted in Figure 2, a cross-sectional view of a pair of horizontal, spaced boreholes in accordance with another application of the present invention is disclosed. In this example application, an underground rock drilling assembly 1000 employs a movable carrier 2 having one or more booms 2-3 connected to the carrier 2. A drilling unit 2-4 may be disposed at the distal end of the boom 2-3. The drilling unit 2-4 may comprise a feed beam 2-5 and a rock drilling machine 2-6 which drives the drill rod 4 and hence drill bit 8 into a rock wall 1. In this application the drilling assembly is used to form a series of boreholes in the rock face, wherein each borehole is formed such that it follows a predetermined path in three-dimensional space within the rock wall/structure 1.

[0091] Like the application depicted at Figure 1, the measurement system 1000 features a magnetic source apparatus 10 (that includes the spring mass isolation filter) and a magnetic field measurement sensor 50. (Again, in some applications the sensor 50 may include the spring mass isolation filter). In the application depicted at Figure 2, however, a cross-sectional view of a pair of horizontal, spaced boreholes is shown. Like the previous application shown at Figure 1, this view illustrates a method and apparatus for guiding the directional drilling of a second borehole 3 relative to a first (previously drilled) borehole 5 such that the new borehole 3 is separated from the existing borehole 5 by a predetermined distance along their respective paths. The new borehole 3 contains a carriage assembly having a magnetic source apparatus 10. As before, the magnetic field sensor 50 is located at an observation point 52 and may incorporate a plurality of fluxgate magnetometers (e.g., up to three) having their axes of maximum sensitivity intersecting each other at the observation point and substantially at right angles to each other. (In another embodiment there can be multiple sets of magnetometers (of up to three per set)). The magnetometers measure the amplitude and the phase of two or more perpendicular components of the magnetic field 300. The measuring tool 50 may also include additional sensors such as earth's field sensors, gravity sensors, inclinometers, and/or a gyroscope depending on the application.

[0092] As embodied herein and depicted in Figure 3, a diagrammatic depiction of a magnetic source downhole assembly 10 in accordance with an embodiment of the present invention is disclosed. The downhole assembly 10 includes a carriage apparatus 20 coupled to a structural member 4. In one embodiment, the structural member can be a drill rod 4, which is typically employed in the example applications depicted at Figures 1 and 2. However, the present invention should not be deemed to be limited to the example applications depicted at Figures 1 and 2.

[0093] One skilled in the art will appreciate that the present invention may be employed in other applications and thus, the drill rod 4 may be implemented using any structural member suitable for the application at hand. One such alternate application includes performing a borehole surveying operation. In another alternate application, the carriage apparatus 20 includes a sensor assembly 16 for use in a previously drilled borehole, in an extant pipeline, in a borehole survey or any other suitable application.

[0094] The drill rod 4 (or structural member) may include shoulder members (4-2, 4-4) that are used to accommodate the carriage apparatus 20 therebetween. The drill rod 4 may include a box portion 4-6 (i.e., a female thread) at one end thereof, and a pin portion 4-1 (i.e., a male thread) at second, opposite end thereof. The pin portion 4-1 may also include a drill bit shoulder 4-10 which abuts the drill bit 8 when the drill bit 8 is screwed onto the pin portion 4-1. The box portion 4-6 may be configured to accommodate a drive member associated with the drilling assembly 1000 (figs. 1 and 2). The pin portion 4-1 may be configured to accommodate other tools suitable for a given application as well as a drill bit 8.

[0095] The carriage apparatus 20 is shown to include a protective cover member 30. The cover member 30 is employed to protect a downhole carriage housing 12 disposed under the cover member 30, between the shoulders 4-2 and 4-4. The cover 30 may be fastened to the housing 12 using any suitable fastener elements or techniques (e.g., screws, rivets, press fit, etc.).

[0096] The carriage apparatus also includes a plurality of spring elements 14 that are coupled between the carriage apparatus 20 and the shoulders (4-2, 4-4). As described below, the spring elements 14 and the mass of the carriage apparatus 20 form an isolation filter that is characterized by a low pass frequency transfer function (Fig. 15B) that is substantially below an operational frequency spectrum (See, e.g., Fig. 15A).

[0097] Specifically, the low pass frequency transfer function is a function of a predetermined mass of the carriage apparatus and the total effective spring rate (force-displacement relationship) of springs 14. Specifically, each spring 14 may have a spring rate equal to k, where k is some numerical value. Also, the spring may have a variable rate. The springs 14 at each end of the carriage apparatus 20 can be implemented as four springs 14 disposed in a parallel spring arrangement with a composite spring rate being substantially equal to 4k. Since there are four springs at each end, the total spring rate would be about 8k. The spring rate is selected based on the carriage apparatus mass to obtain a desired low pass frequency transfer function (see Fig. 15B) relative to the operational frequency spectrum (Fig. 15A).

[0098] The operational frequency spectrum can refer to the frequency content of surface accelerations propagating along the drill rod as a result of a given drilling or mining operation. (The surface accelerations are derived from the stress wave energy produced by drilling/hammering). Because the frequency content of the surface accelerations mostly includes frequencies greater than the low pass frequency (spectral) transfer function, the stress wave energy is attenuated and substantially prevented from disturbing the carriage apparatus 20. Those skilled in the art will appreciate that the resonant frequency is selected so that it is well below the operational frequency spectrum (Fig. 15A). While there may be some small amount of energy at or near the resonant frequency, it is not enough to induce a carriage failure mode.

[0099] As embodied herein and depicted in Figure 4, a detail view of a carriage apparatus 20 depicted in Figure 3 is disclosed. In this view, the cover member 30 is removed from the carriage apparatus 20 to show the downhole housing 12. The downhole housing 12 includes a first housing portion 12-1 and a second housing portion 12-2. During assembly, the first housing portion 12-1 is coupled to the second housing portion 12-2 with the drill rod 4 therebetween so that the downhole housing 12 is spatially registered to the drill bit 8. The gap between each edge of the carriage housing 12 and its respective drill rod shoulder (4-2, 4-4) is a function of the spring constant and carriage assembly weight, so that under typical conditions the carriage apparatus 20 will not contact the shoulders. If the conditions are such that carriage assembly 20 does make contact with a shoulder (4-2, 4-4), each spring 14 is configured to fully retract into its respective spring pocket 12-8 (Fig. 8) without fully compressing.

[00100] In the magnetic source embodiment, each housing portion (12-1, 12-2) includes a plurality of magnetic field source elements (e.g., permanent magnets, electromagnets) 100 disposed within respective pockets 12-3. The permanent magnets 100 are configured to generate magnetic field 300 (as shown at Figures 1 and 2).

[00101] As noted above, the downhole housing 12 may also be configured to accommodate a sensor assembly 16 (Figs. 27-29) wherein the housing portions (12-1, 12-2) may include compartments configured to accommodate various sensor components such as inclinometers (tilt sensors), magnetometers, environmental sensors (pressure, temperature, radiation, etc.), gravity sensors (accelerometers), rotation sensors (gyroscope), a power supply and/or battery, a receiver, transmitter, a processor/controller, memory, etc., depending on the application.

[00102] As embodied herein and depicted in Figure 5, a diagrammatic depiction of a drill rod structure 4 shown in Figure 3 is disclosed. (Here, the carriage apparatus 20 is removed for clarity of illustration). The drill rod 4 includes a source/sensor carrying region 4-9 disposed between the shoulder members (4-2, 4-4). (Depending on the housing embodiment, region 4-9 either carries the magnetic source housing or the sensor housing). As before, the drill rod 4 may include a box portion 4-6 at one end thereof, and a pin portion 4-1 at second, opposite end thereof. Fluid channels 4-3 and key members 4-8 are disposed within the payload carrying region 4-9 between the shoulder members (4-2, 4-4). The remaining features of the drill rod were previously described above.

[00103] Referring to Figure 6, a detail view of carrying portion 4-9 of the drill rod depicted in Figure 5 is shown. In this embodiment, the carrying region 4-9 includes four fluid channels 4-3 and two key members 4-8 disposed in a central region of the carrying region 4-9. Specifically, a set of two fluid channels 4-3alternates with a key member 4-8 at 90° increments around the circumference of the central area of the carrying region 4-9. Thus, a set of two fluid channels 4-3 are disposed 180° away from the second set of fluid channels 4-3, and one key member 4-8 is disposed 180° away from the second key member 4-8.

[00104] Those skilled in the art will appreciate that the size and number of the fluid channels 4-3 may vary depending on the application. For example, the number and size of the fluid channels 4-3 may be a function of the type of fluid traversing the channels (e.g., air, water, etc.) as well as the application for which the assembly is being used. Those skilled in the art will appreciate that the number of fluid channels 4-3 may vary depending on the thermal energy characteristics of the operating environment. In relatively warmer environments, the drill rod 4 will include additional fluid channels 4-3 to better direct the thermal energy away from the carriage 20. In relatively cooler environments, the drill rod 4 may include fewer fluid channels 4-3 (or none at all if cooling is not an issue in the application). The number of fluid channels 4-3 shown in Figure 6 is merely a representative example.

[00105] The number of key members 4-8 may vary depending on the application for which the assembly is being used. Accordingly, more or less channels 4-3 and/or key members 4-8 may be employed depending on the embodiment and/or application.

[00106] The existence of fluid channels 4-3 presupposes the existence of a central fluid-flow channel (not shown) that extends through the entire length of the drill rod 4 and is centered about the longitudinal axis 7 (see, e.g., Fig. 1). In one embodiment, the diameter of the central fluid-flow channel may be about 0.870 inches. The outer diameter of the source/sensor carrying region 4-9 may be about 2.470 inches. (The fluid transmitted through via 4-12 may be air or some other suitable fluid).

[00107] In one embodiment, the drill rod 4 is formed by a machining a steel alloy billet (e.g., using a CNC milling machine) to produce an integrally formed drill rod. In another alternate embodiment, the shoulder members (4-2, 4-4) and/or the key members 4-8 may be formed on a steel alloy rod using a sputter-welding process, wherein layers of steel material are deposited and built-up along the circumference of the rod at appropriate locations. The built-up portions are then machined (using, e.g., a lathe) to form the shoulder portions (4-2, 4-4) and the key members 4-8. The box portion 4-6 and the pin portion 4-1 may be welded to their respective ends of the drill rod 4 by way of a friction-welding process. In the various alternate embodiments, those of ordinary skill in the art will appreciate that the shoulders (4-2, 4-4), key members 4-8, pin 4-1, box 4-6, and other such features may be formed and/or machined using any suitable fabrication method(s).

[00108] In one embodiment of the present invention, the drill rod may be formed using a chrome-molybdenum AISI Alloy 4140 steel bar (which has, e.g., a tensile strength of about 95,000 psi, and an elastic modulus within a range of about 27,557 – 30,458 ksi). Thus, chrome-molybdenum AISI Alloy 4140 steel bars may be employed in each of the fabrication and machining embodiments described above.

[00109] As embodied herein and depicted in Figure 7, an isometric view of the carriage apparatus 20 depicted at Figure 3 is disclosed. In this view, the non-magnetic cover 30 is disposed over the carriage housing 12. Each set of four spring elements 14 extend from their respective ends of the carriage housing 12. The non-magnetic cover 30 may be formed using any suitable non-magnetic material including stainless steel, titanium, BeCu, aluminum, etc. In one embodiment, the cover 30 may be formed using an austenitic nickel-chromium alloy material such as the Inconel alloys manufactured by Special Metals Corporation. The austenitic nickel-chromium alloys are oxidation-corrosion-resistant materials well suited for service in extreme environments subjected to pressure and heat.

[00110] Each spring 14 may be formed using any suitable material, but in one embodiment, the springs 14 are formed from a chrome-silicon steel material. In one embodiment, the spring conforms to a spring pocket 12-8 diameter of about 3/8" and has an interior diameter of about 3/16". The spring rate may be about 10.5 N/mm. In one embodiment, the springs 14 may be manufactured by McMaster-Carr and be implemented by the McMaster-Carr Blue Chrome-Silicon Steel Die Spring PN 9573K11.

[00111] Referring to Figure 8, an isometric view of the carriage housing 12 depicted at Figure 7 is disclosed. The carriage housing 12 includes a first housing portion 12-1 connected to a second housing portion 12-2. As noted previously, the exterior surface of each housing portion includes a plurality of pockets 12-3, each pocket 12-3 being configured to accommodate a permanent magnet 100 (not shown).

[00112] A key channel 12-6 is formed in an interior portion of the housing 12 at the connection interface 12-4. Each key channel 12-6 is configured to accommodate one of the key members 4-8 therein. When the key members 4-8 are disposed within their respective key channels 12-6, the carriage housing 12 is rotationally registered to a predetermined portion of the drill bit 8, and is substantially prevented from rotating about the central longitudinal axis 7 of the drill string (see, e.g., Fig. 1).

[00113] Four spring pockets 12-8 are formed in each end of the carriage housing 12, with two spring pockets 12-8 being formed at one end of each housing portion (12-1, 12-2). The depth of each spring pocket can be a function of the spring composition such that a pocket depth can allow a spring 14 to fully retract within the pocket 12-8 without the spring becoming fully compressed into a solid cylinder.

[00114] Referring to Figure 9, an isometric view of a carriage housing 12 in accordance with an alternate embodiment is disclosed. Descriptions of the magnet pockets 12-3, spring pockets 12-8 and the key channel 12-6 are omitted for brevity's sake since these elements were described above. In this embodiment, the housing portions (12-1, 12-2) include additional features such as mating pins 12-100, mating holes 12-10, and rivet holes 12-12. Moreover, the section B-B, section A-A and section C-C are shown at Figures 11A, 11B and 11C, respectively, and described below.

[00115] In this embodiment, the mating holes 12-10 are configured to accommodate mating pins 12-100 that are used to couple the first housing 12-1 to the second housing

12-2. The rivet holes 12-12 are configured to accommodate rivets which are used to secure the housing cover 30 to the carriage housing 12.

[00116] Referring to Figure 10, a detail view of a portion 12-2 of the carriage housing 12 depicted at Figure 9 is disclosed. (This drawing figure is equally applicable to housing portion 12-1, except that portion 12-1 would be a mirror image of housing portion 12-2 such that each side of the housing 12 would include a set of mating pins 12-100). This view clearly shows that the key channel 12-6 is created by forming a notched region 12-60 along the edges of the housing portions (12-1, 12-2).

[00117] Referring to Figures 11A – 11C, cross-sectional views of the carriage housing depicted at Figure 9 are disclosed. Figure 11A is a cross-sectional view corresponding to section B-B of Figure 9. Here, the rivet holes 12-12 have an hour-glass shape so that the wider portions of the rivet hole 12-12 can accommodate the thicker head portions of a rivet, and wherein the relatively narrow portions of the rivet hole 12-12 are configured to accommodate the relatively narrow body portion of a rivet. This view also provides a sectional view of key channel 12-6 formed at opposite edges of housing 12. Figure 11B is a cross-sectional view corresponding to section A-A of Figure 9. In this view, the mating holes 12-10 configured to accommodate mating pins 12-100 are shown. Figure 11C is a cross-sectional view corresponding to section C-C of Figure 9. In this view, the section includes three magnet pockets 12-3 per housing portion (12-1 or 12-2) for a total of six magnet pockets per section. In reference to Figure 9, therefore, the carriage housing 12 includes five magnet sections for a total of about thirty magnet pockets.

[00118] In one embodiment, the carriage housing 12 may be formed from a cylindrical or tube-shaped material (hereinafter “stock material”) that is divided into two halves to form the first housing portion 12-1 and the second housing portion 12-2. (There is no significance placed on the terms first housing or second housing other than the fact that the housing 12 includes two housing portions (12-1, 12-2)). In one embodiment, the stock material may be comprised of a Teflon PTFE resin material that substantially complies with UL 94V0 and ASTM D1710 standards. In other embodiments, the tube material may be comprised of any suitable material; for example, the material may be an acetal homopolymer (Polyoxymethylene POM) material sometimes known as Delrin. In another example, the material may be a Polyether ether ketone (PEEK) material, which is a colorless, organic, thermoplastic polymer. In yet another embodiment, the material may be bronze or a bronze alloy material, titanium, stainless steel, or any suitable non-magnetic material. Those skilled in the art will appreciate that the materials of the tube used to form the magnetic source housing 12 may vary in accordance with the application since the environment (vibrations, shock, temperature, etc.) may also differ from application to application.

[00119] In one embodiment, the stock material may have an outer diameter (OD) of about 4 inches, an inner diameter (ID) of about two inches, and a wall thickness of about one inch. Those of ordinary skill in the art will appreciate that the dimensions of the stock material used to form the downhole housing 12 may vary in accordance with the embodiment and/or application.

[00120] Before the stock material is separated into two parts (i.e., to form the first housing portion 12-1 and the second housing portion 12-2), the stock material may be machined to include the various features depicted herein. For example, the stock material may be machined to include the mating pins 12-100, mating holes 12-10, rivet holes 12-12, magnetic source pockets 12-3, and the sensor assembly pockets 12-27 (See Figure 27). The rivet holes 12-12 may also be configured to accommodate any suitable fastener element (e.g., a pop-rivet, etc.) for connecting the first housing portion 12-1 to the second housing portion 12-2 during assembly. Alternatively, some or all of the features may be machined after the stock material is separated into two parts.

[00121] Each magnetic source pocket 12-3 is configured to accommodate a magnetic source element 100 and an epoxy (or other) potting material. The potting material is employed to hold the magnetic element 100 in place within its respective pocket 12-3.

[00122] The magnetic sources 100 employed in the invention may vary in accordance with the application since the environment (vibrations, shock, temperature, etc.) or desired operating parameters may also change in accordance with the application. Some non-limiting examples of operating parameters may be remanence, coercivity, Curie temperature, etc. Accordingly, the magnetic source elements 100 may be implemented using neodymium rare earth magnets, samarium cobalt magnets or any suitable magnetic source elements depending on the application. In another embodiment, the magnetic source elements may be implemented by electromagnetic source elements. In this embodiment, a wireline may be fed to carriage apparatus 20 via the central fluid channel of the drill rod. The wireline would provide electrical power from an uphole location to the carriage 20. In another embodiment, one of more piezoelectric transducers would be included in the carriage housing 12 and be configured to convert the mechanical energy (W_h) generated by the drilling operations into electrical energy. The electrical energy would be stored in a battery which would, in turn, provide power to the electromagnets. In another embodiment, a battery without piezoelectric transducers can be employed.

[00123] As described herein, the key channel 12-6 may be configured as a rectangularly-shaped channel that is machined (or otherwise formed) to accommodate the key element 4-8 formed in the carrying region 4-9 of the drill rod 4. (Note that key channel 12-6, the key element 4-8 and source-carrying region 4-9 may be machined to conform to any suitable geometry and is thus not limited to a rectangular shape). In any event, the key channel 12-6 conforms to the key element 4-8 of the drill rod such that the downhole housing 12 is in a fixed spatial relationship and registered to the drill rod 4 in at least two-dimensions. On the other hand, the reader should note that the downhole housing 12 is configured to slide along the source-carrying region 4-9 between the two shoulders (4-2, 4-4) in a substantially frictionless manner under certain circumstances. A person skilled in the art will appreciate that the term *substantially frictionless* is predicated on the coefficient of friction of the interior surface of the housing 12, the coefficient of friction of the carrying region 4-8 of drill rod 4 and the operational characteristics of the isolation filter. In addition, the interface between the interior surface of the housing 12 and the surface of the carrying region 4-8 may be packed with grease or some other lubricant material.

[00124] As embodied herein and depicted in Figure 12, a diagrammatic depiction of stress wave propagation in a top-hammer rock drilling application is disclosed. Here, the stress waves are modeled as a sequence of square or rectangular waves for ease of illustration. In diagram 1200, a top hammer rock drill is shown to include a hammer/piston 2-6 that is used to impact the drill rod 4. (See, e.g., Fig. 2). The hammer 2-6 may be implemented using any suitable hammer type, e.g., such as a pneumatic hammer (which uses compressed air) or a hydraulic hammer (which uses pressurized hydraulic fluid). (The drill rod 4 is a depicted in this view as an elongated cylinder; in practice, however, the drill rod 4 may be of the type depicted at Figs. 5 and 6).

[00125] During operations, examples of which are shown at Figs. 1 and 2, the drilling motor 2-4 may simultaneously provide a reciprocating motion and a rotational motion to drive the drill rod 4. The reciprocating motion provides the hammering action to the drill rod 4 while the rotational force slowly rotates the drill rod 4 and drill bit 8 in a drilling motion. As the borehole length increases, additional drill rods can be added to the drill string by screwing a new drill rod onto the drill string that extends into the borehole. The kinetic energy of the hammering action is transmitted by the drill rod 4 to the drill bit 8 to fragment the rock 1 during the drilling action. Accordingly, any sensor instrument package 16 or magnetic source package 100 attached to a down-hole drill rod 4 must be able to with-stand intense stresses and strains.

