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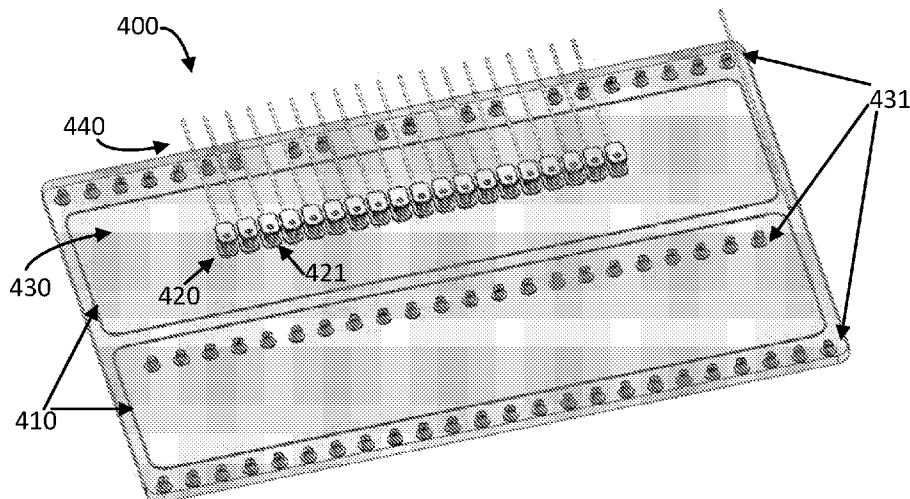


FIG. 4

(57) Abstract: A system is provided for inspecting risers and other test objects. The system may include two or more sensors and mounting arcs for holding the sensors in an arced shape. To obtain full circumferential coverage some sensors may be offset axially relative to others. In some embodiments two or more sensors have the same axial position but are shifted circumferentially so that different portions of the riser can be inspected by each sensor. The arcs and sensors may be held by a scanner with wheels for moving the scanner along the riser. Some or all of the wheels may have a suspension to provide flexibility in the structure if the surface of the object has variations such as localized changes in surface radius. A flexible version does not require rigid arcs allowing the radii of sensor curvature to change during scanning. An instrument may be provided to perform sensor measurements.

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**SENSOR AND SCANNING SYSTEM AND METHOD
FOR RISERS AND OTHER TEST OBJECTS**

RELATED APPLICATION

5 The present application claims priority under 35 U.S.C. §119(e) to U.S. provisional patent application, U.S. Ser. No. 63/507,435 filed June 9, 2023, and to U.S. provisional patent application, U.S. Ser. No. 63/611,519 filed December 18, 2023, which are herein incorporated by reference in its entirety.

TECHNICAL FIELD

10 The present disclosure relates to the field of non-destructive testing.

BACKGROUND

 The various aspects described herein relate to scanning systems and methods.

SUMMARY

15 A system is provided for inspecting risers and other cylinder test objects. The system may include two or more sensors and mounting arcs for holding the sensors in an arced shape. To obtain full circumferential coverage some sensors may be offset axially relative to others. In
20 some embodiments two or more sensors have the same axial position but are shifted circumferentially so that different portions of the riser can be inspected by each sensor. The arcs and sensors may be held by a scanner with wheels for moving the scanner along the riser. Some or all of the wheels may have a suspension to provide flexibility in the structure if the surface of the object has variations such as localized changes in surface radius. A flexible version does not
25 require rigid arcs allowing the radii of sensor curvature to change during scanning. An instrument may be provided to perform sensor measurements. The instrument may be mounted on the scanner, or connected via cabling. Power may be provided via a mounted battery or via wiring to another source. One advantage of this innovation is providing full coverage circumferentially with a more rapid axial scanning capability than is practical if scanning
30 circumferentially with an array.

 One aspect relates to a system comprising a first sensor; a second sensor; a first mounting arc rigidly holding the first sensor at a first radius; a second mounting arc rigidly holding the second sensor at the first radius, wherein the first and second mounting arcs are concentric about an axis, and a first center of the first sensor is at a different angular position about the axis
35 relative to a second center of the second sensor; and a scanner, holding the first and second

mounting arc, having a plurality of wheels, at least one wheel having a suspension for moving the wheel radially relative to the axis.

In some embodiments of the system, the first sensor is an eddy current array sensor having a drive winding common to an array of sensing elements. In some embodiments of the system, each sensing element in the array of sensing elements is at the same distance from the drive winding. In some embodiments, the second sensor is also an eddy current array having the same design as the first sensor. In some embodiments of the system, an angular extent of the array of sensing elements of the first sensor overlaps with an angular extent of the array of sensing element of the second sensor. In some embodiments, the system further comprises an instrument for providing power to the drive winding and measuring electrical responses from the array of sensing elements. In some embodiments of the system, the first and second mounting arcs form a first set, and the system further comprises a second set of mounting arcs having a second radius different from the first radius, wherein the second set is interchangeable with the first set.