[00126] In this case, the isolation filter of the present invention is configured to substantially isolate the housing 12 from the stress, energy and power flow associated with the drilling. To be clear, the spring elements 14 do not function as a damping mechanism, but rather as a low pass filter, since the frequency spectrum of the surface accelerations characterizing the hammering/drilling operations are greater than the low pass frequency response spectrum of the isolation filter, and thus, the stress waves are substantially attenuated and substantially prevented from disturbing the carriage apparatus 20. (The surface accelerations are derived from the stress wave energy produced by drilling/hammering).

[00127] In step 1201, the hammer 2-6 is shown prior to impact and is shown to have a length "L_P" (also referred to herein as "L"). In step 1202, the hammer 2-6 moves toward the drill rod 4 with a velocity v and strikes the drill rod 4. In step 1203, a compressive stress wave C_p is generated in the hammer 2-6 and a compressive stress wave C is also generated in the drill rod 4. These stress waves are depicted in the diagram as an increased diameter in each element. The maximum induced compressive stress (σ) is substantially equal to:

[00128] $\sigma = vE/2c$ (1)

Where, v is the hammer velocity, E is Young's (elastic) modulus of the material (hammer and drill rod), and c is the speed of sound in the hammer/rod. This assumes that the diameter and material of the hammer 2-6 and the drill rod 4 are the same.

[00129] In step 1204, the stress wave C_p reaches the upper end of the hammer 2-6 and is reflected; and the compressive stress wave C continues to propagate down the length of the drill rod 4. In step 1205, the reflected wave C_p propagates down the hammer 2-6 and is transmitted into the drill rod 4 such that the stress waves C and C_p

are combined. In step 1206, the combined stress wave *C* exits the hammer 2-6; and in response to being elastically compressed by the stress waves, a portion of the drill rod 4 has been displaced. Assuming a square wave shape, the elastic compression (Δ) is substantially equal to:

$$\Delta = vL/c \qquad (2)$$

In a typical top hammer application, μ_0 may be about 1.2 mm given a velocity (v) of 10m/s and a hammer length (L) of about 0.6m.

[00130] In step 1207, the stress wave has a length 2L and propagates along the drill rod 4 at the speed of sound c, which is substantially equal to

$$c = \sqrt{(E/\rho)} \qquad (3),$$

wherein ρ is the density of the drill rod material. The stress wave propagates the initial mechanical energy W_h to the drill bit 8, where

$$W_h = 1/2mv^2 \qquad (4),$$

wherein m is the mass of the hammer 2-6. Of course, only a fraction of the mechanical energy W_h is applied to fragment the rock 1 (See, e.g., Fig. 2). Another portion or fraction of the mechanical energy is reflected back up the rod 4.

[00131] Referring to Figures 13A-B, charts showing another idealized stress wave surface velocity and surface acceleration resulting from the hammer blow stress wave depicted at Figure 12 are disclosed. In this analysis, the stress wave is modeled as a sinusoidal wave. Briefly stated, the stress wave surface velocity curve 1300 can be modeled as a sine wave or a cosine wave over an interval from 0 – π radians (0° – 180°). Those skilled in the art will appreciate that the form of the stress wave 1300 depends on the rock drill, drilling parameters, the number of drill rods 4 in a given drill string, the type of rock being drilled, the hardness and the integrity of the rock material, and etc. Nonetheless, the stress wave surface velocity 1300 may be reasonably modeled as a sinusoid (over a 0 – π radian interval) to ascertain the energy and forces being brought to bear on the downhole housing 12 described above. The surface acceleration 1302 is, of course, the derivative of the stress wave surface velocity 1300.

[00132] Referring to Figure 13C-D, charts showing the idealized stress wave and acceleration with reflections are shown. In other words, Figure 13C shows the stress wave surface velocity 1300 (at Fig. 13A) along with the stress wave reflections that develop over time. See Fig. 12 and the related text above. Similarly, Figure 13D shows the surface acceleration signal 1302 (Fig. 13B) along with the reflected surface accelerations that develop over time (see Figure 12 and the related text). Specifically, Figure 13C shows that after a millisecond or so, the reflection waves 1304 begin to propagate along the drill rod. Figure 13D shows the resultant surface acceleration based on the stress wave surface velocity shown at Figure 13C.

[00133] Referring to Figure 13E-F, charts showing the stress wave surface velocity and acceleration signals for multiple (e.g., ten) top hammer blows are disclosed. In these drawings the stress wave surface velocity signals 1302 and 1304 shown at Fig. 13C are compressed as the time scale is changed from milliseconds to seconds. Specifically, the stress wave surface velocity signals (1300 and 1304) shown at Fig. C are shown in a compressed form as signal 1308. The stress wave surface velocity signal 1308 is repeated for each hammer blow. Figure 13E, therefore, shows ten stress wave surface velocity signals 1308 propagating down the drill rod, one for each of the ten hammer blows. The surface acceleration signals (1302 and 1306) shown at Figure 13D are likewise shown at Fig. 113F in compressed form as signal 1310. There are therefore ten surface acceleration bursts 1310, one for each hammer blow.

[00134] Briefly stated, therefore, the mathematical model makes the following assumptions: first, it assumes that the stress wave is sinusoidal; and second, it assumes that the geometry and material of the hammer 2-6 and drill rod 4 are substantially the same so that they both have the same acoustic impedance. The model is based on the stress wave formulation steps shown at Figures 12, except that a sinusoidal approximation is employed. The stress wave modeled by equation (5) is at some drill rod element a distance “x” from the top of the rod 4 at time “t.” In step 1207, e.g., the velocity (“du/dt”) of a point on the drill rod can be represented by:

$$du/dt = -(v/2) \sin[(\pi/2L)(x - c\,t)], \text{ for } -2L < x - ct < 0 \qquad (5)$$

The velocity du/dt is based on u(x,t), which is a tiny displacement of an element on the drill rod from its equilibrium location x at time t. The factor “(x - ct)” indicates that u(x, t) describes a displacement propagating along the longitudinal axis “x” of the drill rod 4 *toward* the drill bit 8. While the shape of a wave pulse may assume any form, x and t must always appear in the combination with each other to satisfy the governing wave equation (i.e., the argument must include either (x - ct) or (x + ct). If the argument is (x + ct), the stress wave displacement is propagating along the longitudinal axis “x” of the drill rod 4 *toward* the hammer 2-6 and away from the drill bit 8.

[00135] Again, while equation (5) models the stress wave as a sinusoidal wave, those skilled in the art will appreciate that the wave could be modeled as a trapezoidal wave, a square wave or as a rectangular pulse. (Those skilled in the art will appreciate that mathematical models are only approximations of real world mechanical phenomena). The factor 2L in equation (5) indicates that the wave has a length 2L, which corresponds to twice the hammer's length, as shown at Figure 12.

[00136] Referring to Figure 14, a diagrammatic depiction of a mechanical isolation filter system 1400 in accordance with the present invention is disclosed. Briefly stated, the stress waves formed by the axial shocks and vibration may be substantially reduced by the isolation filter 1400. Before describing the filter 1400, and its features and benefits, it may be useful to highlight the differences between the mechanical isolation filter system 1400 of the present invention and a damping spring mechanism.

[00137] The mechanical isolation filter system 1400 is configured as a low pass axial shock and vibration filter and not as a damping mechanism. Specifically, note that a damping mechanism typically uses significant dissipative forces (frictional or fluid forces) to dampen vibrational motions; however, these dissipative frictional forces generate thermal energy. In contrast, the mechanical isolation filter system 1400 of the present invention substantially isolates the sensor 16 or the magnetic sources 100 from potentially damaging shock and vibrations (axial or otherwise) while substantially obviating any frictional forces. Stated differently, because of the filtering operation, the carriage 20 will exhibit very little oscillation, if any. As a result, the amount of thermal energy (heat) generated by the spring-mass filter 1400 is relatively small when compared to a frictional damping device.

[00138] In the various drilling applications contemplated by the present invention, such as a reciprocating drilling action (e.g., hammer-drilling), the excitation frequencies propagating along the longitudinal axis 7 of the drill rod 4 are on the order of approximately 100Hz and above (see Fig. 15A). The low pass isolation filter 1300 of the present invention is configured to substantially filter out excitations (shock and vibration) to frequencies well below 50 Hz.

[00139] As shown in Figure 14, therefore, the mechanical isolation filter system 1400 is comprised of the carriage apparatus 20 and the spring system 14 disposed between the carriage apparatus 20 and the drill rod shoulders (4-2, 4-4). The carriage 20 is modeled as a mass $\boldsymbol{m}$ that is connected between a pair of springs 14 (one spring at each end), which have a spring constant "k." The springs 14 are further connected to the drill rod at their respective ends via the shoulders 14. As highlighted by Figures 12 and 13A-13F, and the associated text, the stress waves generated by a reciprocating drilling operation (such as hammer drilling) are primarily directed along its longitudinal axis 7. The natural frequency of vibration of the mass and spring system (at Fig. 14 and Figs. 30-38) is $[1/(2\pi)]*[\text{sqrt}\ (2k/m)]$, wherein k is the spring constant of one spring. Since there is one spring 14 at each end of the carriage housing 12 (and two (2) total springs), the term "2k" is used in the natural frequency equation. (If only one spring 14 is employed, the natural frequency is $[1/(2\pi)]*[\text{sqrt}\ (k/m)]$).

[00140] Note that in the embodiments depicted Figs. 3 – 11C and 16-28, there are a set of four (4) springs at each end (and eight (8) total), and thus the natural frequency of vibration of the mass and spring system is $[1/(2\pi)]*[\text{sqrt}\ (8k/m)]$. In these embodiments, the spring rate k for one spring is approximately 10.5 N/mm. After converting the spring rate k from mm to meters, the spring rate becomes 10,500 N/m. Accordingly, with the two sets of four springs 14 (one set at each end) disposed in parallel, the two sets of springs 14 would have a combined spring rate of about 84,000 N/m. With a carriage housing 12 having a mass of about 3kg, the natural or fundamental frequency would be $f = [1/(2\pi)] * [\text{sqrt}\ (84{,}000/3)]$ which equals about 26 Hz.

[00141] In another example embodiment, the carriage apparatus 20 may be coupled between the shoulders (4-2, 4-4) by a set of two springs at each end, i.e., four springs total. In this case the two sets of springs 14 would have a rate of about 42,000 N/m; and with a carriage mass of 3 kg, the natural frequency would be about 18.8 Hz. In all of these embodiments, a variable rate spring may be employed.

[00142] Accordingly, one skilled in the art will appreciate that the design may be adapted to various environmental scenarios. That is, the stress wave parameters may vary depending on the type of drilling/mining application, and thus, the carriage mass, spring rate and/or total number of springs may be selected in accordance with a given application. Any excitations along the longitudinal axis that are greater than 1.5 times the natural (fundamental) frequency will be substantially attenuated (i.e., filtered out) by the low pass filter 1400. The spring rate k used in the above calculations is a constant value; however, the present invention contemplates that the spring rate may be non-constant (i.e., non-linear). Thus, the present invention contemplates that the spring rate may be construed to refer to or encompass any predetermined force-displacement relationship.

[00143] In reference to Figures 15A – 15C, the plots shown in these charts recapitulate the teachings articulated herein, e.g., at Figures 12-14 and the associated text. For example, Figure 15A shows a fast Fourier transform (FFT) of the surface accelerations depicted at Figure 13F. In Fig. 15A, most of the frequency content of the surface accelerations is between 100 Hz (10^2) and 100 KHz (10^5) or less. The peak acceleration is about 250g at about 3,500 Hz. (Note that since 1g is approximately equal to 10 m/s^2, 250g is approximately equal to about 2500 m/s^2).

[00144] Figure 15B is a chart showing transfer functions (1502, 1503) for the spring mass isolation filter 1400 of Figure 14 (and implemented by spring 14 and mass (carriage apparatus 20) system depicted at Figures 3-11 and 17-38. The transfer function curve 1502 represents the first filter example wherein the isolation filter has two sets of four springs 14 (one at each end) that are disposed in parallel. In this case, the system example is characterized by a natural frequency of about 26 Hz. Note that the 26 Hz natural frequency is the location of the peak frequency of curve 1502, and represents the resonant frequency of the isolation filter 1400. Frequencies below the natural frequency represent the filter passband wherein the attenuation factor is equal to one. Frequencies greater than the 26 Hz natural frequency are attenuated with the curve falling off at an attenuation rate of $1/f^2$.

[00145] The transfer function curve 1503 represents the second filter example wherein the isolation filter has two sets of two springs 14 (one at each end) that are disposed in parallel. In this case, the system example is characterized by a natural frequency of about 18.8 Hz. Thus, the adaptability of isolation filter 1400 to different drilling/mining environments should be readily apparent to the reader. As noted herein, the isolation filter uses very little damping to avoid generating thermal energy. Briefly stated, 2% of critical damping is assumed in the calculations. This damping amount represents small spring losses, minimal friction between the drill rod and the carriage assembly, etc. Also, those skilled in the art will appreciate that this minimal amount of damping is included in the transfer functions of Fig. 15B so that the motion at resonance remains finite. (If no damping is assumed in the calculations, then the peak attenuation multiple (at Fig. 15B) will go to infinity at resonance).

[00146] Figure 15C is a chart showing the output of the spring mass isolation filter when subject to the excitations shown at Figure 15A. This chart is directed toward the first example wherein the filter has a 26 Hz resonant frequency. The peak filtered acceleration of the filter 1400 is about 5 m/s^2 (i.e., about 0.5g) at approximately 30 Hz. Comparing the surface accelerations of Fig. 15A to the filter output chart of Fig. 15C, the surface acceleration curve 1500 has a peak acceleration of 250g (i.e., 2,500 m/s^2) whereas the peak filter output is again, only about 5 m/s^2. As the frequencies of the surface accelerations increase, the surface accelerations of the carriage apparatus 20 decrease until they approach 0 m/s^2 at about 3,000 Hz. Essentially, in stark contrast to a damping system, the carriage 20 becomes stationary as the vibrational frequencies increase.

[00147] Thus, the isolation filter implemented by the carriage apparatus 20 is characterized by a low pass frequency transfer function 1502 (1503) that includes pass band frequencies that are substantially below the operational frequency spectrum (1500) wherein stress waves propagating along the drill rod 4 from a predetermined drilling operation are substantially attenuated and substantially prevented from disturbing the carriage apparatus 20.

[00148] As embodied herein and depicted at Figure 16, a diagrammatic depiction of a downhole assembly 10 in accordance with an alternate embodiment of the present invention is disclosed. Here, the carriage apparatus 20 is substantially identical to those described above, and hence, any further description is redundant and omitted for brevity's sake.

[00149] On the other hand, in this embodiment the drill rod 4 is modified so that the shoulders (4-2, 4-4) are replaced by clamped collar devices (18-1, 18-2). Here, collar 18-1 is shown as having a smaller diameter than collar 18-2; however, the collar diameter size may be relatively unimportant in this case since the collars 18 can be attached to drill rod 4 after the carriage apparatus 20 is coupled to the drill rod 4. The collars (18-1, 18-2) are two-piece devices that include matching tap holes 18-3 that are configured to accommodate a screw or other such fastener used to tighten the collar pieces around the drill rod 4.

[00150] In reference to Figure 17, a diagrammatic depiction of a downhole assembly in accordance with another alternate embodiment of the present invention is disclosed. Again, the carriage apparatus 20 is substantially identical to those described above, and hence, any further description is redundant and omitted for brevity's sake. This embodiment features a hybrid drill rod 4 that is a cross between the drill rod depicted at Figs. 3-6 and the drill rod shown at Fig. 16. That is, the drill rod features a shoulder 4-4 (like Figs. 3-6) along with a collar device 18 (like Fig. 16). In other words, the shoulder 4-2 (Figs. 3-6) is replaced by a collar 18. Thus, the carriage apparatus 20 or cover 30 may be inserted over the drill pin 4-1 and moved down the drill rod 4 until the springs 14 are coupled between the carriage 20 and the shoulder 4-4. Then, the collar 18 is attached to secure the other set of springs 14 between the carriage 20 and the collar 18.

[00151] Those skilled in the art will appreciate that the collar 18 may be implemented as a two-piece shaft collar with a 60mm bore, 88mm OD, and 19mm width. The collar may be manufactured from 1215 lead free steel having a black oxide finish that increases holding power and resists corrosion. In one embodiment, the collar 18 may be implemented by an MSP-60-F collar arrangement manufactured by the Ruland Manufacturing Company.

[00152] In reference to Figures 18A – 18D, detail views of a clamp keying arrangement employed at Figs. 16-17 are disclosed. In Figs. 18A-18C, a shallow groove 4-18 may be machined or otherwise formed in the drill rod 4 to accommodate the collar therein. In Figs. 18B and 18C, a stop portion 4-19 is included to substantially prevent the collar from slipping or rotating about the drill rod 4.

[00153] Figure 18D shows a collar 18 that is disposed in situ within a groove 4-18. The collar 18 includes a proud surface 18-4 that has a larger diameter than the recessed portion 18-3 adjacent thereto. The recessed portion 18-3 may be employed to accommodate an extended-length protective cover 30.

[00154] Note that each drawing (Figs. 18A-D) shows a sectional view of the drill rod such that the central fluid channel 4-12 is shown. (This channel may be used to direct a pressurized fluid from an uphole region (e.g., control station 2 at Fig. 1) to the drill bit 8. The fluid may be air pressurized at 150 PSI).

[00155] Referring to Figure 19, a detail view of the carriage apparatus employing the clamping arrangement depicted at Fig. 18D is disclosed. In this view, the protective cover 30 fits within the recessed portion 18-3 of the collar 18. At the same time, the cover 30 is substantially flush with the proud surface 18-4 of collar 18.

[00156] Figure 20 is a cross-sectional view of the carriage apparatus 20 shown at Figures 18D and 19. That is, the carriage apparatus 20 is coupled to a drill rod 4 that employs the clamping arrangement 18 depicted at Fig. 18D. Again, the protective cover 30 is disposed within the recessed portion 18-3 of the collar 18 such that it extends over the springs 14 and the housing 12. The cover 30 is substantially flush with the proud surface 18-4.

[00157] As embodied herein and depicted in Figure 21, a diagrammatic depiction of a downhole assembly in accordance with another alternate embodiment of the present invention is disclosed. In this embodiment, the drill rod 4 is substantially the same as the one shown at Figs. 5-6. Moreover, the carriage apparatus 20 is substantially identical to those described in previous embodiments. Accordingly, only the new elements of the carriage 20 are described for the sake of brevity. Here, a bumper arrangement 20 is provided at each end of the carriage housing 20. The bumper arrangement 20 includes two semi-circular pads (20-1, 20-2) that are applied to each end of the housing portions (12-1, 12-2).

[00158] Turning to Figures 22-23, detail views of a carriage apparatus 20 of the downhole assembly depicted in Figure 21 is disclosed. These views show the bumper arrangement 20 with greater clarity. The semi-circular pads (20-1, 20-2) take the form of a gasket that includes four holes 20-3. The holes 20-3 accommodate the springs 14. The gasket pads 20-1, 20-2 may be formed using any suitable material configured to protect the carriage housing 12 from a hard impact from the drill rod shoulders (4-2, 4-4); the materials may include rubber, polymer, composite materials, a relatively soft metal, etc.

[00159] As embodied herein and depicted in Figure 24, a detail view of a carriage cover 30 in accordance with another alternate embodiment of the present invention is disclosed. In this embodiment the cover 30 has one end with a relatively large diameter opening (as in previous embodiments) and an opposing end with a relatively small diameter opening. This allows the protective cover 30 to slide over the drill rod pin 4-1 and be held in place by the drill bit 8 (not shown) when it is screwed onto the pin 4-1.

[00160] Figure 25 is a cross-sectional view of a carriage apparatus 20 depicted in Figure 24. Note that the cover end (left side of Fig. 25) abutting shoulder 4-2 has a larger diameter 30D1; and the cover end that abuts shoulder 4-10 has a smaller diameter 30D2. Thus, the larger diameter opening is large enough to slide over the shoulders (4-4, 4-10) and the carriage 20 until an end cap portion 30-1 abuts the shoulder 4-10. Once the drill bit 8 is threaded onto the pin 4-1, the end cap 30-1 is firmly caught between the shoulder 4-10 and the drill bit 8 to secure the cover to the apparatus 10.

[00161] As embodied herein and depicted in Figure 26, a detail view of a portion 12-1 of the carriage apparatus in accordance with yet another alternate embodiment of the present invention is disclosed. Most of the housing portion 12-1 is substantially identical to embodiments described above, and hence, a description of previously described elements is omitted for brevity's sake. In this view, a series of spring holes 12-15 are formed in the surface of the key channel 12-6. Each hole 12-15 is configured to accommodate a spring 15; thus, upon the assembly of housing 12, the springs 15 extend into holes 12-15 formed in each housing portion 12-1, 12-2. The springs 15 and the carriage mass m form another filter that is configured to filter any torqueing forces that may be applied to the housing 12 during a rotational drilling process (in a manner similar to the spring isolation filter 1400 described above). In one embodiment, the springs 15 are manufactured using chrome-silicon steel, have a 1 inch long free length, and have a spring rate of 0.6 N/mm. The holes 12-15 may have a 0.2" diameter. In one embodiment, the springs 15 may be manufactured by McMaster-Carr and be implemented by the McMaster-Carr Blue Chrome-Silicon Steel Die Spring PN 9657K49.

[00162] As embodied herein and depicted in Figure 27, a diagrammatic depiction of a downhole assembly in accordance with yet another alternate embodiment of the present invention is disclosed. In this view, the carriage housing 12 is configured to accommodate a sensor assembly 16 instead of a magnetic source assembly. Here, the sensor carriage 20 is shown with the protective cover 30 removed. The housing portion 12-1 is shown with a protective enclosure 12-16 formed therein. The enclosure 12-16 is configured to accommodate the sensor circuit assembly 16 and some potting material. The potting material is employed to hold the circuit elements in place within the protective enclosure 12-16. The drill rod 4 and spring 14 arrangement is substantially identical to previous embodiments described above, and thus any description of previously described elements is omitted for brevity's sake.

[00163] Figure 28 is a detail view of a carriage apparatus 20 depicted in Figure 27. In this view, the protective cover 30 is shown with a cutaway view that reveals the housing 12 underneath. As before, the sensor circuit 16 is disposed within the protective enclosure 12-16 and the cover 30 serves to protect the circuitry 16.

[00164] Referring to Figure 29, a diagrammatic depiction of the sensor assembly depicted at Figure 27 is disclosed. The sensor assembly 16 includes various components disposed, e.g., on a printed circuit board (PCB) and coupled together by a bus system 16-1. The bus system 16-1 is coupled to a microprocessor 16-2 and computer readable memory 16-3. The sensor assembly 16 may also include an accelerometer module 16-4, a magnetometer module 16-5, an inclinometer 16-6, a gyro rate sensor 16-7, as well as an environmental module 16-11.

[00165] As those skilled in the art will appreciate, the accelerometer module 16-4 may be configured to measure the Earth's gravity vector and provide the gravity vector components gx, gy, gz of the Earth's gravity vector g. The gyroscope 16-7 is used for measuring the device's orientation and/or angular velocity. The gyro 16-7 may be configured as a rate gyroscope which is configured to produce an output voltage proportional to a rate of rotation. The magnetometer module 16-5 may include a plurality of fluxgate magnetometers having their axes of maximum sensitivity intersecting each other at one or more observation points and substantially at right angles to each other. (As before, the magnetometer module 16-5 may have a magnetometer sensor having up to three magnetometers; and, the magnetometer module 16-5 may have multiple magnetometer sensors). Magnetometers measure the amplitude and the phase of two perpendicular components of the magnetic field 300. The inclinometer may be employed to measure the angles of slope/tilt of carriage 20 with respect to the gravity vector. The environmental sensor module 16-11 may be configured to measure one or more of temperature, pressure, radiation, etc.

[00166] The microprocessor 16-2 may be configured to use the sensor inputs to determine the spatial relationships between the borehole axis 7, borehole inclination, roll angle, borehole azimuth, the Earth's rotation vector, and other such spatial relationships.

[00167] The sensor assembly 16 also includes a piezoelectric transducer 16-8 that is configured to convert the mechanical energy (W_h) generated by the drilling operations into electrical energy. (An expression for the mechanical energy is provided herein). As those skilled in the relevant arts would appreciate, the piezoelectric effect converts mechanical strain into electric current or voltage. The electrical current is provided to an electrical storage device 16-9 which includes a battery for storing the harvested energy. In an alternate embodiment, electrical power may be provided to the carriage 20 (and sensor assembly 16) by way of wireline.

[00168] Finally, the sensor assembly 16 may include a transmitter device 16-10 and a receiver 16-12. The transmitter 16-10 and receiver may be configured as a wireless or as a wireline transceiver configured to communicate with an uphole telemetry system (not shown in this view). In one embodiment, the uphole telemetry system is configured to manipulate all of the sensor data provided by the sensor assembly 16 (disposed down-hole). This information, or some of the information, may be transmitted to a driller controller (FIGs. 1 - 2) so that an appropriate course correction can be made (if necessary). In another embodiment, data transfer may be effected when the device 10 is retrieved from the downhole environment.

[00169] The microprocessor 16-2 may be configured to bi-directionally communicate with the various components coupled to the bus 16-2. In this embodiment, the microprocessor 16-2 may include on-board analog-to-digital conversion (ADC) channels that accommodate the analog output signals of the accelerometers (16-4 – 16-6). The analog voltage output signal of the gyro sensor 16-7 may also be converted into digital signals.

[00170] The sizing and selection of the microprocessor 16-2 is considered to be within the skill of one of ordinary skill in the art with the following proviso: obviously, if the functionality of the up-hole control system is incorporated into the down-hole system, the computational burden of the resultant processor will necessarily be greater. In any event, in accordance with the embodiment of FIG. 5C, the microprocessor 16-2 may be implemented using any suitable processing device depending on processing speed, cost, and durability considerations. In one embodiment, therefore, processor 16-2 may be implemented using a 16 bit, a 32-bit, a 64 bit, or any suitable microcontroller coupled to any suitable computer readable media 16-3. As noted above, the microcontroller may be more or less powerful depending on cost/processing speed considerations.

[00171] The term “computer-readable medium” as used herein refers to any medium that participates in providing data and/or instructions to the processor 16-2 for execution. Such a medium may take many forms, including but not limited to RAM, PROM, EPROM, EEPROM, FLASH-EPROM or any suitable memory device, either disposed on-board the processor 16-2 or provided separately. In one embodiment, the processor 16-2 may include 256 KB of flash memory and 32 KB of SRAM.

[00172] As embodied herein and depicted in Figure 30, a diagrammatic depiction of a downhole assembly 10 in accordance with yet another alternate embodiment of the present invention is disclosed. In this view, the housing 12 is configured to provide a protective housing for the magnetic source elements 100. As described below, the magnetic source elements may be disposed within the housing 12 via the interior of the housing so that they are protected from the ambient environment. The magnetic source housing 12 is coupled to a first spring member 14-1 at a first end thereof, and is coupled to a second spring member 14-2 at a second end portion of the housing 12. In this embodiment, the spring members (14-1, 14-2) may be formed by machining metallic cylinders to form a spring structure.

[00173] The spring member 14-1 is coupled to the collar member 16-1 at a first end portion of the magnetic source apparatus 20; the collar members (16-1, 16-2) function as attachment points for the apparatus 20. Stated differently, the collar member 16-1 is fixedly attached to a portion of the drill string 4 proximate to the drill bit 8 (not shown in this view). Similarly, the spring member 14-2 is coupled to a second collar member 16-2 at a second end portion of the magnetic source apparatus 10 distal from the drill bit 8. The second collar member 16-2 is fixedly attached to an up-hole portion of the drill string 4.

[00174] As described below, the carriage apparatus 20 is configured such that the magnet elements 100 are rotationally registered to a registration portion of the drill bit 8 such that measurements of the magnetic field by the sensor apparatus 50 will include knowledge of the drill bit (tool face) 8 orientation. This allows the measurement system 1000 (Fig. 1) to instantaneously control the drilling direction via control station 2. Having said that, note that only the collar portions (16-1, 16-2) are coupled to the drill string 4. The carriage housing 12 and the spring members (14-1, 14-2) are spatially separated from a drill rod portion 4-1 and thus configured to float or glide over the drill rod portion 4-1 as the drill string 4 rotates (during the drilling process). In one embodiment, the drill rod 4-1 is not deemed to be a component part of apparatus 10, i.e., the apparatus 10 may be coupled to any similar structure. In another embodiment, the apparatus may include a drill rod 4-1 manufactured and machined especially for apparatus 10; and in this case, the drill rod 4-1 would be a component part of the apparatus 10.

[00175] In reference to Figure 31, a diagrammatic depiction of a magnetic source apparatus 10" shown in Figure 30 is disclosed. In this embodiment, a protective sleeve 1300 may be disposed over the entire assembly 10". The protective sleeve may be formed from any suitable material such as BeCu, stainless steel, plastic, etc.

[00176] As embodied herein and depicted in Figure 32, a diagrammatic depiction of a downhole apparatus 10"' in accordance with another embodiment of the present invention is disclosed. The number of components in assembly 10 is identical to the assembly depicted in Figure 30; however, some of the individual members may be implemented differently. For example, in this embodiment, the spring members (14-1, 14-2) may be implemented using a wire spring structure. Both implementations may have similar performance characteristics). As before, the spring members (14-1, 14-2) are configured to register the housing 12 so that the magnetic source elements 100 are rotationally registered with the drill bit 8 and/or an orientation feature on the drill bit 8. Moreover, the collar portions (16-1, 16-2) are configured to be rotationally registered with the spring members (14-1, 14-2). Detail views of the collar assemblies (16-1, 16-2) are described below in conjunction with Figures 35 and 36.

[00177] Figure 33 is a diagrammatic depiction of the drill rod structure 4 depicted in Figure 32 with the carriage apparatus removed. In one embodiment, the assembly 10 may include a specially fabricated drill rod that provides rotational registration features configured to register the source housing 12, the spring elements (14-1, 14-2) with the drill bit 8. Specifically, the drill bit 8 may include a drill bit registration feature 8-1 that is configured to be aligned with a registration mark 4-4 formed on drill rod 4-1. At the same time, the drill rod 4-1 also includes key indents 4-2 at each end thereof. The key indents 4-2 are configured to accommodate a key ring portion of the collars (16-1, 16-2) to thus rotationally register the collars to the rod 4-1. Moreover, the indent gap 4-20 is configured to accommodate an end portion of the wire spring (14-1, 14-2) to rotationally register the springs (14-1, 14-2) to the drill rod 4-1. Finally, a plurality of cooling holes 4-3 are formed in the drill rod 4-1. The cooling holes 4-3 are in communication with the central fluid channel 4-10 of the drill rod 4-1. The central fluid channel 4-10 extends the length of the drill string 4 and allows a cooling fluid (such as air) to be directed from the source 200 (Figs. 1, 2) to the drill bit 8.

[00178] The housing 12 is assembled such that each magnetic source 100 is positioned over a corresponding cooling hole 4-3. Thus, the cooling holes 4-3 may be used to rotationally register the magnetic source housing 12 to the drill rod 4-1, and hence to the drill bit registration feature 8-1 formed on the drill bit 8. At this point, a few words concerning the meaning of the term "rotational registration" may be in order. If the drill bit registration feature 8-1 is designated as, for example, 0°, every other feature on the drill rod will have a predetermined angular position θ relative to feature 8-1 when the assembly 10 is properly configured. The drill bit orientation feature 8-1 may be an asymmetrical feature or drill orientation that allows the drilling control system 2 to perform directional drilling (i.e., precisely control the direction of the borehole as it is being drilled). The orientation is known and programmed in software. The magnetic field orientation relative to the magnet source elements 100 is also known and programmed in software. By determining the magnetic field orientation via the sensor assembly (Figs 1 and 2), the drill bit orientation may also be determined.

[00179] As before, the springs 14-1 and 14-2, along with the mass of the carriage are configured to form a low pass isolation filter in accordance with the principles outlined above. See Figs. 12 – 15C and the associated text.

[00180] In reference to Figure 34, a cross-sectional view of the magnetic source housing 12 depicted in Figures 30 and 32 is disclosed. In this view, the housing portions 12-1 and 12-2 are shown as being disposed around the drill rod 4 such that the magnetic sources 100 are aligned with the cooling holes 4-3. In one application, the cooling air is directed down the pipe 4-10 at about 150 PSI. Accordingly, the cooling air is directed into the cooling holes 4-3 and into the gap 124 that is formed between the inner surface of the housing 12 and the outer surface of the drill rod 14-1. As a result, the cooling air is employed to direct thermal energy away from the magnets 100 and thus lower the ambient temperature of the magnetic source elements 100.

[00181] In reference to Figure 35, a detail view of a collar assembly 16-1 depicted in Figure 32 is disclosed. (Note that the retention collar 16-2 disposed on the other end of drill rod 4-1 (see Figs. 30 and 32) is of like or similar construction). The retention collar 16-1 may include a first collar portion 16-10 coupled to a second collar portion 16-12 (disposed behind drill rod 4-1 and thus not shown in this view). The first and second collars (16-10, 16-12) may be coupled together using any suitable means such as a weld 16-11 or other suitable fastener means. A first retention key 16-14 is disposed within a key indent 4-2 (see Fig. 33) and a retention feature formed within the interior surface of the first collar portion 16-10, to thus rotationally register the collar 16-1 to the drill rod 4-1. (The second collar 16-12, disposed behind the drill rod 4-1 in this view, also accommodates a second retention key 16-16 disposed within its respective key indent 4-2). Note that a spring registration portion 14-10 is disposed within the indent gap 4-20 to rotationally register the spring 14-1 with the drill rod 4-1. (In reference to Fig. 37, the spring registration portion 14-10 is not depicted for clarity of illustration, but may be employed in that embodiment).

[00182] In reference to Figure 36, a detail view of a collar assembly 16-1 depicted in Figure 32 in accordance with an alternate embodiment of the present invention is disclosed. In this alternate embodiment, the retention collar 16-1 includes a first collar portion 16-10 that includes a ramped sleeve 16-11 that slides over the drill rod 4-1. A second collar portion 16-12 slides over the ramped portion 16-11 and is tightened by fasteners 16-20 to exert pressure on the sleeve 16-11. The ramped sleeve 16-11 features a relatively small angle φ between the ramp and the interior surface of the collar portion 16-10. The angle φ may be of any suitable amount; for example, in one embodiment the angle φ is between $1^\circ - 2^\circ$.

[00183] In another embodiment, the attachment collars (16-1, 16-2) may also be implemented as an end portion of the spring members (14-1, 14-2). In this embodiment, the end-collar portion of the spring includes a registration mark or indicia that are aligned to a registration mark/indicia formed on the drill rod. Upon alignment, the end-collar may be welded to the drill rod 4-1.

[00184] In yet another embodiment of the invention, the attachment collars (16-1, 16-2) may be integrally formed with the drill rod 4-1 itself. In this embodiment, each attachment collar includes a spring member interface that accommodates the spring registration portion 14-10 to rotationally register the spring 14-1 with the drill rod 4-1.

[00185] As embodied herein and depicted in Figures 37 and 38, detail views of the spring elements depicted in Figure 32 are disclosed. In Figure 37, the spring element 14-1 is shown as being disposed over the drill rod 4-1. In this embodiment the free length F/L may be about 4 inches. In Figure 38, the outside diameter (ID) is about 2.87 inches in order to accommodate the outside diameter of the drill rod 4-1. The wire diameter in this embodiment may be about 0.2 inches. In this embodiment, the spring members 14-1, 14-2 are configured as compression springs and are implemented as open-coil helical springs wound or constructed to oppose compression along the longitudinal axis 7 (see, e.g., Figs. 1, 2). (As noted previously, while the spring registration portion 14-10 (shown at Figure 35 and described above) is not depicted in Figure 37 for clarity of illustration, the springs (14-1, 14-2) may include the registration feature 14-10 or other such features such as 14-10 to thus provide rotational registration).

[00186] While several inventive embodiments have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the function and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the inventive embodiments described herein. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific inventive embodiments described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto; inventive embodiments may be practiced otherwise than as specifically described and claimed.

[00187] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

[00188] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[00189] The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising," "having," "including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. The term "connected" is to be construed as partly or wholly contained within, attached to, or joined together, even if there is something intervening.

[00190] As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[00191] It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

[00192] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about" and "substantially", are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged; such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

[00193] The recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein.

[00194] All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate embodiments of the invention and does not impose a limitation on the scope of the invention unless otherwise claimed.

[00195] No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[00196] In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of,” and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases “consisting of” and “consisting essentially of” shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

[00197] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. There is no intention to limit the invention to the specific form or forms disclosed, but on the contrary, the intention is to cover all modifications, alternative constructions, and equivalents falling within the spirit and scope of the invention, as defined in the appended claims. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. An apparatus for use on a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum, the apparatus comprising:

a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device, the housing assembly being configured to be rotationally registered to the structural member when coupled to the structural member, the housing assembly being characterized by a predetermined housing mass; and

a spring arrangement coupled between the structural member and the first end and/or coupled between the structural member and the second end in the operational state, the spring arrangement being characterized by a predetermined force-displacement relationship, the housing assembly and the spring arrangement forming an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship, the predetermined spectral transfer function including a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing assembly is substantially isolated from the stress wave energy.

2. The apparatus of claim 1, wherein the spring arrangement includes at least one first spring element coupled between the first end and the structural member in the operational state, and wherein the spring arrangement includes at least one second spring element coupled between the second end and the structural member in the operational state.

3. The apparatus of claim 2, wherein the housing assembly is substantially cylindrical, and wherein the at least one first spring element and the at least one second spring

element have an outer diameter substantially equal to an outer diameter of the housing assembly.

4. The apparatus of claim 2, wherein the at least one first spring element includes a plurality of first spring elements coupled in parallel between the first end and the structural member in the operational state, and the at least one second spring element includes a plurality of second spring elements coupled in parallel between the second end and the structural member in the operational state.

5. The apparatus of claim 4, wherein the plurality of first spring elements includes four spring elements or the plurality of second spring elements includes four spring elements.

6. The apparatus of claim 1, wherein the spring arrangement includes at least one compression spring, the at least one compression spring being configured to oppose compression along the longitudinal axis.

7. The apparatus of claim 1, wherein the at least one device includes at least one sensor device or at least one magnetic source element.

8. The apparatus of claim 7, wherein the at least one sensor device includes at least one accelerometer, at least one magnetometer, a gyro sensor, at least one environmental sensor, a piezoelectric transducer, or a battery device.

9. The apparatus of claim 7, wherein the at least one protective enclosure includes at least one set of pockets orientated in a plane perpendicular to the longitudinal axis, and wherein each pocket of the at least one set of pockets is configured to accommodate a magnetic source element.

10. The apparatus of claim 1, wherein the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies substantially greater than the natural resonant frequency, and wherein the stress wave

energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum, and wherein the attenuation factor increases as the frequency f increases.

11. The apparatus of claim 1, wherein the housing assembly is substantially cylindrical having an inner diameter and an outer diameter respectively defining an interior housing surface and an exterior housing surface; and

wherein the housing assembly includes a first housing portion coupled to a second housing portion, each of the first housing portion and the second housing portion having a substantially semicircular cross-section so that the housing assembly has a substantially circular cross-section when the first housing portion is coupled to the second housing portion; and

wherein a key channel arrangement is formed in the interior housing surface where the first housing portion coupled to the second housing portion, the key channel arrangement being configured to mate with a portion of the structural member to effect rotational registration.

12. The apparatus of claim 11, wherein the at least one protective enclosure includes a plurality of pockets formed in the interior housing surface or the exterior housing surface, each pocket of the plurality of pockets being configured to accommodate a magnetic source device; or wherein the at least one protective enclosure is formed in the exterior housing surface and configured to accommodate a sensor assembly.

13. The apparatus of claim 12, wherein the magnetic source device is selected from a group of magnetic source devices including a permanent magnet and an electromagnet.

14. The apparatus of claim 11, further comprising a protective cover disposed over the housing assembly in the operational state, the protective cover substantially configured to conform to the exterior housing surface.

15. The apparatus of claim 14, wherein the protective cover is disposed over the spring arrangement in the operational state.

16. The apparatus of claim 1, wherein the predetermined force-displacement relationship includes a constant spring rate or a variable spring rate.

17. An assembly comprising:

a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum; and

an apparatus coupled and rotationally registered to the structural member, the apparatus comprising,

a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device, the housing assembly being characterized by a predetermined housing mass; and

a spring arrangement coupled between the structural member and the first end and/or coupled between the structural member and the second end, the spring arrangement being characterized by a predetermined force-displacement relationship, the housing assembly and the spring arrangement forming an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship, the predetermined spectral transfer function including a passband having frequencies that are substantially outside the operational frequency spectrum wherein the stress wave energy is substantially attenuated in the operational state so that the housing assembly is substantially isolated from the stress wave energy.