Another aspect relates to a method of inspecting a cylindrical test object having an electrically insulating exterior surface layer and an electrically conducting interior layer, the method comprising acts of (i) providing a system having a first sensor; a second sensor; a first mounting arc rigidly holding the first sensor at a first radius; a second mounting arc rigidly holding the second sensor at the first radius, wherein the first and second mounting arcs are concentric about an axis, and a first center of the first sensor is at a different angular position about the axis relative to a second center of the second sensor; and a scanner, holding the first and second mounting arc, having a plurality of wheels, at least one wheel having a suspension for moving the wheel radially relative to the axis; (ii) securing the system to the cylindrical test object such that the first second sensors are concentric with the cylindrical test object; (iii) moving the scanner in a scan direction along the cylindrical test object; (iv) during the moving, measuring sensor responses from the sensors; and (v) characterizing a condition of the electrically conducting interior layer based on the sensor responses.

In some embodiments of the method, the act of characterizing comprises converting the sensor response at each of a plurality of sensing elements into a measure of the properties of the electrically conducting interior layer. In some embodiments of the method, the act (v) comprises storing a precomputed database modeling sensor responses over a range of sensor liftoffs; and in the act (ii) the plurality of wheels ride along the surface of the cylindrical test object and the arcs are held at a distance from the cylindrical test object such that the liftoff is within the range. In some embodiments of the method, the electrically conducting interior layer of the cylindrical test object is an outer armor layer and the cylindrical test object further comprises an inner armor

layer concentric with and nested within the first armor layer; in the act (iv) the sensors are excited at a plurality of frequencies and sensor responses are measured at each frequency; and in the act (v) a sensor response at a higher frequency is utilized to characterize the outer armor layer, and a sensor response at a lower frequency is utilized to characterize the inner armor layer.

5 In some embodiments of the method, the electrically conducting interior layer of the cylindrical test object is an outer armor layer and the cylindrical test object further comprises an inner armor layer concentric with and nested within the first armor layer, and the method further comprises generating a precomputed database of sensor responses with a model that accounts for the presence of the outer armor layer, the inner armor layer, and the electrically insulating exterior
10 surface layer. In some embodiments of the method, in the act of generating, the model includes at least one additional electrically conducting layer. In some embodiments of the method, the electrically conducting interior layer of the cylindrical test object is an outer armor layer formed by a plurality of helically wrapped riser wires; and the first sensor is an eddy current array sensor having a drive winding common to an array of sensing elements, the drive winding oriented at a
15 same angle as the helically wrapped riser wires.

Yet another aspect relates to a system for inspecting a cylindrical test object having an electrically insulating exterior surface layer and an electrically conducting interior layer, the system comprising a plurality of conformable sensors; a plurality of conformable arcs for holding the conformable sensors; a plurality of wheels for riding along the cylindrical test object,
20 the wheels connected to the plurality of conformable arcs and enabling the plurality of sensors to maintain a shape that follows the curvature of the cylindrical test object, wherein the arcs allow for continuous adjustment to the external shape; and a data analysis module to characterize the cylindrical test object based on measurements from the plurality of sensors, wherein the data analysis module assumes that the plurality of sensors maintain a concentric shape relative to an
25 axis of the cylindrical test object.

Yet further aspect relates to a flat riser test bed intended to simulate inspection of cylindrical flexible pipe, the test bed comprising one layer of riser wire this is long and rectangular in shape in a single plane with minimal gap between riser wires, where the riser wires are cut to a length ending at the edge of a square platform where the platform provides a
30 rigid base for the test bed; a means for adding electrically insulating layers above the riser wire layer to simulate electrically insulating material on a flexible pipe.

In some embodiments, a second riser wire layer is included in the same orientation as the first riser wire layer for convenient removal of riser wires. In some embodiments a second riser wire layer is included in a different orientation, where the orientation of the two riser wire layers
35 is approximately the same as the armor wire layers in a flexible pipe. In some embodiments, a

sensor can be located in the approximate center of the square test bed and a wire failure can be simulated by providing a gap between two rectangular cross section wires, where the gap is moved under the sensor in the first or second wire layer by pushing a second wire in the same location as the first wire keeping the gap approximately constant by the two wires, wherein
5 insulating layers are used between the sensor and the outer wire layer to simulate the thickness of an outer electrically insulating layer on a riser. In some embodiments, a riser wire failure is simulated by using two wires and a small gap located approximately in the center of the test bed in either the outer or inner wire layer, where a sensor is moved from one end of the test bed to the other in a path that includes the simulated wire failure, wherein insulating layers are used
10 between the sensor and the outer wire layer to simulate the thickness of an outer electrically insulating layer on a riser. In some embodiments, a system is used with software to detect riser wire failures where the system is intended to detect failures on either or flat or cylindrical shaped test objects and the data from the flat test bed is used to validate the intended inspection on a cylindrically shaped test object.