18. The assembly of claim 17, wherein the spring arrangement includes at least one first spring element coupled between the first end and the structural member, and at least one second spring element coupled between the second end and the structural member.

19. The assembly of claim 18, wherein the at least one first spring element and the at least one second spring element have an outer diameter substantially equal to an outer diameter of the housing assembly.

20. The assembly of claim 18, wherein the at least one first spring element includes a plurality of first spring elements coupled in parallel between the first end and the structural member, and wherein the at least one second spring element includes a plurality of second spring elements coupled in parallel between the second end and the structural member.

21. The assembly of claim 20, wherein the plurality of first spring elements includes four spring elements and/or wherein the plurality of second spring elements includes four spring elements.

22. The assembly of claim 17, wherein the structural member is a drill rod or a drill rod attachment including a central fluid channel configured to conduct a pressurized fluid along the longitudinal axis in the operational state, the structural member including a plurality of fluid openings in a region where the structural member is coupled to the housing assembly, the pressurized fluid including a gas or a liquid.

23. The assembly of claim 17, wherein the structural member includes a carrying region, a first shoulder member being disposed at a first end portion of the carrying region and a second shoulder member being disposed at a second end portion of the carrying region, wherein the housing assembly is coupled to the carrying region between the first shoulder member and the second shoulder member, and wherein the spring arrangement includes at least one first spring element coupled between the first end and the first shoulder member, and at least one second spring element coupled between the second end and the second shoulder member.

24. The assembly of claim 23, wherein the structural member further comprises a box portion disposed at a first end of the structural member, a pin portion disposed at a second end of the structural member, and a carrying region being disposed between the

box portion and the pin portion, the box portion being configured to accommodate a drive element of a drill string and the pin portion being configured to accommodate a tool bit or a drill bit.

25. The assembly of claim 17, wherein the spring arrangement includes at least one first spring element and at least one second spring element, and wherein the structural member further comprises a first collar member and a second collar member, and wherein the at least one first spring element is coupled between the first end and the first collar member, and wherein the at least one second spring element is coupled between the second collar member and the second end.

26. The assembly of claim 25, wherein the first collar member includes a first registration feature configured to rotationally register the at least one first spring element to an orientation feature on the structural member, and/or wherein the second collar member includes a second registration feature configured to rotationally register the at least one second spring element to an orientation feature on the structural member.

27. The assembly of claim 17, wherein the at least one device includes at least one sensor device or at least one magnetic source element.

28. The assembly of claim 27, wherein the at least one sensor device includes at least one accelerometer, at least one magnetometer module, a gyro sensor, at least one environmental sensor, a piezoelectric transducer, or a battery device.

29. The assembly of claim 27, wherein the at least one protective enclosure includes at least one set of pockets orientated in a plane perpendicular to the longitudinal axis, and wherein each pocket of the at least one set of pockets is configured to accommodate a magnetic source element.

30. The assembly of claim 17, wherein the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies

substantially greater than the natural resonant frequency, wherein the stress wave energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum and wherein the attenuation factor increases as the frequency f increases.

31. The assembly of claim 17, wherein the predetermined force-displacement relationship includes a constant spring rate or a variable spring rate.

32. A method comprising:

providing a structural member having a longitudinal axis, the structural member being configured to propagate stress wave energy in an operational state, the stress wave energy being characterized by an operational frequency spectrum;

providing a housing assembly including a first end, a second end, and at least one protective enclosure configured to accommodate at least one device, the housing assembly being characterized by a predetermined housing mass;

providing a spring arrangement, the spring arrangement being characterized by a predetermined force-displacement relationship, the housing assembly and the spring arrangement forming an isolation filter characterized by a predetermined spectral transfer function, the predetermined spectral transfer function being a function of the predetermined housing mass and the predetermined force-displacement relationship, the predetermined spectral transfer function including a passband having frequencies that are substantially outside the operational frequency spectrum;

coupling the housing assembly to the structural member such that the housing assembly is rotationally registered to the structural member;

coupling the spring arrangement between the structural member and the first end and/or between the structural member and the second end; and

entering an operational state wherein stress wave energy propagates along the structural member, the stress wave energy being substantially attenuated by the isolation filter so that the housing assembly is substantially isolated from the stress wave energy.

33. The method of claim 32, wherein the isolation filter is a low pass filter and the passband includes frequencies substantially between 0 Hz and a natural resonant frequency, and wherein the isolation filter includes a stopband having frequencies substantially greater than the natural resonant frequency, wherein the stress wave energy includes frequencies within the stopband so that the stress wave energy is substantially attenuated in the operational state in accordance with a $1/f^2$ roll-off attenuation factor, wherein f is a frequency within the operational frequency spectrum and wherein the attenuation factor increases as the frequency f increases.