15 Yet another aspect relate to a system for inspecting a cylindrical test object having an electrically insulating exterior surface layer and at least one interior electrically conducting layer, the system comprising a first set of two rigid arcs having a first diameter; a first sensor mounted on one rigid arc; a second sensor mounted on a second rigid arc, wherein the first and second sensors are positioned at different axial locations along the cylindrical test object but at
20 the same radial distance where the sensors each cover a substantially different circumferential segment a scanner that moves the two sensors in the axial position, having wheels that maintain a fixed non-contact positioning between the sensors and the outer surface of the electrically insulating exterior surface; an instrument for providing power to a drive conductor in each sensor and measuring an electrical response at two or more sensing elements; and a data analysis
25 module that has, as input, the nominal radial position of the rigid arcs and a means for converting the sensor response at each sensing element into a measure of the properties of the electrically conducting interior layer.

In some embodiments, the two circumferential segments at least partially overlap. Some embodiments further comprise a second set of rigid arcs having a second diameter, wherein the
30 second set is interchangeable with the first set such that only one set of rigid arcs with one diameter are used at the same time. In some embodiments, the wheels have a mechanism to raise and lower the arcs in a radial direction to cover the range of radial extent necessary to enable the set of arcs with different diameters to cover the full range necessary to inspect a family of risers with varying electrically insulating layer thicknesses. In some embodiments, the wheels ride
35 along the outer surface of the electrically insulating outer layer and the arcs are held at a

prescribed distance above the outer surface of the electrically insulating layer such that the response remains within a range that the magnetic permeability of the electrically conducting inner layer has been modeled and stored in a precomputed database where the precomputed database is used to estimate at least one magnetic permeability of one electrically conducting interior layer and the proximity (liftoff) distance between the sensor the plane and the outer surface of the electrically conducting inner layer. In some embodiments, a model is used to generate a precomputed database accounting for the presence of an outer armor layer, and inner armor layer and at least one additional electrically insulating layer. In some embodiments, the model includes additional conducting layers. In some embodiments, the sensor consists of an essentially linear central drive conductor oriented in the circumferential direction with a row of sensing elements at a fixed distanced from the central drive conductor. In some embodiments, the sensor consists of an essentially linear central drive conductor oriented in alignment with a prescribed angle of the riser wires so that the central drive conductors are running parallel to the outer riser wire orientation. In some embodiments, there are 5 sets of arcs each having a fixed diameter to cover a range of outer electrically insulating thicknesses where the incremental change in arc diameter is selected so that a set of adjustable wheels can provide continuous coverage of the radial position for the arcs over a range from 10 mm to 80 mm for the electrically insulating layer thickness.

The foregoing is a non-limiting summary of the invention, which is defined by the attached claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings are not intended to be drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures may be represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing. In the drawings:

FIG. 1A is a block diagram of an inspection system, according to some embodiments;

FIGs. 1B-1D shows eddy current sensor array designs, according to some embodiments;

FIG. 2 is a block diagram of an instrument, according to some embodiments;

FIG. 3 is a cross-section of an example riser that may be a test object in some embodiments;

FIG. 4 shows a eddy current sensor array, according to some embodiments;

FIGs. 5A-5AG show steps in a manufacturing process for an eddy current array sensor, according to some embodiments;

FIG. 6A is a pair of double-D eddy current array sensors, according to some embodiments;

FIG. 6B shows a pair of double-D eddy current array sensors positioned for inspecting a cylindrical test object, according to some embodiments;

5 FIG. 6C is a pair of single-D eddy current array sensors, according to some embodiments;

FIG. 6D shows a pair of single-D eddy current array sensors positioned for inspecting a cylindrical test object, according to some embodiments;

10 FIG. 6E shows a perspective view of a scanner with 4 sensors in a closed position about a cylindrical test object, according to some embodiments;

FIG. 6F shows a perspective view of the scanner with 4 sensors in an open position about a cylindrical test object, according to some embodiments;

FIG. 6G shows the position of the sensors when the scanner with 4 sensors is in a closed position about a cylindrical test object, according to some embodiments;