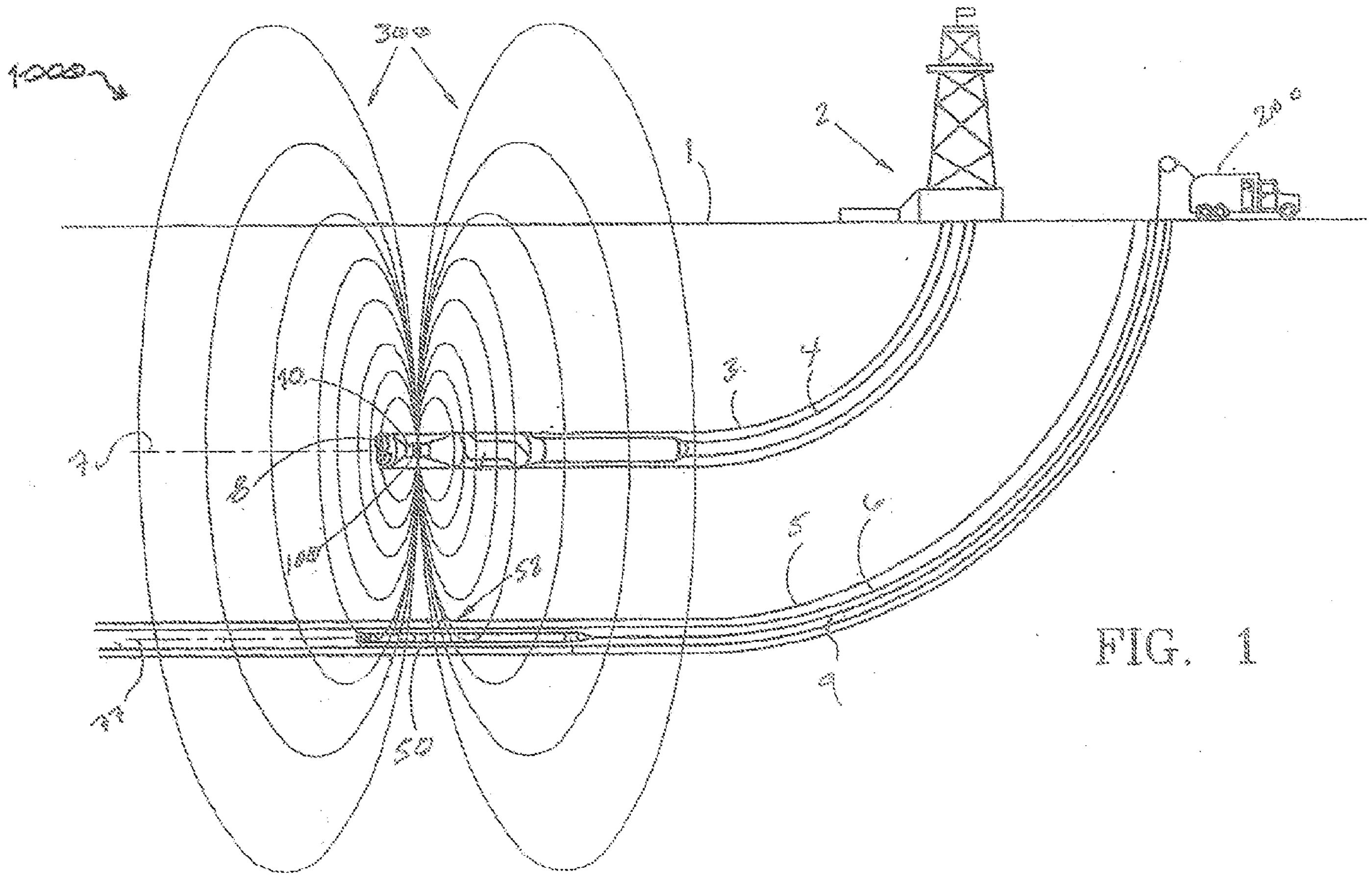

1000
300
2
1
200
3
4
10
7
8
100
5
6
52
77
9
50

FIG. 1

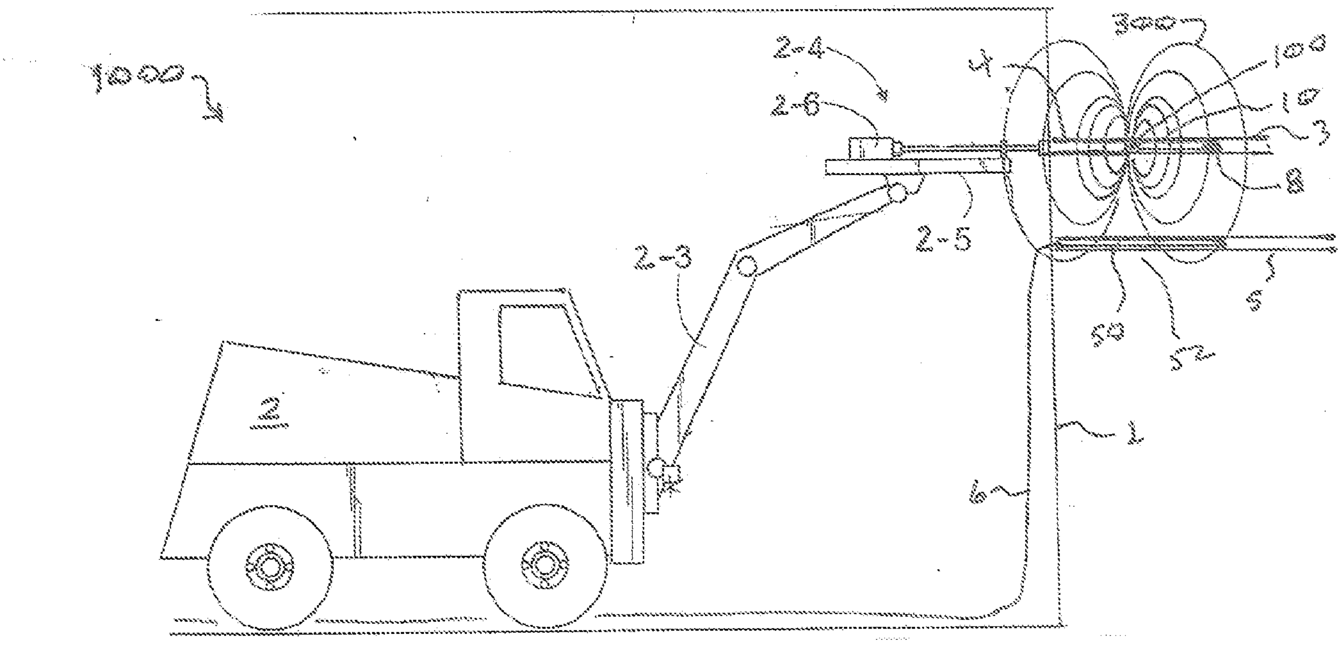

1000
300
2-4
2-6
4
100
10
3
8
2-5
2-3
5
50
52
2
1
6

Fig. 2

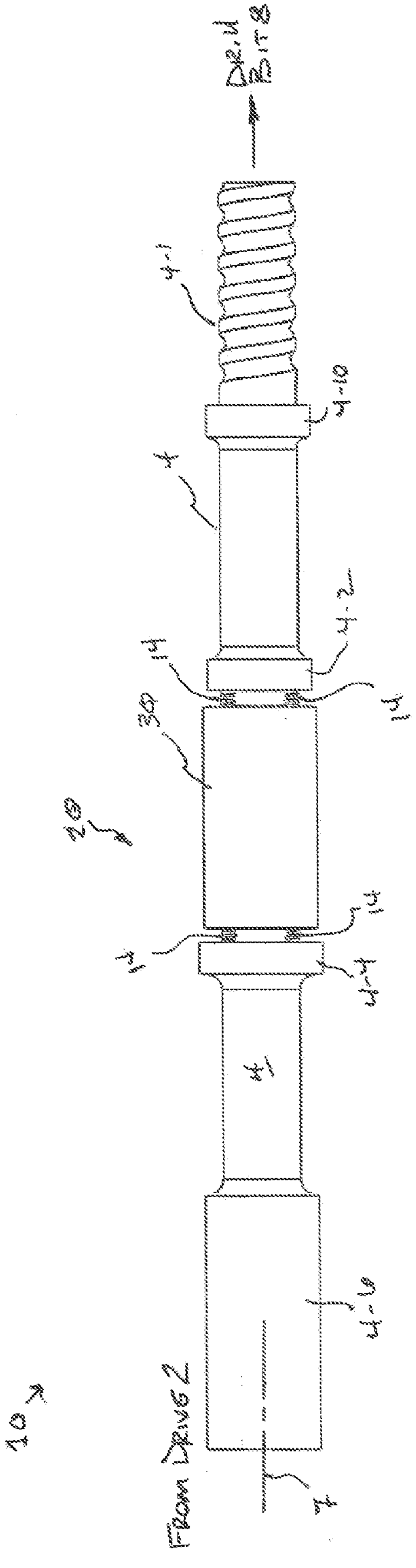

Drill Bit 8
4-1
4-10
4
4-2
14
14
30
20
14
14
4-4
4
4-6
10
From Drive 2
2

Fig. 3

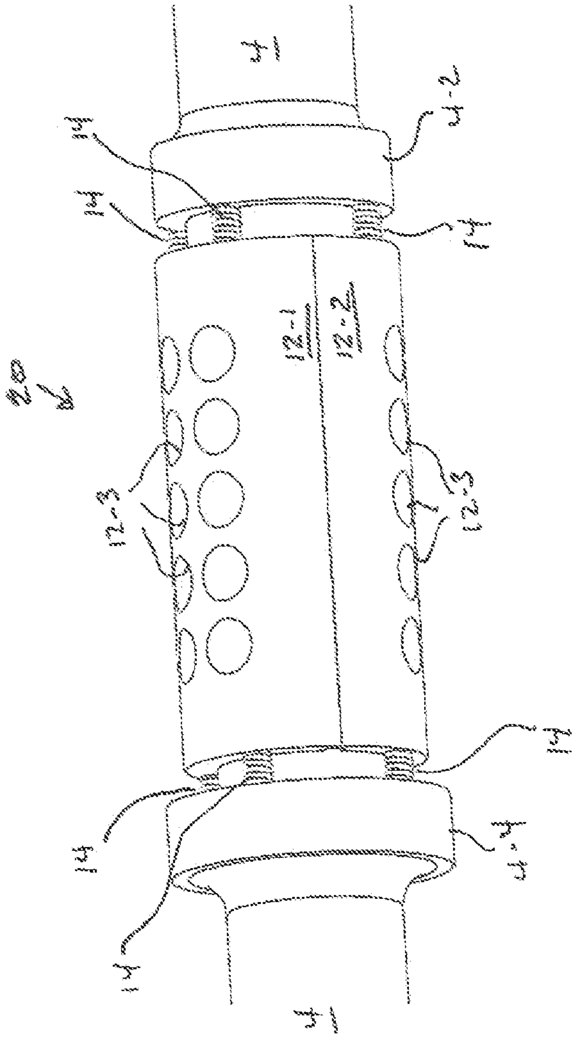

4
4-2
14
14
14
12-1
12-2
20
12-3
12-3
14
14
14
4-4
4

Fig. 4

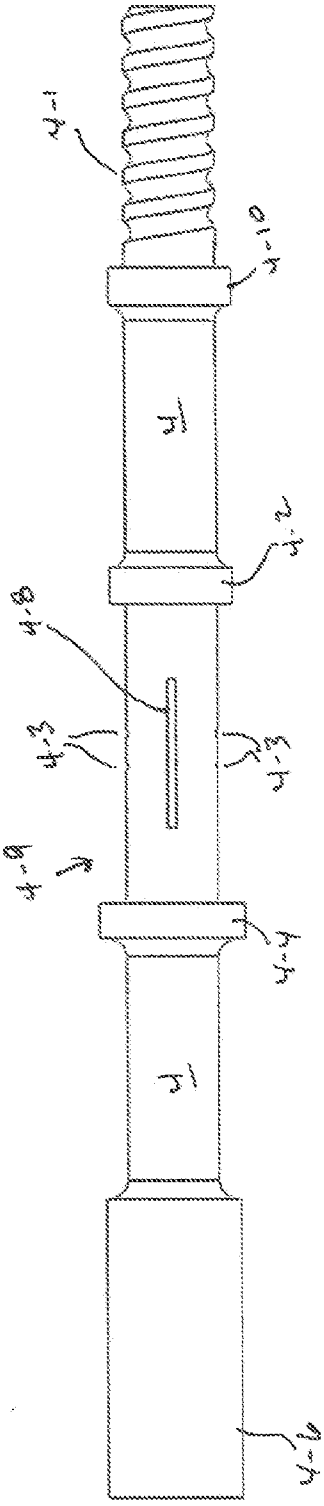


Fig. 5

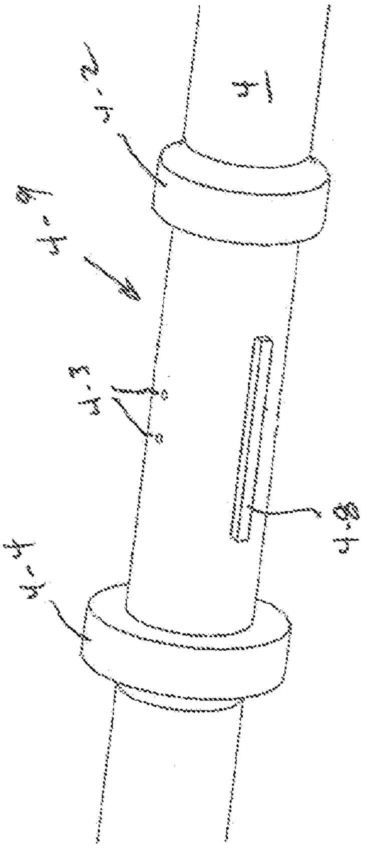


Fig. 6

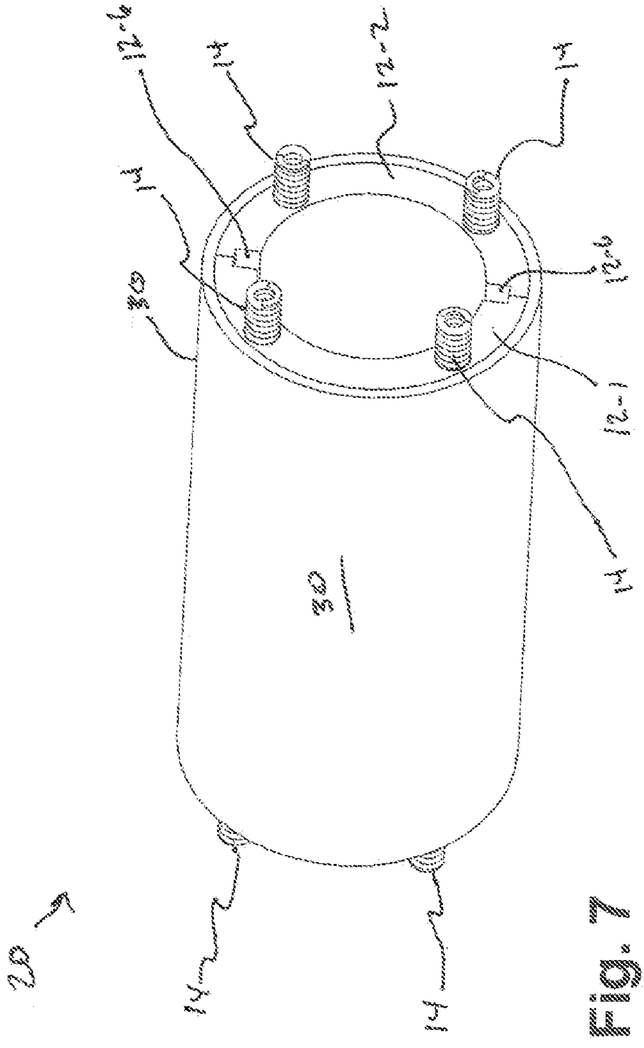

20
30
30
12-6
14
12-2
14
14
12-6
12-1
14
14
14

Fig. 7

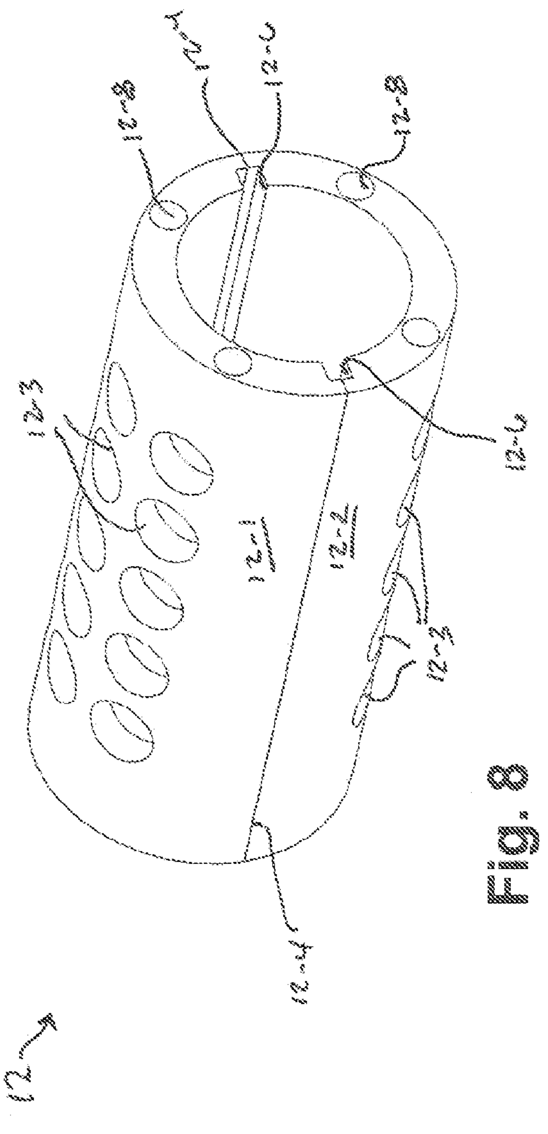

12
12-8
12-7
12-6
12-8
12-3
12-1
12-2
12-6
12-3
12-4

Fig. 8

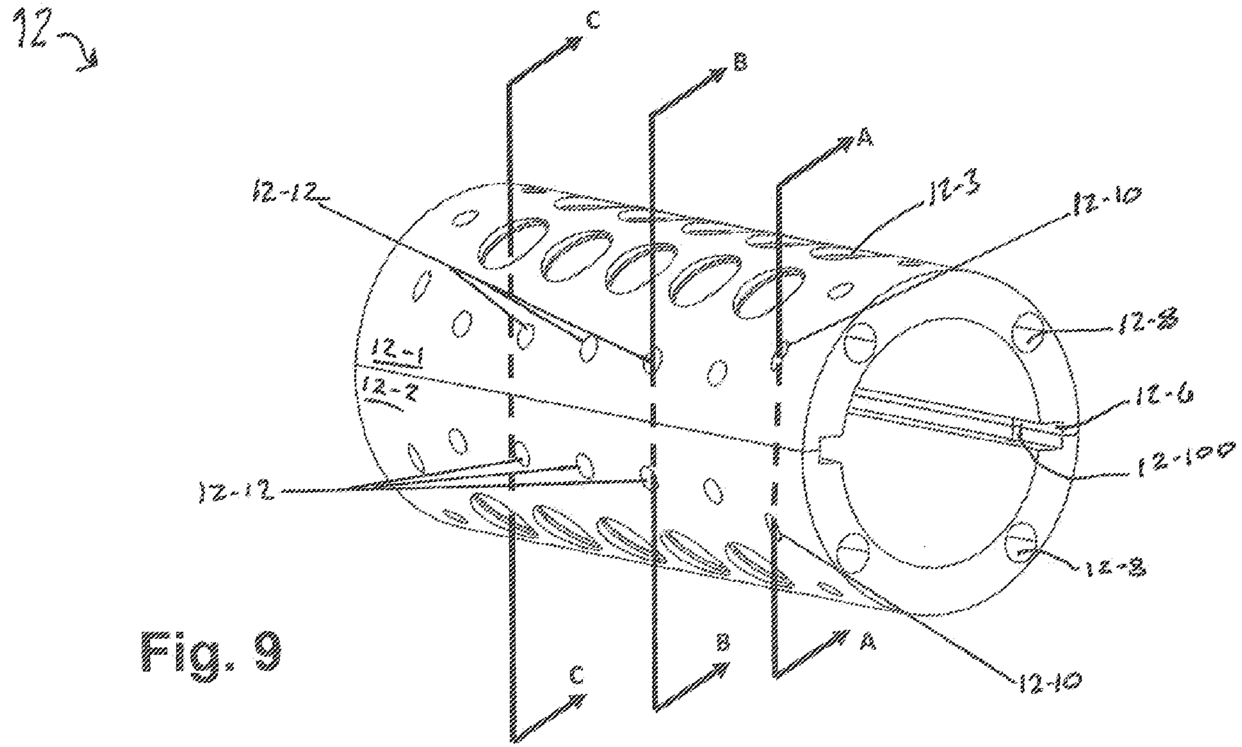

12
C
B
A
12-12
12-3
12-10
12-8
12-1
12-2
12-6
12-100
12-12
12-8
12-10
C
B
A

Fig. 9

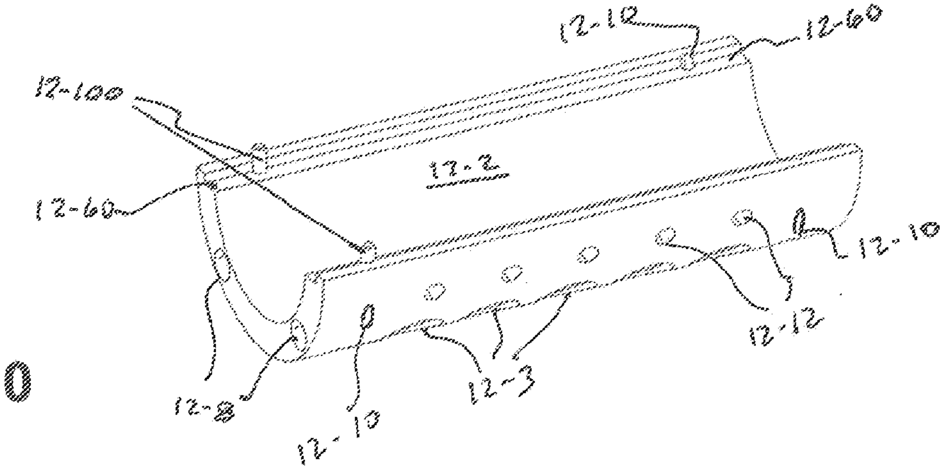

12-12
12-60
12-100
12-2
12-60
12-10
12-12
12-8
12-10
12-3

Fig. 10

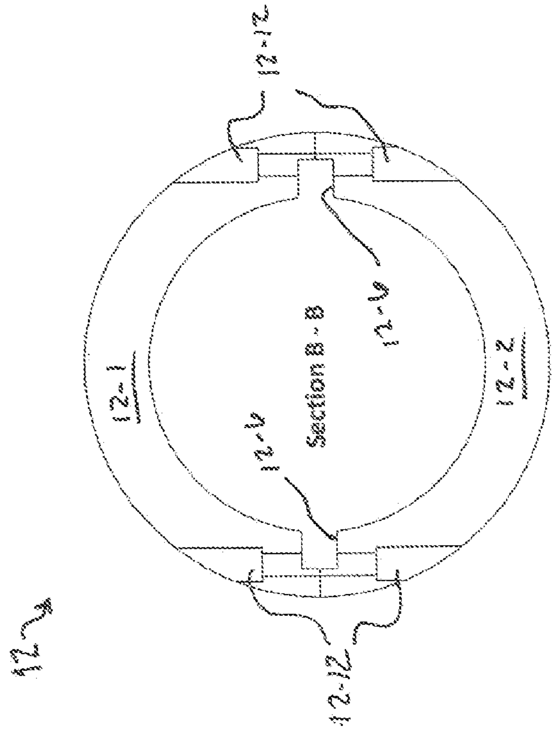


Fig. 11A

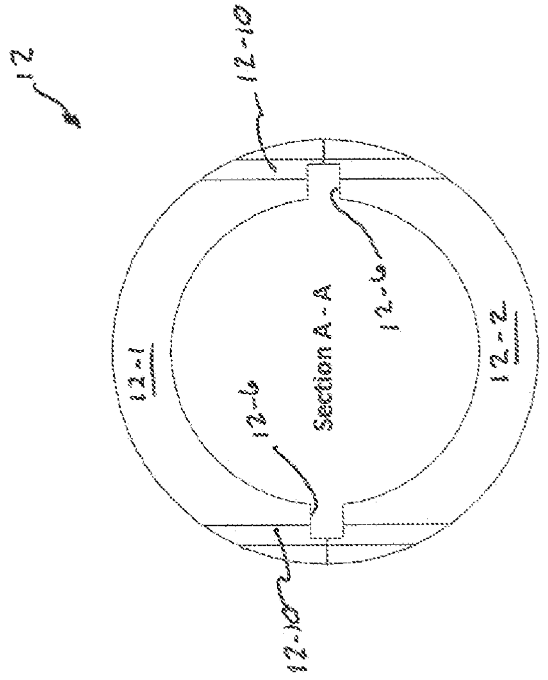


Fig. 11B

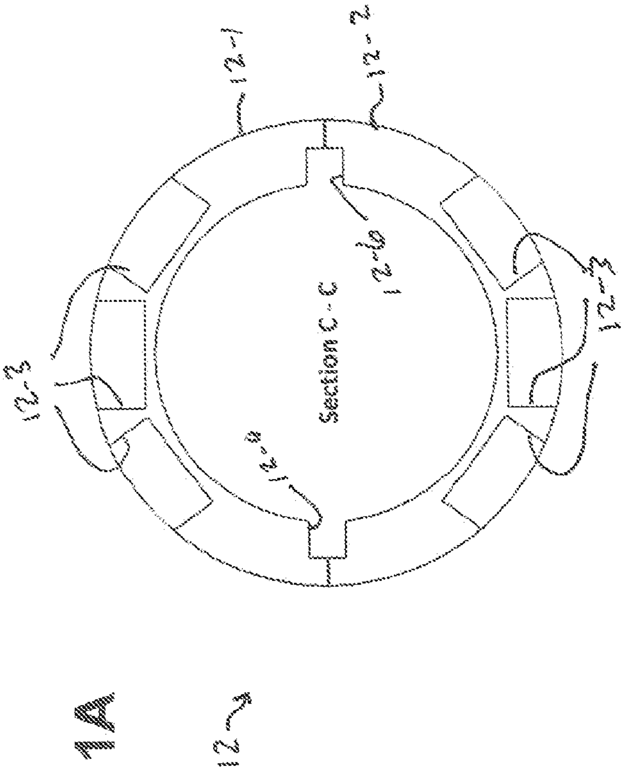


Fig. 11C

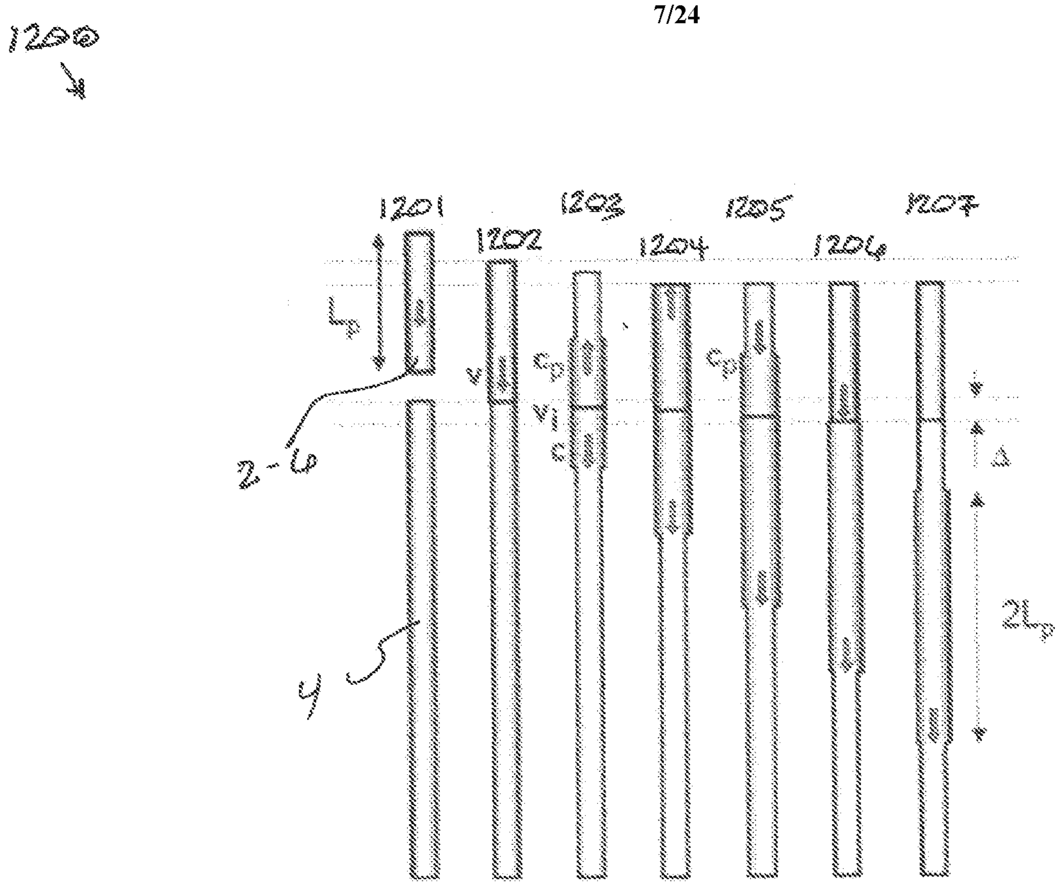


Fig. 12

Fig. 13A

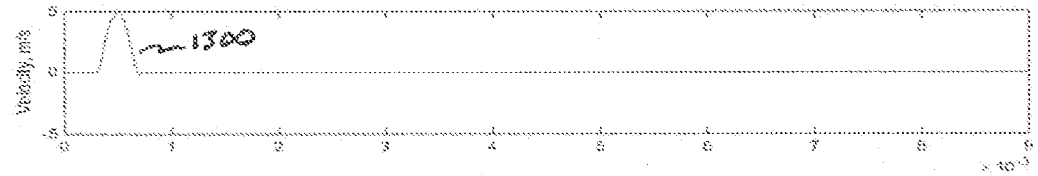


Fig. 13B

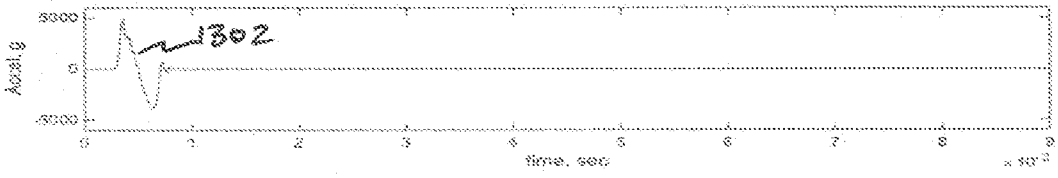


Fig. 13C

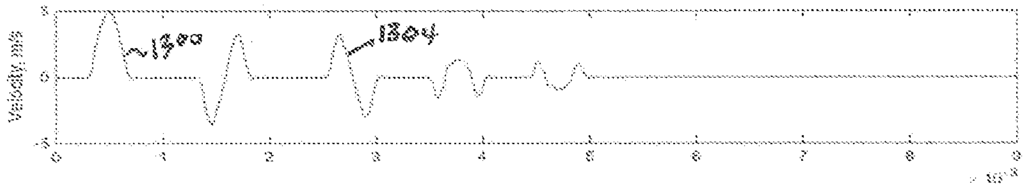


Fig. 13D

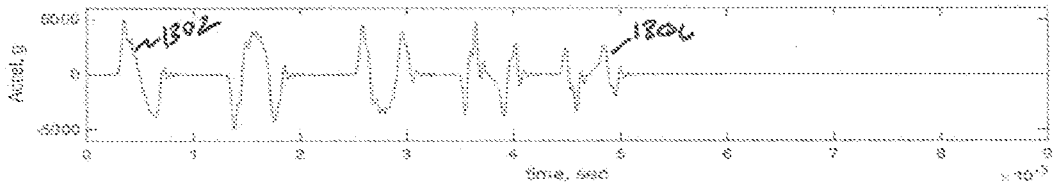


Fig. 13E

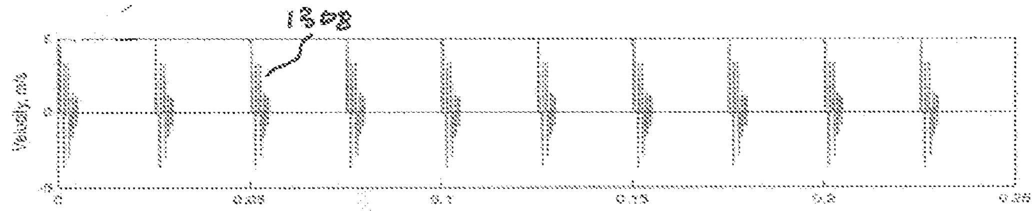
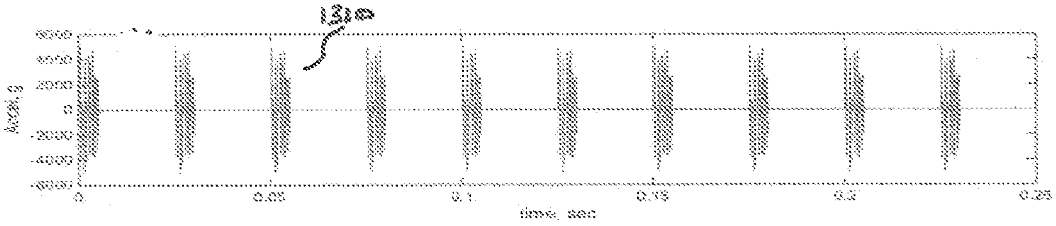


Fig. 13F



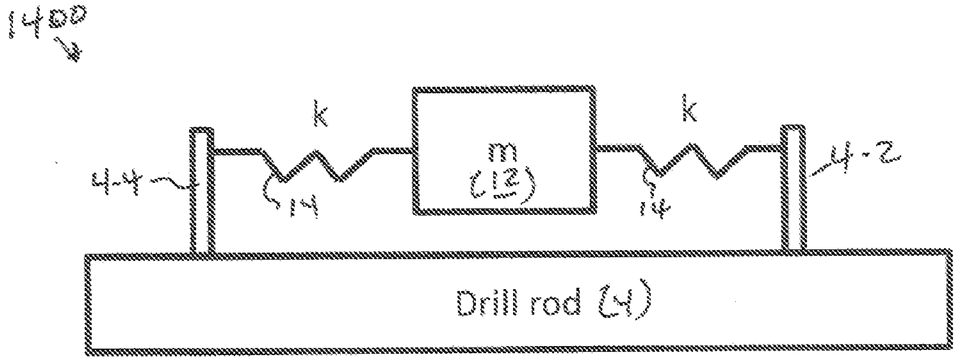


Fig. 14

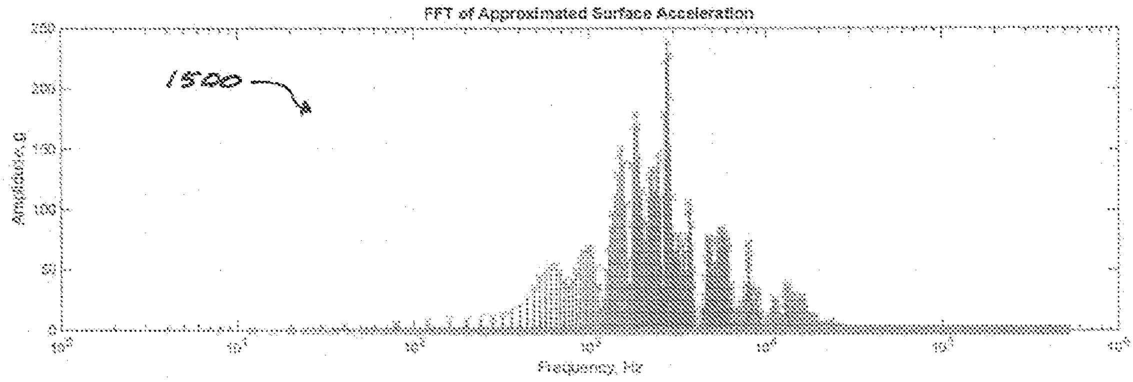


Fig. 15A

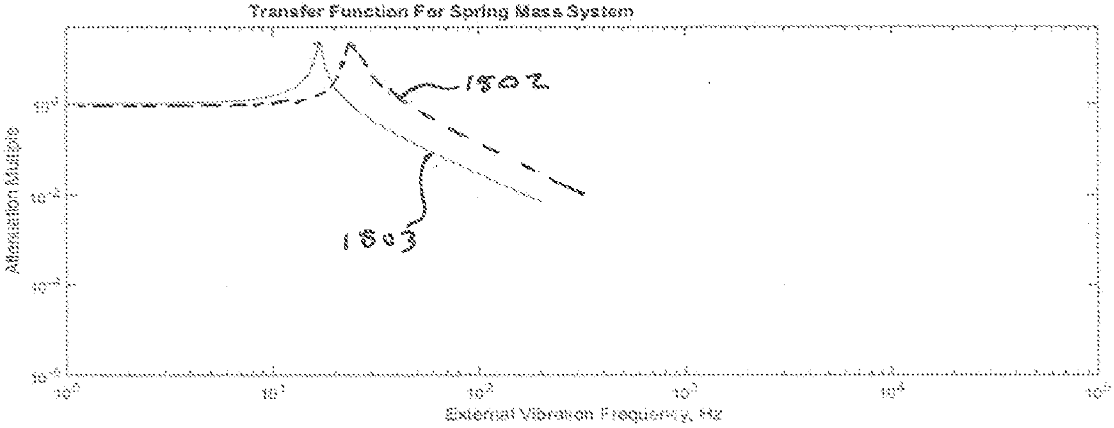


Fig. 15B

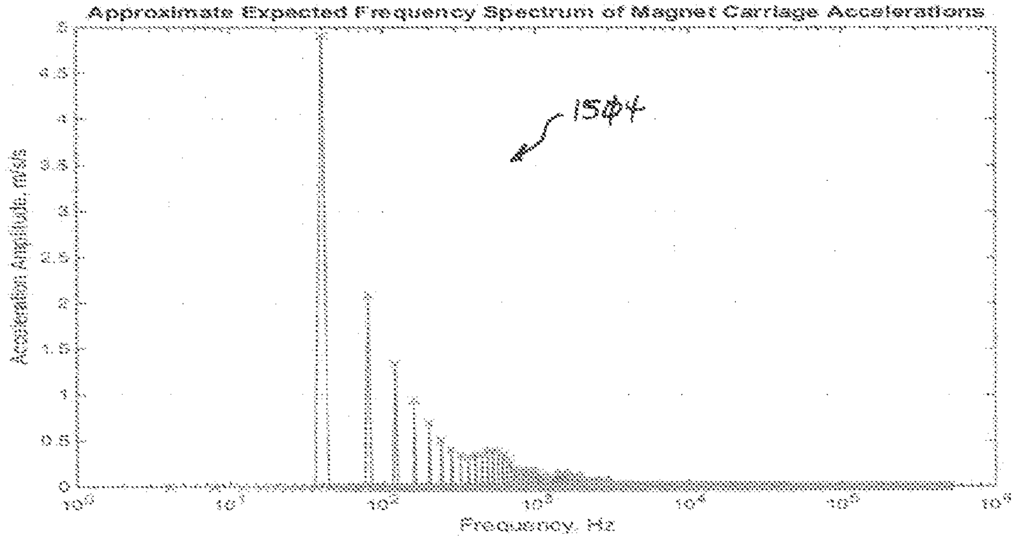


Fig. 15C

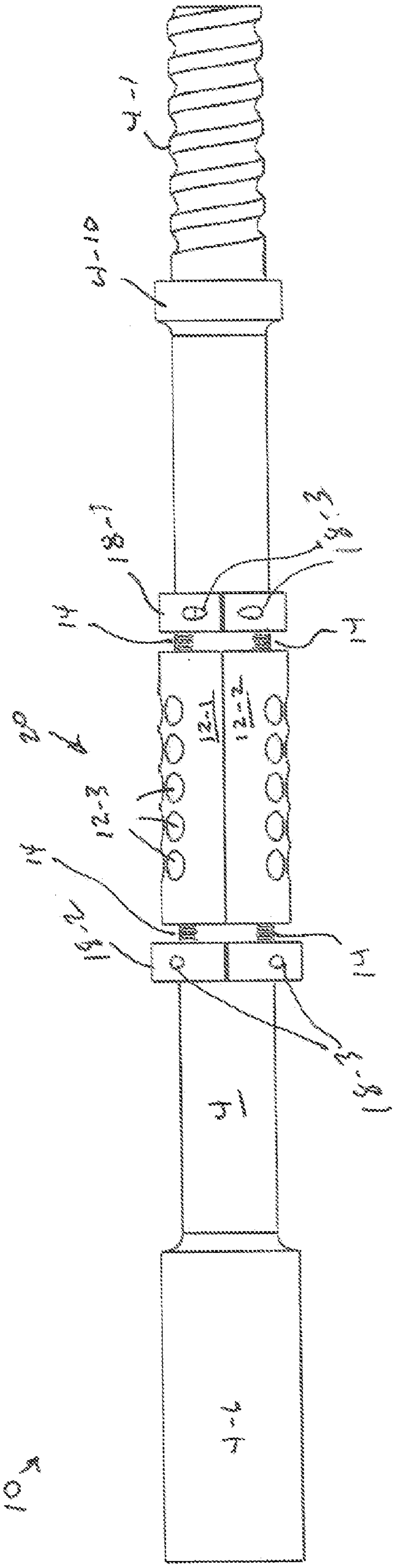

4-1
4-10
18-1
18-3
14
14
12-1
12-2
20
12-3
14
14
18-2
18-3
4
4-6
10

Fig. 16

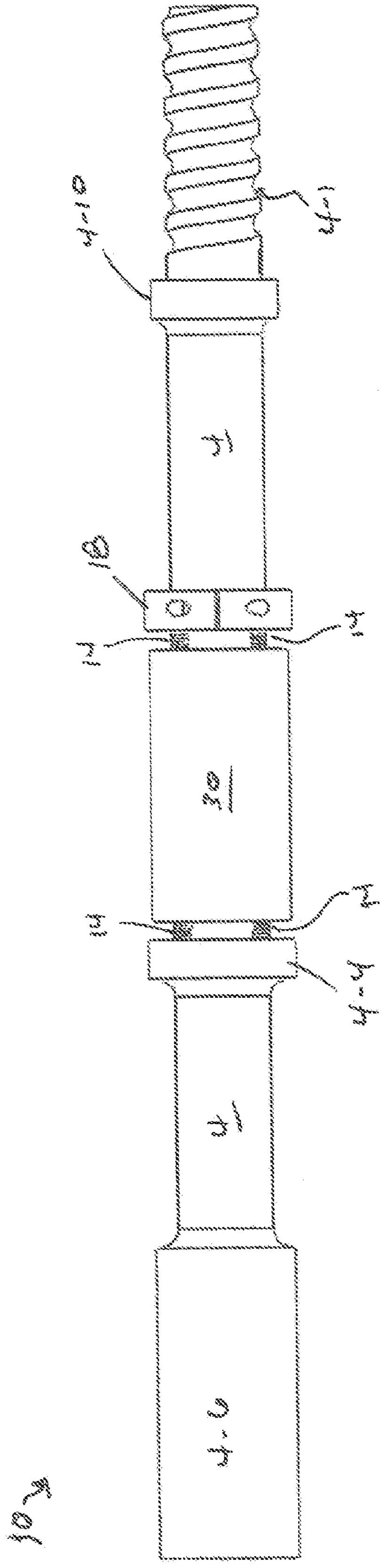

4-10
4-1
4
18
14
14
30
14
14
4-4
4
4-6
10

Fig. 17

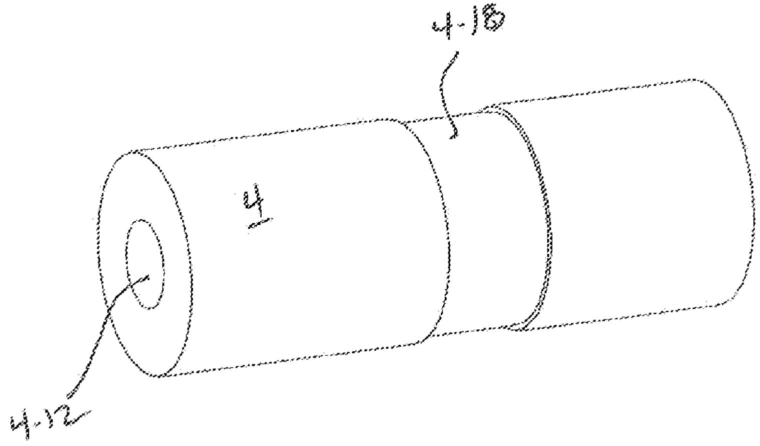


Fig. 18A

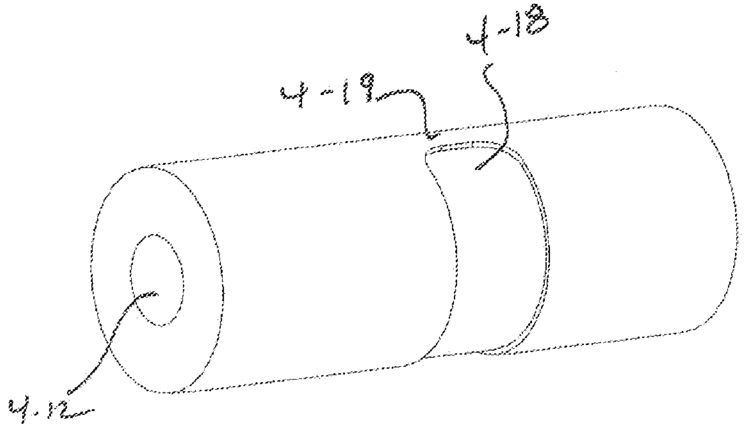


Fig. 18B

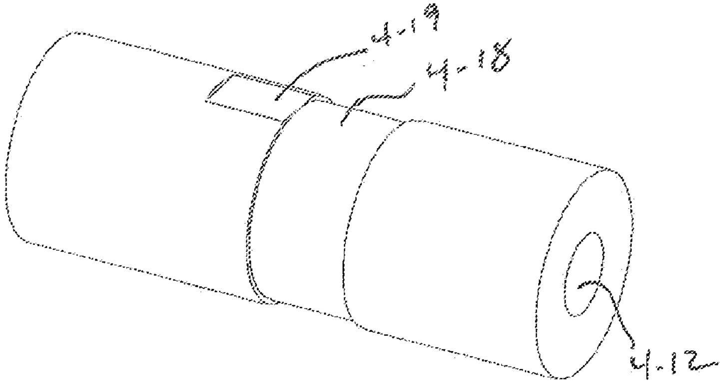


Fig. 18C

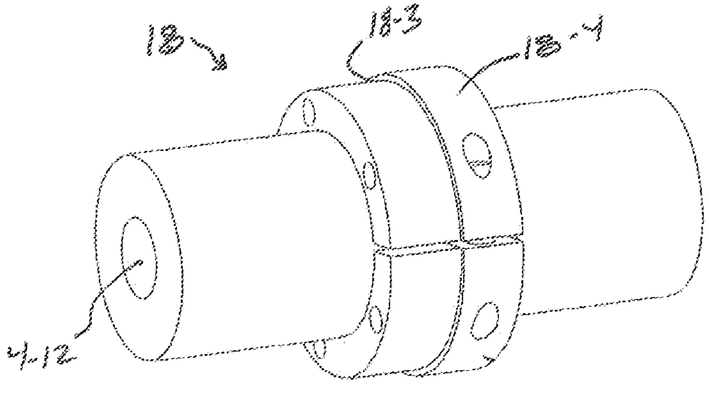


Fig. 18D

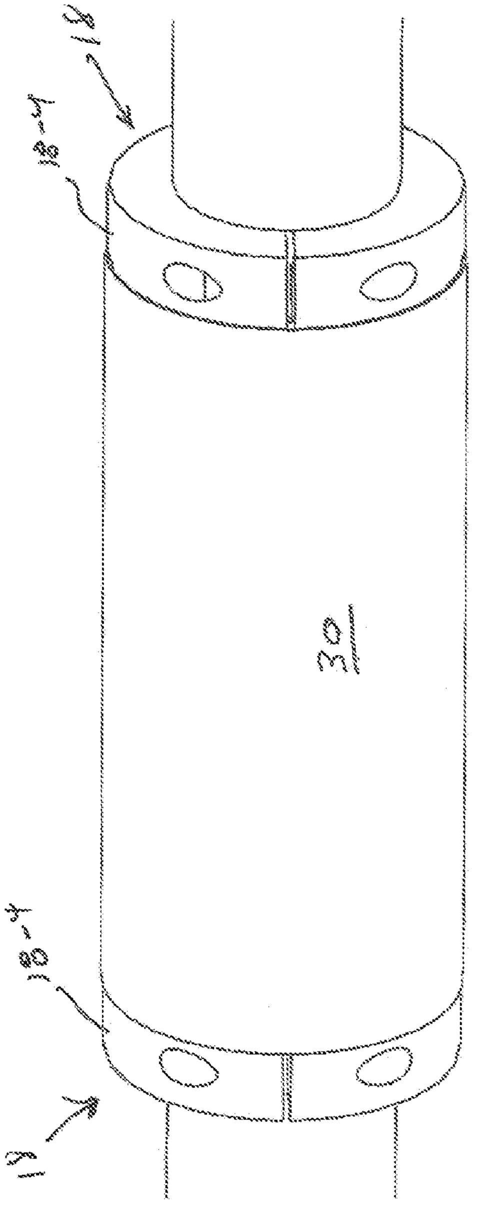


Fig. 19

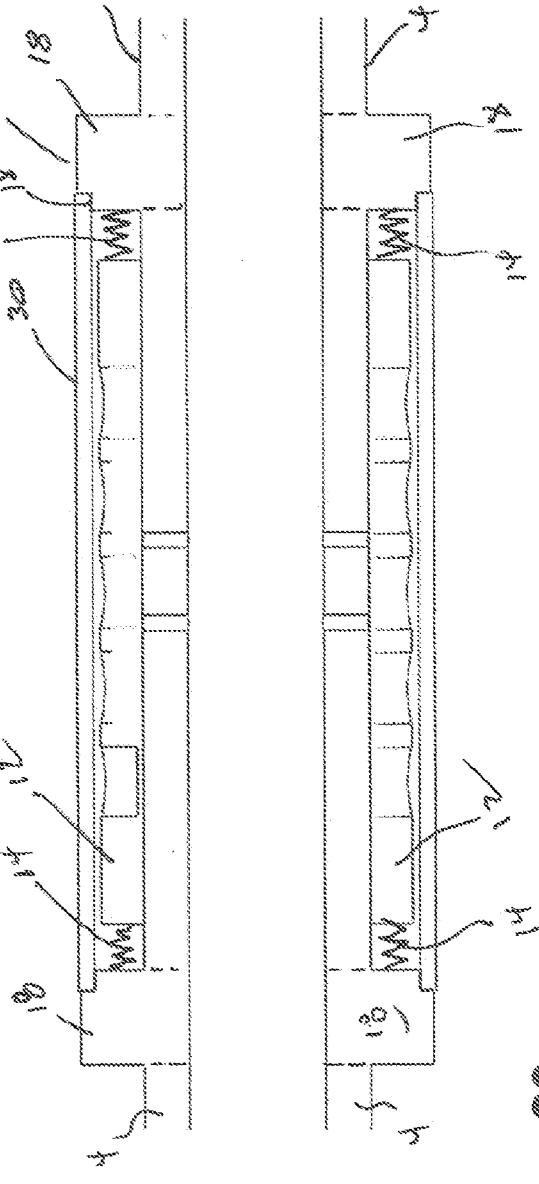


Fig. 20

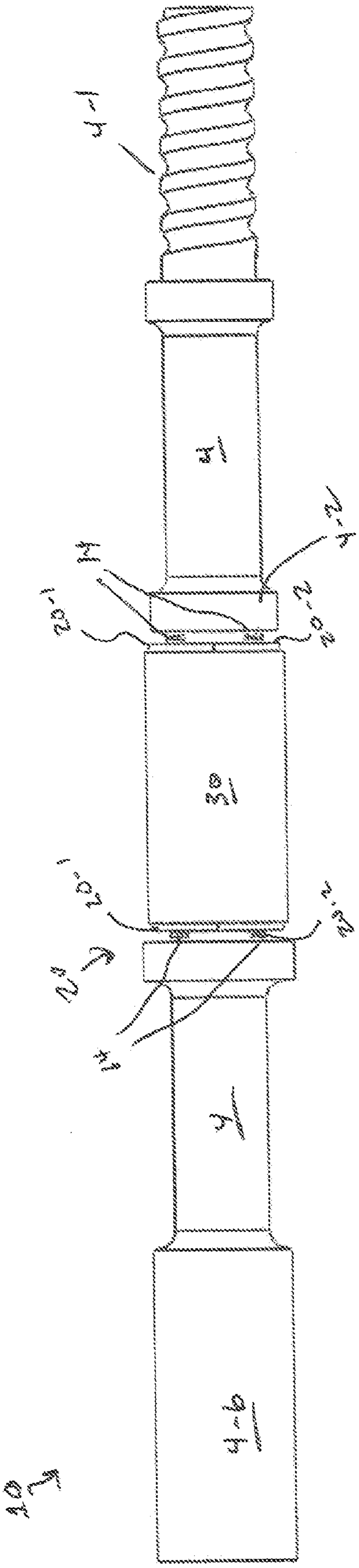

4-1
4
4-2
14
20-1
20-2
30
20-1
20-2
20
14
4
4-6
10

Fig. 21

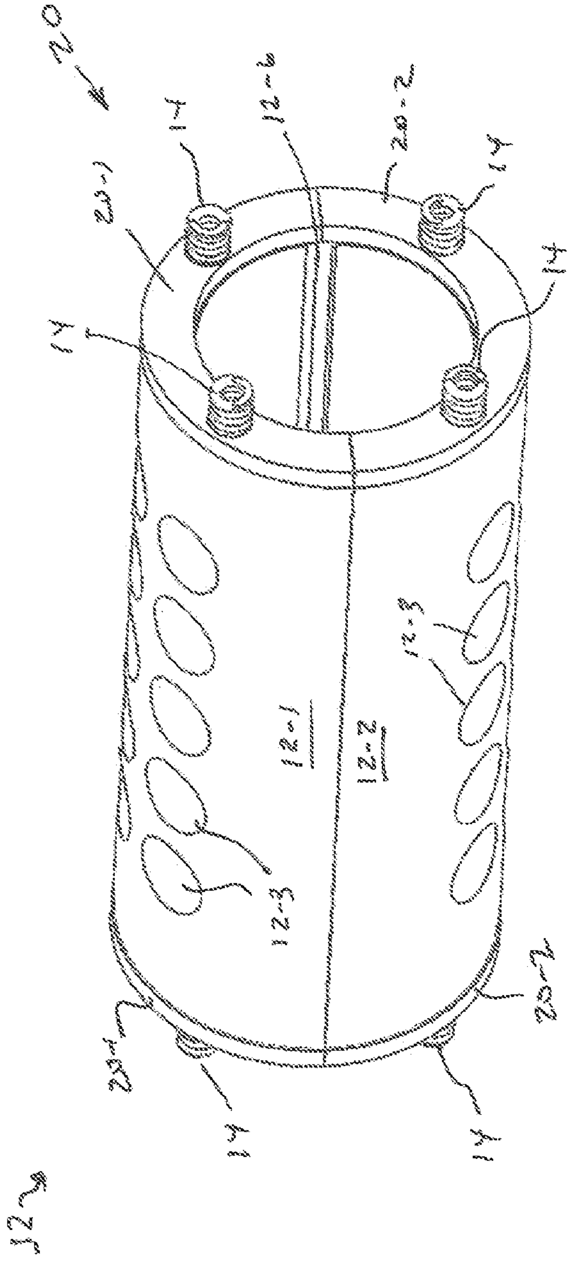

20
20-2
12-6
20-1
14
14
14
14
12-3
12-1
12-2
12-3
12-3
20-1