15 FIG. 6H shows a top view of a scanner with 4 sensors in a closed position about a cylindrical test object, according to some embodiments;

FIG. 6I shows a top view of the scanner with 4 sensors in an open position about a cylindrical test object, according to some embodiments;

20 FIG. 6J shows a perspective view of a scanner with 4 sensors and wheels in a closed position about a cylindrical test object, according to some embodiments;

FIG. 7A is a flat test sample, according to some embodiments;

FIG. 7B is a depth of penetration chart for a representative material and eddy current sensor, according to some embodiments;

25 FIG. 7C is a normalized transimpedance space plot showing sensor data superimposed over a grid database, according to some embodiments; and

FIGs. 7D-7E are plots of magnetic permeability estimated from sensor data during testing on a flat testbed, according to some embodiments.

DETAILED DESCRIPTION

30 The inventors have recognized and appreciated the need for eddy current testing (ET) technologies and techniques for complex components such as risers in the oil and gas industry. FIG. 3 shows a cutaway view of an example offshore riser 300 used in the oil and gas industry to raise raw materials from the sea floor. The layers include an outer sheath 301, an outer layer of tensile armor 302, a first anti-wear layer 303, an inner layer of tensile armor 304, a second anti-
35 wear layer 305, an interlocked pressure armor 306, an internal pressure armor 307 and a carcass

308. The tensile armor layers 302 and 304 may be made up of many “wires” helically wrapped over the underlying layers. The outer armor 302 may be helically wrapped in the opposite direction as the inner armor 304 (e.g., clockwise and counter-clockwise helically wrapping respectively). In other riser designs there may be fewer, additional or different layers.

5 A technical challenge presented by risers is breaking of the wires of the tensile armor layers. The inventors have recognized and appreciated that cracking, complete breaks and stress change in the wire may be detected and characterized using an appropriate ET sensor system such as system 100 shown in FIG. 1 and introduced further in Section I. The large dimensions and substantial thickness of outer sheath 301 contributes to a large eddy current (ET) sensor
10 liftoff making conventional ET sensors such as pencil probes and arrays unsuitable for such an inspection.

This application is organized into several sections to discuss various aspects that may be utilized in some embodiments. Section I provides an overview of a measurement system that may be used in some embodiments. Section II provides a description of the ET sensor according
15 to some embodiments. Section III provides a description of the manufacturing process of the ET sensor, according to some embodiments. Section IV provides a description of the scanner that may be used to inspect a test object, such as riser 300, with an ET sensor system, according to some embodiments. Section V provides a description of an inspection procedure using the scanner and ET sensor system, according to some embodiments. Section VI provides a closing
20 discussion.

Section I - System Overview

Aspects of some embodiments relate to the use of a system 100 for inspecting a test object 130. System 100 is shown as a block diagram in FIG. 1A. System 100 includes an instrument 110 and a sensor cartridge 140. In some embodiments, system 100 includes a scanner
25 150 for providing mechanical support for instrument 110, sensor cartridge 140, and/or test object 130 as well as facilitating relative motion between sensor cartridge 140 and test object 130.

Instrument 110 may be housed in a housing 107; in some embodiments the housing is substantially cylindrical in shape such as that described in U.S. Patent No. 10,416,118, Measurement system and method of use, by Goldfine et al. issued September 17, 2019 and
30 herein incorporated by reference in its entirety (the ‘118 patent). Sensor cartridge 140 may have a rigid connector which interfaces both mechanically and electrically with an instrument side connector 105.

In some embodiments, sensor cartridge 140 is connected to instrument side connector 105 via cable 150. Cable 150 may be of arbitrary length in accordance with the requirements of
35 the application. Although cable 150 is shown with only excitation signals 121 and response

signals 123 passing through it, it should be appreciated that cable 150 may also convey other signals (including power). For example, power and/or measurement signals for position encoder 103 may be conveyed through cable 150. Similarly, power and/or control signals for actuator 101 may be conveyed through cable 150.

5 In some other embodiments, sensor 120 is directly connected to instrument side connector 105. Sensor cartridge 140 in some embodiments also includes a flexible sensor 120, and a mechanical support 141 to which the sensor is attached. Sensor 120 may be attached to mechanical support 141 with glue, tape, double sided tape, or in any suitable way. Instrument 110 is configured to provide excitation signals 121 to sensor 120 and measure the resulting
10 response signals 123 of sensor 120. Response signals 123 may be measured and processed to estimate properties of interest, such as electromagnetic properties (e.g., electrical conductivity, permeability, and permittivity), geometric properties (e.g., layer thickness, sensor liftoff), material condition (e.g., fault / no fault, crack size, layer to layer bond integrity, porosity, residual stress level, temperature), or any other suitable property or combination thereof
15 including properties of the fabricated part and the powder. (Sensor liftoff is a distance between the sensor and the closest surface of the test object for which the sensor is sensitive to the test object's electrical properties.)