20-2
14
14
12

Fig. 22

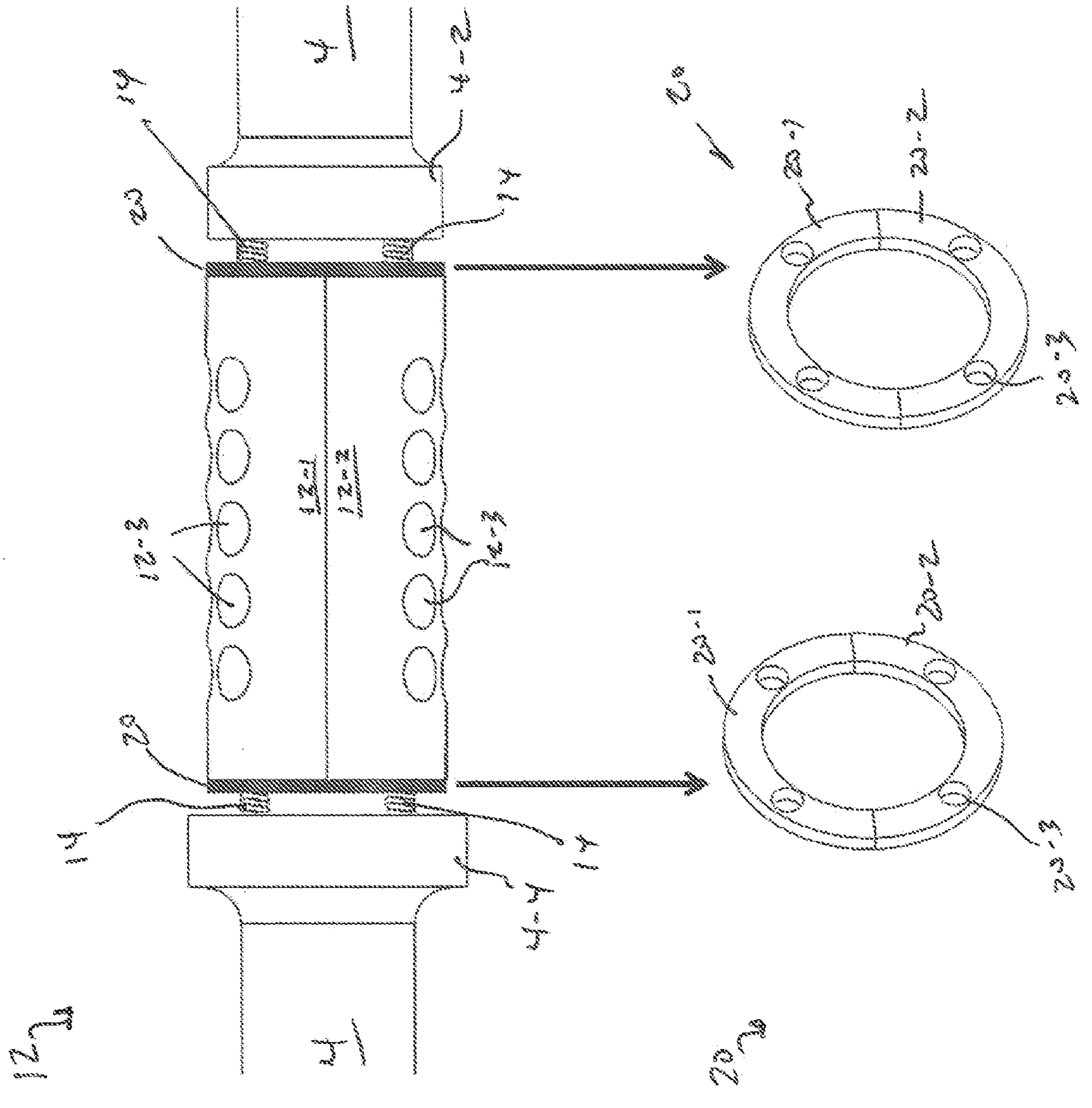

12
4
4-2
14
14
20
20
12-1
12-2
12-3
12-3
14
14
4-4
4
20
20-1
20-2
20-3
20-1
20-2
20-3
20

Fig. 23

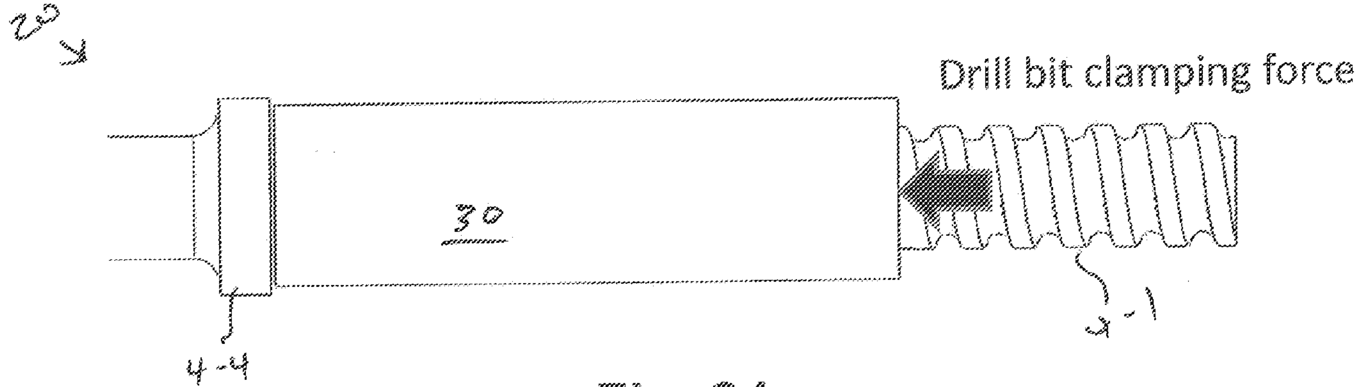

20
Drill bit clamping force
30
4-4
4-1

Fig. 24

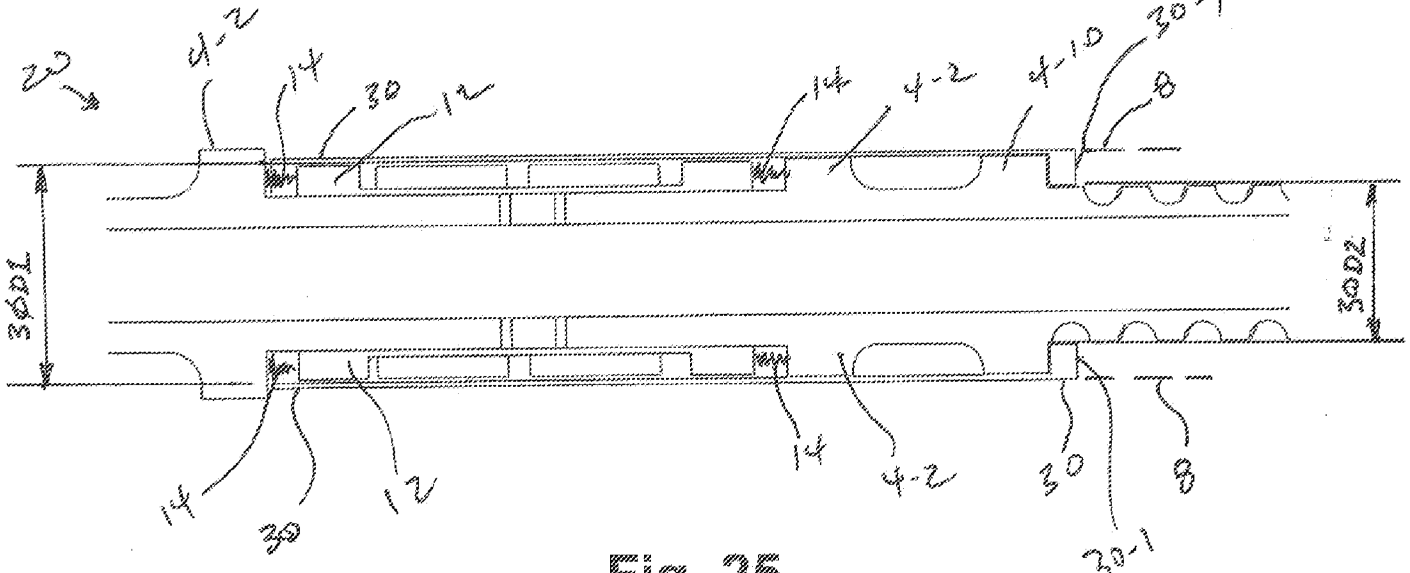

20
4-2
14
30
12
14
4-2
4-10
30-1
8
30D1
30D2
14
30
12
14
4-2
30
8
30-1

Fig. 25

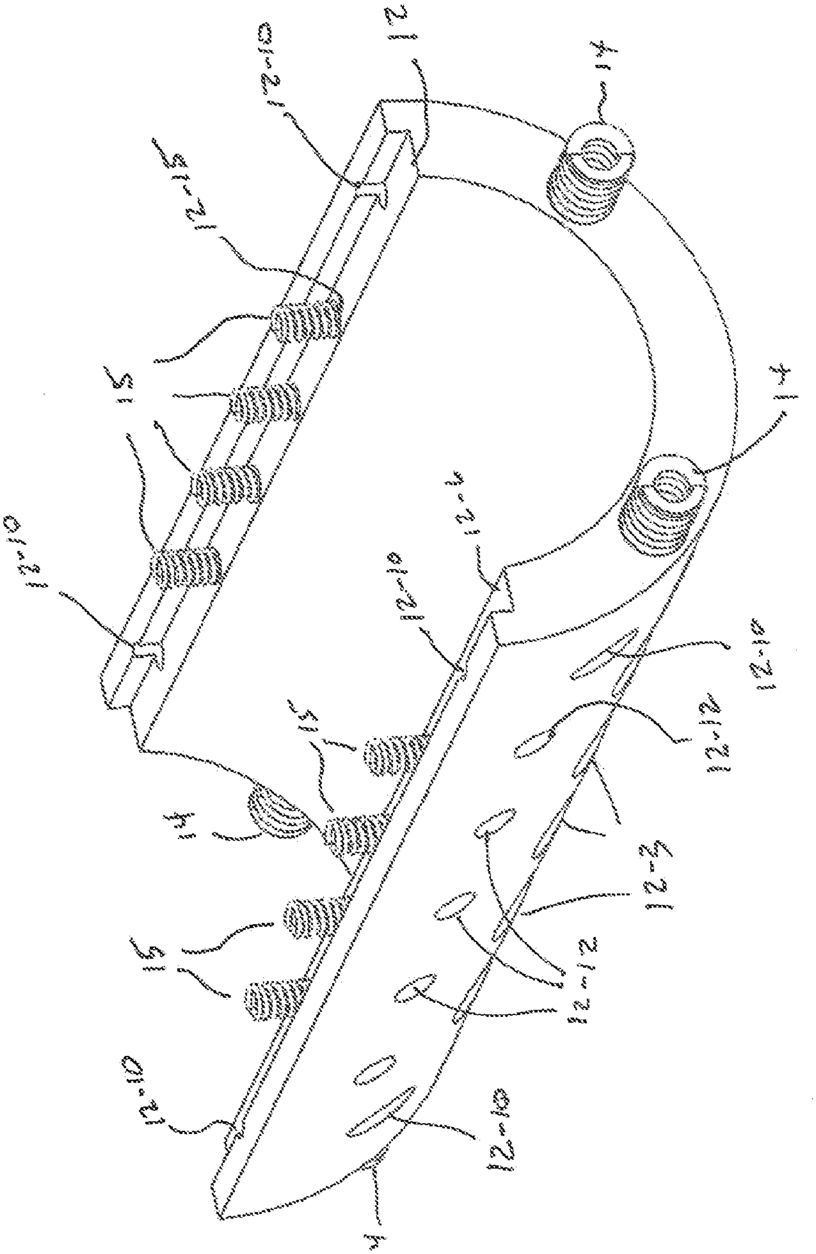

12-6
12-10
12-15
15
14
12-10
12-4
12-10
14
15
12-10
12-12
12-3
12-12
15
14
12-10
12-10
14
12-1

Fig. 26

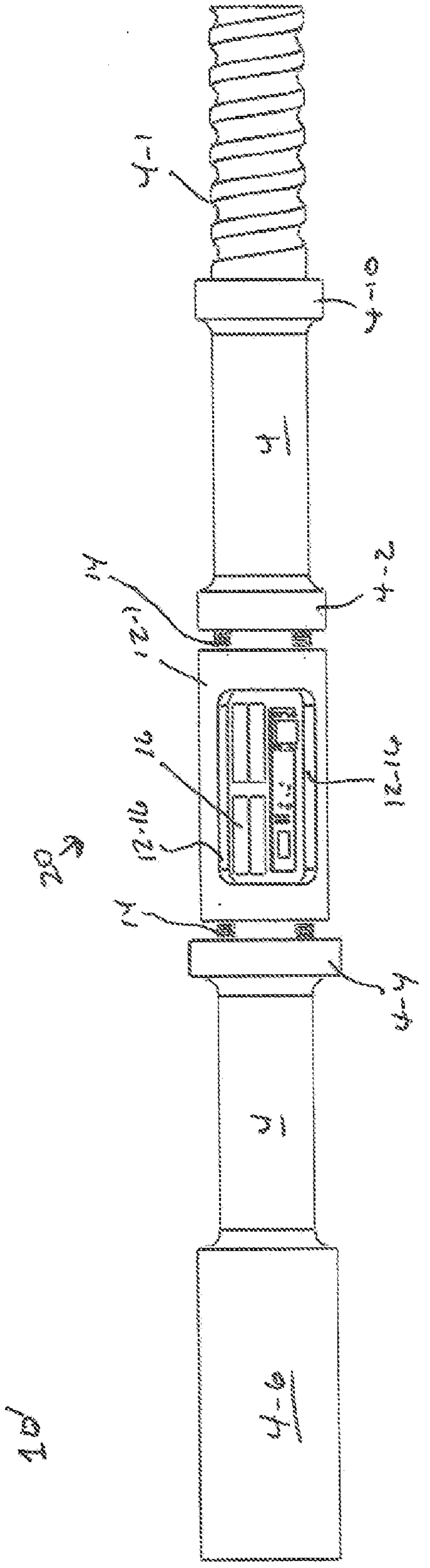

4-1
4-0
4
4-2
14
12-1
12-16
16
12-14
20
14
4-4
4
4-6
10'

Fig. 27

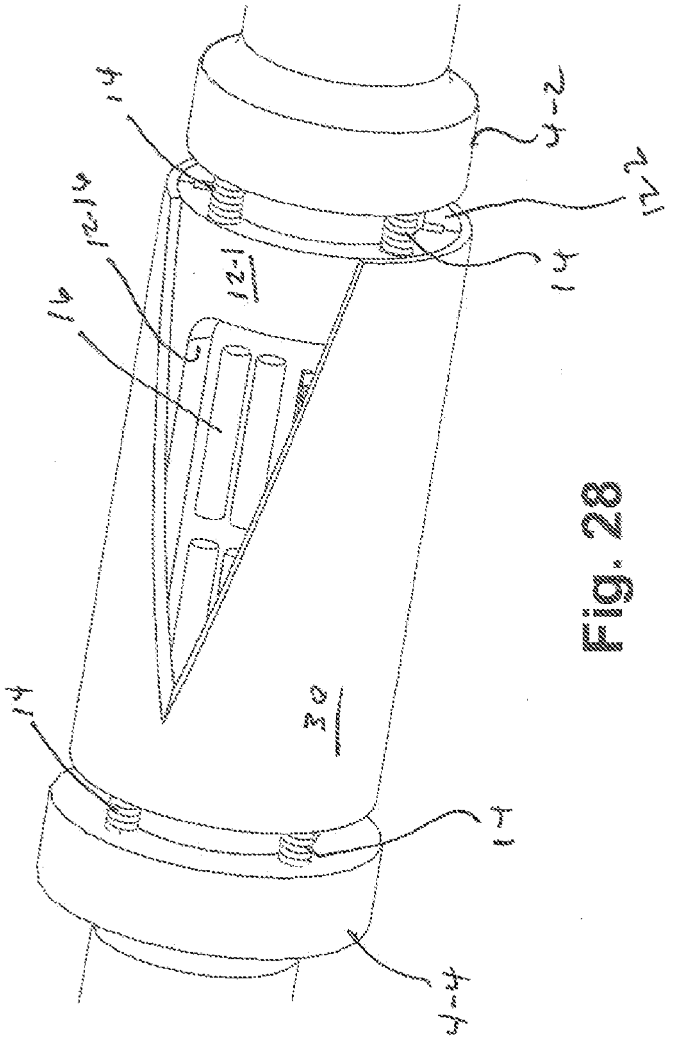

14
4-2
12-14
12-1
16
12-2
14
14
30
14
4-4

Fig. 28

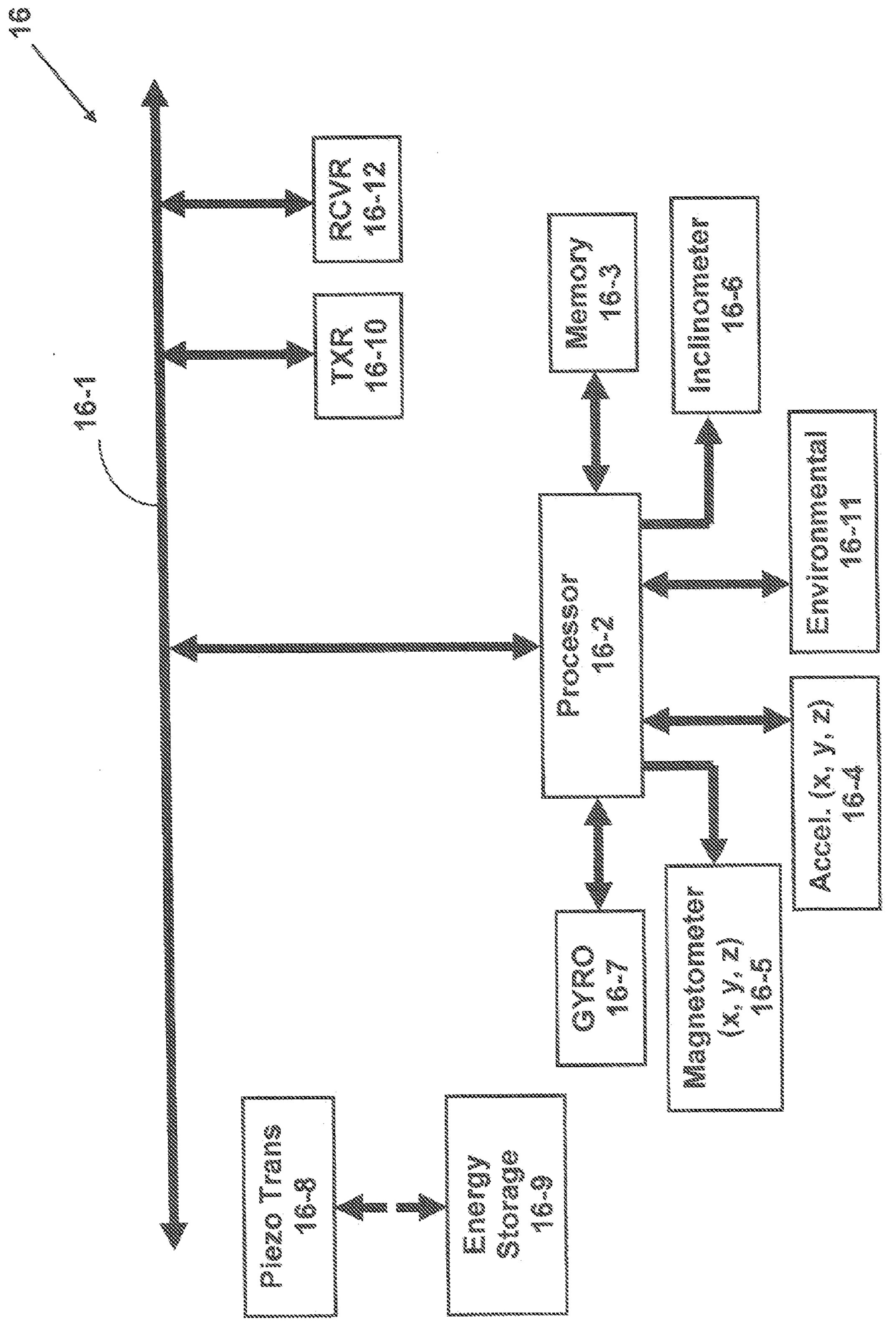

16
16-1
RCVR
16-12
TXR
16-10
Memory
16-3
Inclinometer
16-6
Processor
16-2
Environmental
16-11
Accel. (x, y, z)
16-4
GYRO
16-7
Magnetometer
(x, y, z)
16-5
Piezo Trans
16-8
Energy
Storage
16-9

Fig. 29

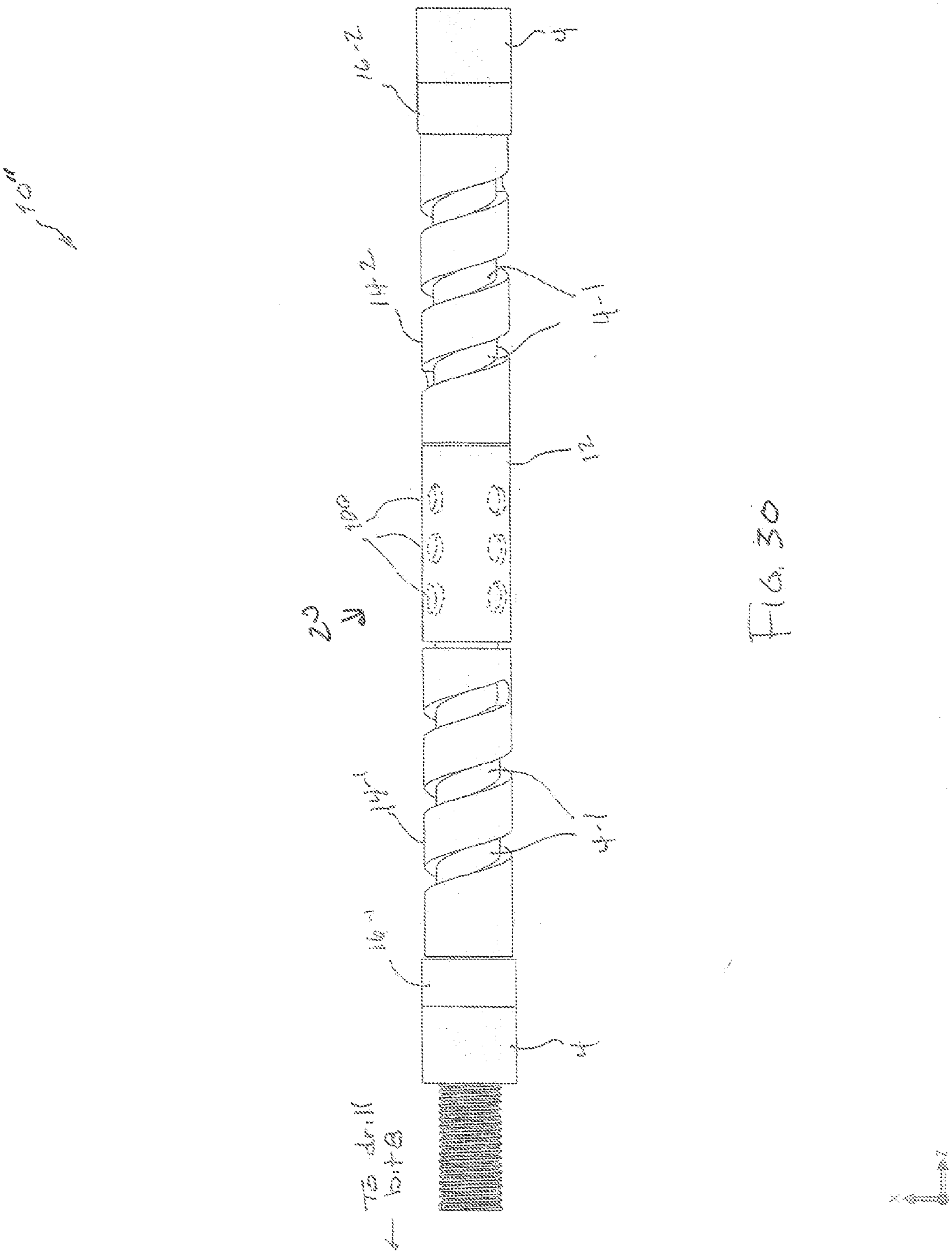


FIG. 30

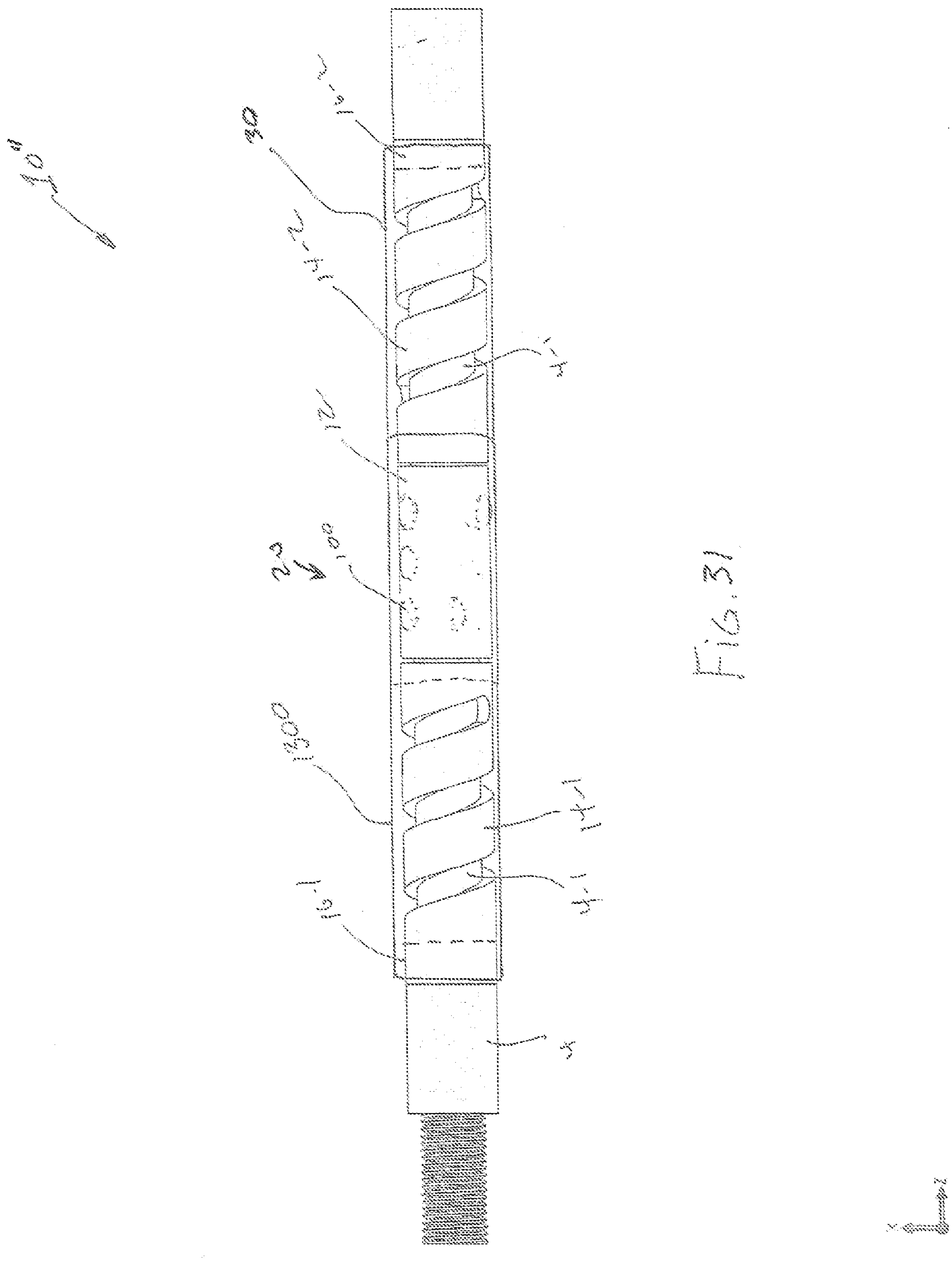


FIG. 31

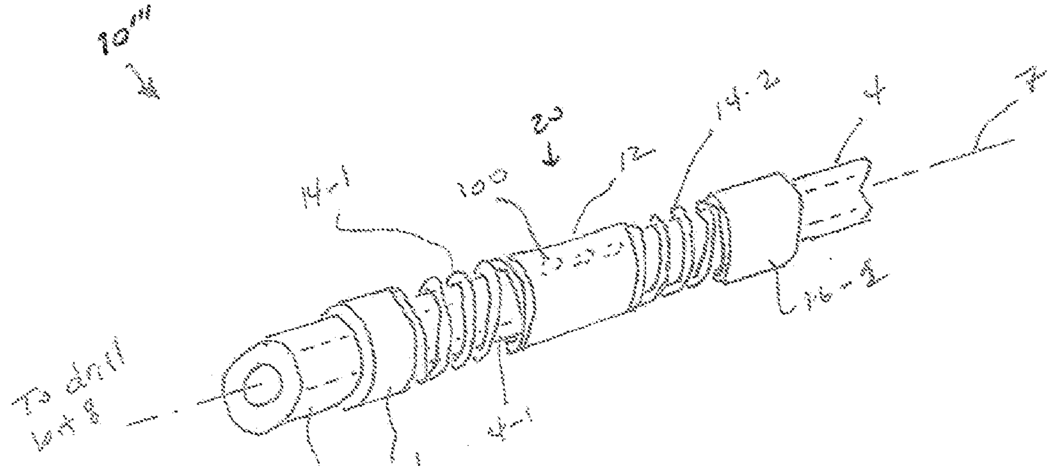

10'''
22
14-1
100
12
14-2
4
7
To drill bit 8
4
16-1
4-1
16-2

FIG. 32

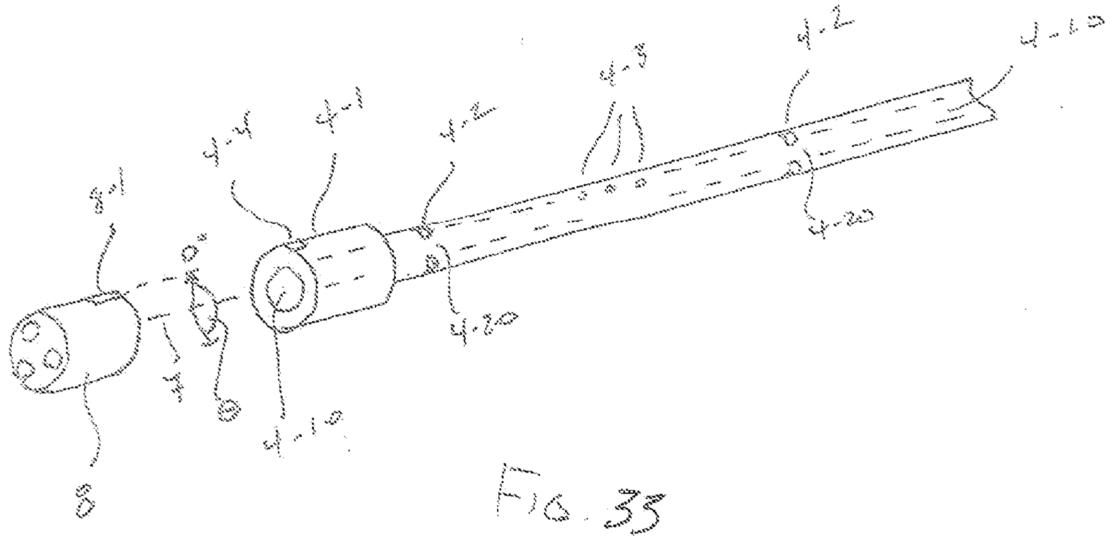

8-1
4-4
4-1
4-2
4-3
4-2
4-10
θ°
4-20
4-20
7
θ
4-10
8

FIG. 33

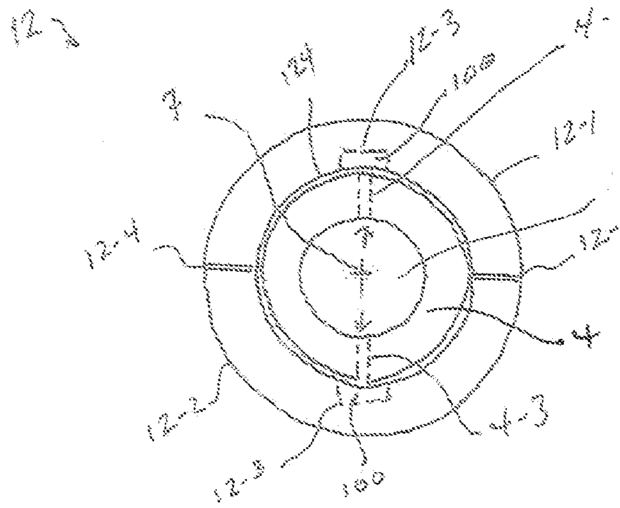


FIG. 34

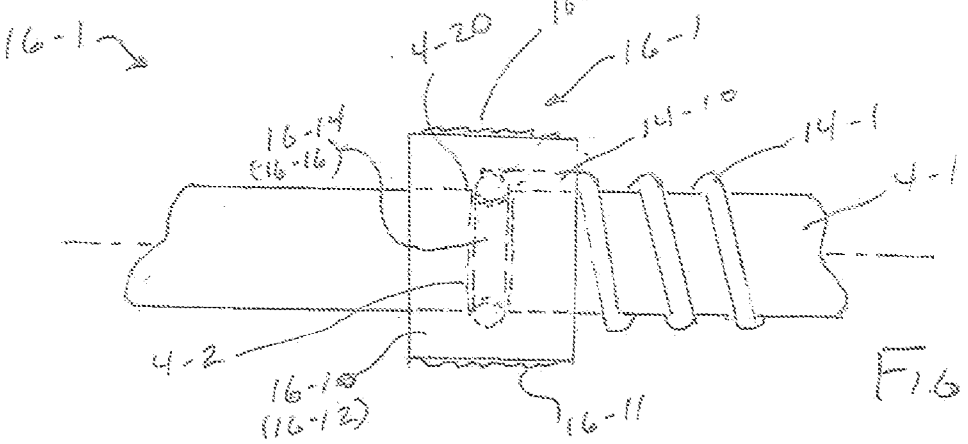


FIG. 35

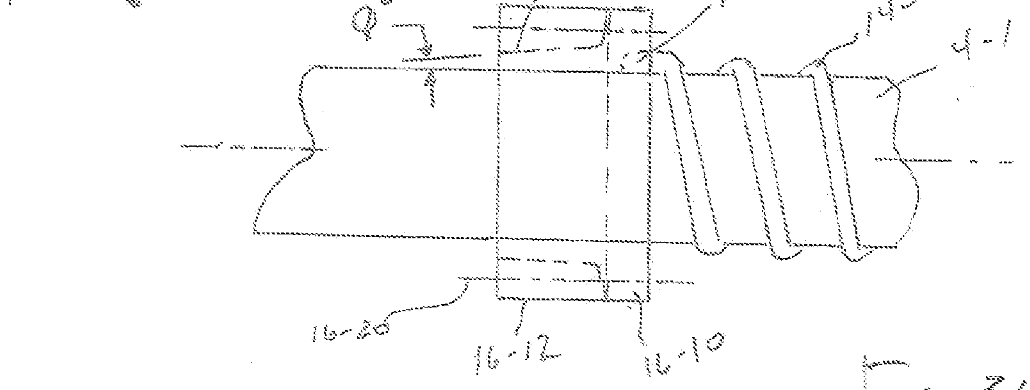


FIG. 36

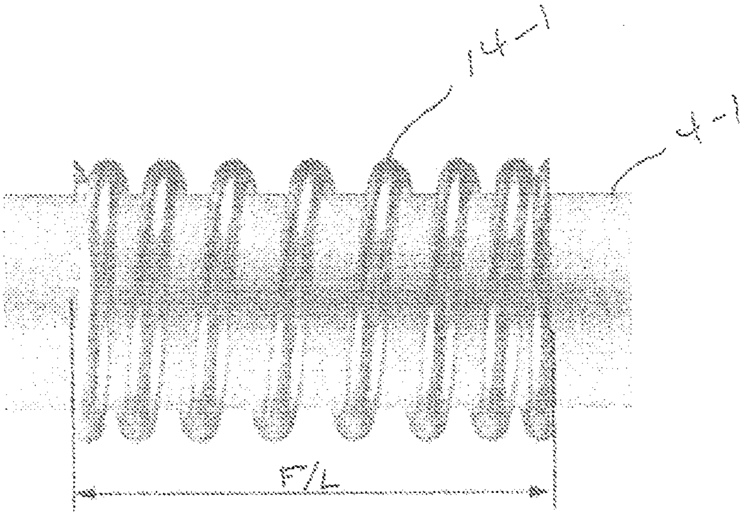


Fig. 37

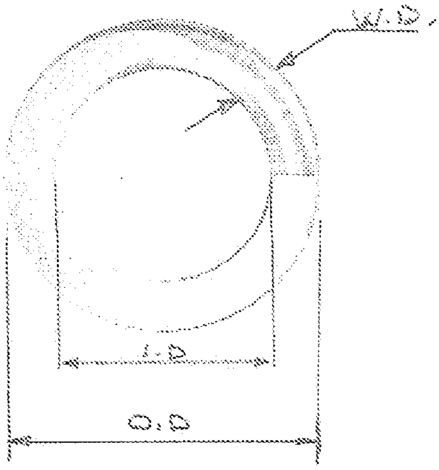


Fig. 38

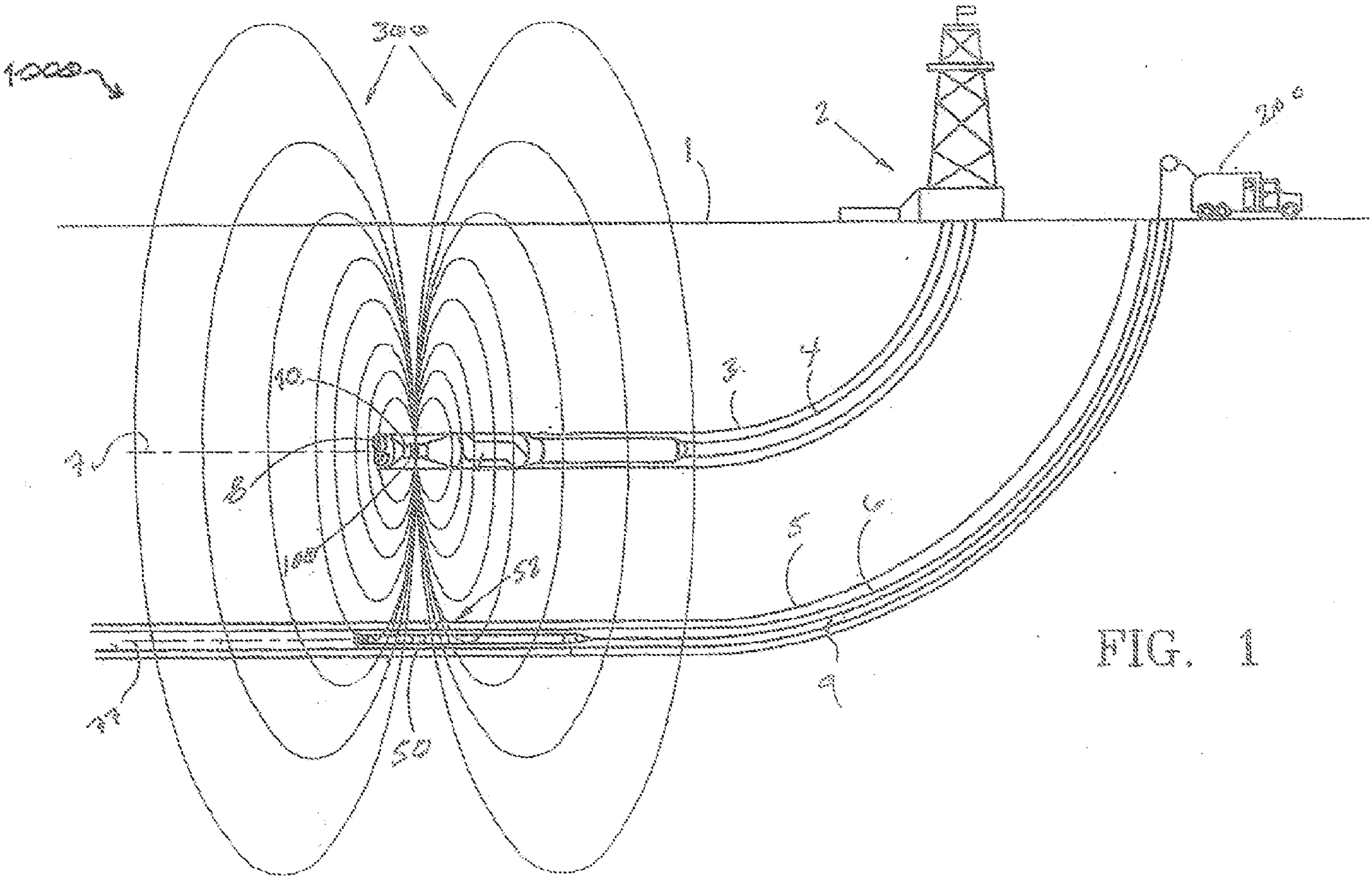


FIG. 1