Instrument 110 may include a processor 111, a user interface 113, memory 115, an impedance analyzer 117, and a network interface 119. Though, in some embodiments of
20 instrument 110 may include other combinations of components. While instrument 110 is drawn with housing 107, it should be appreciated that instrument 110 may be physically realized as a single mechanical enclosure; multiple, operably-connected mechanical enclosures, or in any other suitable way. For example, in some embodiments it may be desired to provide certain components of instrument 110 as proximal to sensor 120 as practical, while other components of
25 instrument 110 may be located at greater distance from sensor 120.

Processor 111 may be configured to control instrument 110 and may be operatively connected to memory 115. Processor 111 may be any suitable processing device such as for example and not limitation, a central processing unit (CPU), digital signal processor (DSP), controller, addressable controller, general or special purpose microprocessor, microcontroller,
30 addressable microprocessor, programmable processor, programmable controller, dedicated processor, dedicated controller, or any suitable processing device. In some embodiments, processor 111 comprises one or more processors, for example, processor 111 may have multiple cores and/or be comprised of multiple microchips. Processing of sensor data and other computations such as for control may be performed sequentially, in parallel, or by some other
35 method or combination of methods.

Memory 115 may be integrated into processor 111 and/or may include “off-chip” memory that may be accessible to processor 111, for example, via a memory bus (not shown). Memory 115 may store software modules that when executed by processor 111 perform desired functions. Memory 115 may be any suitable type of non-transient computer-readable storage medium such as, for example and not limitation, RAM, a nanotechnology-based memory, optical disks, volatile and non-volatile memory devices, magnetic tapes, flash memories, hard disk drive, circuit configurations in Field Programmable Gate Arrays (FPGA), or other semiconductor devices, or other tangible, non-transient computer storage medium.

Instrument 110 may have one or more functional modules 109. Modules 109 may operate to perform specific functions such as processing and analyzing data. Modules 109 may be implemented in hardware, software, or any suitable combination thereof. Memory 115 of instrument 110 may store computer-executable software modules that contain computer-executable instructions. For example, one or more of modules 109 may be stored as computer-executable code in memory 115. These modules may be read for execution by processor 111. Though, this is just an illustrative embodiment and other storage locations and execution means are possible.

Instrument 110 provides excitation signals for sensor 120 and measures the response signal from sensor 120 using impedance analyzer 117. Impedance analyzer 117 may contain a signal generator 112 for providing the excitation signal to sensor 120. Signal generator 112 may provide a suitable voltage and/or current waveform for driving sensor 120. For example, signal generator 112 may provide a sinusoidal signal at one or more selected frequencies, a pulse, a ramp, or any other suitable waveform. Signal generator 112 may provide digital or analog signals and include conversion from one mode to another. The ‘062 patent provides a discussion of an impedance analyzer that may be used in some embodiments. See, for example, the discussion in connection with FIG. 19a which provides a discussion on how impedance analyzer 117 can take a measurement. The ‘218 patent provides further discussion on how such impedance measurements may be calibrated to remove certain systematic bias from the measurements.

In some embodiments, impedance analyzer 117 has a current sensor 109 that is used to measure a current leaving signal generator 112. Current sensor 109 may be any suitable sensor for measuring such current. For example, current sensor 109 may include a known series resistance in the drive current signal path and current sensor 109 may measure the voltage across such known resistance such that the current may be calculated using Ohm’s Law. As another example, current sensor 109 may measure the voltage induced on an inductive pick-up coil having a well known transimpedance.

Sense hardware 114 may comprise multiple sensing channels for processing multiple sensing element responses in parallel. As there is generally a one to one correspondence between sense elements and instrumentation channels these terms may be used interchangeably. It should be appreciated that care should be used, for example, when multiplexing is used to allow a single channel to measure multiple sense elements. For sensors with a single drive and multiple sensing elements such as the MWM®-Array eddy current array available from JENTEK® Sensors, Inc., the sensing element response may be measured simultaneously at one or multiple frequencies including simultaneous measurement of real and imaginary parts of the transimpedance (or mathematically equivalent measurements/representations such as the magnitude and phase of the transimpedance or the in-phase and quadrature components of the transimpedance). Though, other configurations may be used. For example, sense hardware 114 may comprise multiplexing hardware to facilitate serial processing of the response of multiple sensing elements and for eddy current arrays. Some embodiments of sensor 120 use certain MWM-Array formats to take advantage of the linear drive and the ability to maintain a consistent eddy current pattern across the part using such a linear drive. Sense hardware 114 may measure sensor transimpedance for one or more excitation signals at one or more sense elements 124 of sensor 120. It should be appreciated that while transimpedance (sometimes referred to simply as impedance), may be referred to as the sensor response, the way the sensor response is represented is not critical and any suitable representation may be used. In some embodiments, the output of sense hardware 114 is stored along with temporal information (e.g., a time stamp) to allow for later temporal correlation of the data, and positional data correlation to associate the sensor response with a particular location on test object 130. Instrumentation may also operate in a pulsed mode with time gates used to provide multiple sensing outputs and multiple channels used to acquire data from multiple sensing elements. If these sensing elements 124 have different drive-sense gaps (distance between a drive conductor 122 and the sense elements 124, then this is referred to as a segmented field sensor. Thus, sensor operation can be at a single frequency, multiple frequencies, or in a pulsed mode where the drive is turned on and off in a prescribed manner or switched between two or more modes of excitation.

Sensor 120 is shown as an eddy-current sensor, though other sensor types may be used with system 100. For example, in some embodiments, sensor 120 is one or more of an eddy current sensor, an optical sensor, an ultrasonic testing (UT) sensor, a thermographic sensor, and a radiography sensor.

Sensor 120 has a drive conductor 122, a sense element 124 (or multiple sense elements), and a current sense element 125, each of which is discussed further herein. In some embodiments sensor 120 provides temperature measurement, voltage amplitude measurement,

strain sensing or other suitable sensing modalities or combination of sensing modalities. In some embodiments, sensor 120 is an eddy-current sensor such as an MWM, MWM-Rosette, or MWM-Array sensor available from JENTEK Sensors, Inc., Marlborough, MA. A discussion of some MWM-Array sensors may be found, for example, in the '662 patent. Sensor 120 may be a magnetic field sensor or sensor array such as a magnetoresistive sensor (e.g., MR-MWM-Array sensor available from JENTEK Sensors, Inc.), a segmented field MWM sensor, and the like. Segmented field sensors have sensing elements at different distances from the drive winding to enable interrogation of a material to different depths at the same drive input frequency. Sensor 120 may have a single or multiple sensing and drive elements. Sensor 120 may be scanned across, mounted on, or embedded into test object 130.

FIGs. 1B-1C show some eddy current array embodiments of sensor 120. In FIG. 1B, sensor 120 is an eddy current array having an array of sensing elements 123 and a drive winding 121. Drive winding 121 has a single rectangular drive construct 122. Drive construct 122 has a linear segment along which sensing elements 123 are each equidistant. The distance 124, shown as the distance from the nearest linear drive segment to the center of sensor elements may be defined as a drive-sense gap. Other definitions of drive-sense gap may be found in literature or used - for example, the distance between the nearest linear drive segment and the nearest segment of the sense element coil.

In FIG. 1B, sensor 120 has sensing elements 123 within the confines of rectangular drive construct 122. Sensor 120 shown in FIG. 1C is essentially identical to sensor 120 shown in FIG. 1B except that sensing elements 123 outside the confines of rectangular drive construct 122. The drive-sense gap, distance 124, may be defined in the same way for both designs.

In FIG. 1D, sensor 120 has a drive winding 121 where the drive construct 122 is a dual-rectangular drive construct. In some embodiments the dual rectangular drive constructs are connected such that current flows in the same direction in the two adjacent drive segments.

When selecting or developing a sensor geometry, a variety of considerations may be taken into account, such as (to name a few), the sensor's physical size, its depth of penetration and depth of sensitivity, the desired operating frequency or frequencies, and the volume of space/material which the sensor will be sensitive to (i.e., the sensor footprint). Regarding footprint - assume a defect response produce a local minimum in the sensor response. A sensor with a large footprint will begin to have the sensor response change well before the sensor response reaches the minimum value and a sensor with a small footprint will begin to have the sensor response change closer to when the sensor response reaches the minimum value. Said another way, the smaller the footprint the closer two defects can be and still be distinguishable.

In some embodiments, the computer-executable software modules 109 may include a sensor data processing module that, when executed, estimates properties of test object 130. The sensor data processing module may utilize multi-dimensional precomputed databases that relate one or more frequency transimpedance measurements to properties of test object 130 to be estimated. The generation of suitable databases and the implementation of suitable multivariate inverse methods (MIMs) are described, for example, in U.S. Patent No. 7,467,057, issued on December 16, 2008 (the '057 patent), and U.S. Patent No. 8,050,883, issued on November 1, 2011 (the '883 patent), both of which are herein incorporated by reference in their entirety. The sensor data processing module may take the precomputed database and sensor data and, using a multivariate inverse method, estimate material properties for the processed part or the powder. Though, the material properties may be estimated using any other analytical model, empirical model, database, look-up table, or other suitable technique or combination of techniques.

User interface 113 may include devices for interacting with a user. These devices may include, by way of example and not limitation, keypad, pointing device, camera, display, touch screen, audio input and audio output.

Network interface 119 may be any suitable combination of hardware and software configured to communicate over a network. For example, network interface 119 may be implemented as a network interface driver and a network interface card (NIC). The network interface driver may be configured to receive instructions from other components of instrument 110 to perform operations with the NIC. The NIC provides a wired and/or wireless connection to the network. The NIC is configured to generate and receive signals for communication over network. In some embodiments, instrument 110 is distributed among a plurality of networked computing devices. Each computing device may have a network interface for communicating with other computing devices forming instrument 110.

In some embodiments, multiple instruments 110 are used together as part of system 100. Such systems may communicate via their respective network interfaces. In some embodiments, some components are shared among the instruments. For example, a single computer may be used to control all instruments. In one embodiment multiple areas on the test object are scanned using multiple sensors simultaneously or in an otherwise coordinated fashion to use multiple instruments and multiple sensor arrays with multiple integrated connectors to inspect the test object surface faster or more conveniently.

Actuator 101 may be used to position sensor cartridge 140 with respect to test object 130 and ensure that the liftoff of the sensor 120 is in a desired range relative to the test object 130. For example, actuator 101 may drive the movement of mechanical components of scanner 150 that in turn move the sensor 120 relative to test object 130. Actuator 101 may be an electric

motor, pneumatic cylinder, hydraulic cylinder, or any other suitable type or combination of types of actuators for facilitating movement of sensor cartridge 140 with respect to test object 130. Actuators 101 may be controlled by motion controller 118. Motion controller 118 may control sensor cartridge 140 to move sensor 120 relative to test object 130.

5 Regardless of whether motion is controlled by motion controller 118 or directly by the operator, position encoder 103 and motion recorder 116 may be used to record the relative positions of sensor 120 and test object 130. This position information may be recorded with impedance measurements obtained by impedance analyzer 117 so that the impedance data may be spatially registered.

10 For some applications the performance of system 100 depends (among other things) on the proximity of sensor 120 to test object 130; that is to say the sensor liftoff may be critical to performance for such applications. For example, crack detection in an aerospace application may require cracks 0.5 mm (0.02 inches) in length be reliably detectable in test object 130 (e.g., a turbine disk slot). In order to achieve reliable detection of a small crack, sensor 120's liftoff may
15 need to be kept to under 0.25 mm (0.010 inches). Further, for such an application, sensor 120 may preferably be a sensor array, thus the liftoff of each element in the array may need to be kept to under 0.25 mm (0.010 inches). (It should be appreciated that these dimensions are illustrative and the specific requirements will be dictated by the details of the application.) Measurements may be complicated when test object 130 has a complex curved surface that may
20 change along a measurement scan path.

 To permit high-performance operation at higher excitation frequencies, use of current sensor 109 to measure the current in drive conductor 122 may not be sufficient. The inventors have recognized and appreciated that measurement performance may be improved by measuring the current in drive conductor 122 closer to the portion of the drive conductor that is inductively
25 coupling to sense element 124. Specifically, a current sense element 125 located on sensor 120 can be used to much more accurately measure the current in drive conductor 122 that is inductively coupling to sense element 124. This is contrasted with measurement of the drive current much further from sense element 124 using current sensor 109 which is typically within instrument housing 107. Although the electrical impedance of cable 150 may alter the current at
30 the instrument, the local measurement can account for any variation of the current due to the cable.

 FIG. 2 shows embodiments of instrument 110 with a specific focus on data collection and analysis. It should be appreciated that other aspects of instrument 110 discussed in connection with FIG. 1A or elsewhere may also be part of such an embodiment.

Prior to using instrument 110 to collect and analyze sensor data as part of system 100, instrument 110 may be configured for a specific measurement application. An instrument control module 230 may be used to configure instrument 110 for a specific measurement application. Instrument control module 230 may utilize a session file 210 to store an instrument configuration 211, a measurement sequence instructions 212, and an interpolation configuration 213.

Instrument configuration 211 may store information identifying the type of sensor to be used, the excitation frequencies and their respective amplitudes, specific grids within precomputed database 203 for impedance data interpolation, the type of calibration to be used, the modules that used as part of the measurement such as the specific signatures within signature library 205 for data analysis, and other information for configuring instrument 110 for a measurement application. The calibration typically uses an air calibration or an air with a one point reference measurement calibration. For an air calibration itself, a measurement of the sensor response in air is used to adjust the measurement impedances to known and reproducible values. This approach does not require the use of reference standards for the instrument adjustment, but measurements on a reference part or material is recommended for verification of the calibration itself. To reduce channel-to-channel variations in the sense element responses and improve consistency of the conductivity measurement, a second measurement point can be used as part of the calibration. This second measurement is usually for a reference material with known electrical properties. This provides consistency with other standard procedures for conductivity measurements. Note that one or more reference point measurements could be used but this tends to be less robust than including a measurement response in air since the reference part measurement for calibration requires knowledge of the conductivity of the reference material. The instrument configuration 211 typically also includes information about the data acquisition rate and the configuration of auxiliary information that could be associated with each measurement such as position encoder information, temperature, strain gages, etc.

Measurement sequence instructions 212 may define the sequence of actions that are to take place for a measurement. Instructions 212 may specify motor control, triggers, changes to the instrument configuration, and prompt user actions. For example, instructions 212 may indicate that after initializing a measurement, a first motor is to move at a certain speed during measurement collection and, after reaching an end point, measurement is to stop. As another example, after a first measurement is taken the instructions 212 may indicate the user is to be prompted to take an action (e.g., lay a non-conducting layer between the test object and the sensor to increase sensor liftoff) and then wait until a user initiated trigger is received. As yet another example, after taking first measurements the instructions may cause instrument 110 to

be reconfigured to an alternate instrument configuration (e.g., having different excitation frequencies or other configuration properties).

Measurement sequence instructions 212 may also include definitions of the views to be presented to the end user. These views may be read by graphics generation module 270 to affect the graphical presentation to the user. Note that the graphics generation could also be in the form of data tables.

In some embodiments, an inverse interpolation module 220 is used to process impedance data 201 obtained from sensor 120 by impedance analyzer 117. Inverse interpolation module 220 utilizes a grid database 203 to estimate physical properties from impedance data 201.

Physical properties estimated may include properties such as layer and gap thicknesses, electrical conductivity as a function of spatial position, and magnetic permeability as a function of spatial position. For example, the physical properties estimated by inverse interpolation module 220 for a sensor scanning a coated substrate material may include (i) liftoff, (ii) coating thickness, (iii) coating electrical conductivity, and (iv) substrate electrical conductivity.

Interpolation configuration 213 of session file 210 may be used to specify aspects of the inverse interpolation. For example, in some embodiments a hierarchical approach can be used to increase numerical stability and accuracy of the multiple unknown inversion. Property effects can be systematically separated from one another by using specific excitation frequencies and/or segmented fields to estimate the properties they are most sensitive to. For example, a coating conductivity property may be estimated using only a high frequency excitation measurement, and then both the high and a low frequency used to determine coating thickness and substrate conductivity (with the coating conductivity in this second step assigned the value determined from the high frequency alone).

Further discussion of the operation of inverse interpolation module 220 may be found in the '057 patent and the '883 patent.

In some embodiments, instrument 110 is also equipped with a forward model module 240 for precomputing grids for grid database 203 using a sensor-material model. The model may be a physics-based model, an empirical model based on prior measurements, or any other suitable type of model for creating measurement grids. The PhD Thesis of Darrell Schlicker, "Imaging of Absolute Electrical Properties Using Electroquasistatic and Magnetoquasistatic Sensor Arrays", dated October 2005, presents a physics-based, semi-analytical forward model. Those of skill in the art will recognize several other forward models have been published. In some embodiments, forward model module 240 is not made a part of instrument 110 and only grids are stored in grid database 203 of instrument 110. For example, forward model module 240

may be a software application run on a computer to produce grids which are then stored in grid database 203.

In some embodiments, instrument 110 includes a signature definition module 250 for defining characteristic responses (“signatures”) of a feature to be enhanced or suppressed in measurement data. Signature definition module 250 may allow a user to identify signatures and store them in a signature library; alternatively or additionally, signatures may be identified in an automated or semi-automated way. For example, a crack defect signature may appear in the electrical conductivity response measured by a sensor scanning over the crack. In the case of a sensor array, the response may be observed on a single or multiple adjacent channels. A signature may be identified as a single channel response or a multi-channel response. Signature definition module 250 may standardize signatures prior to storing them in library 205. For example, signatures may be standardized to a specific number of points or a specific amplitude range. Signatures may also include metadata that provide additional information about the signature such as the size of the defect the signature was obtained from.

Detection and sizing module 260 may be used to detect and size defects in measurement data from a test object using signatures from signature library 205. Module 260 may evaluate the correlation between a measurement and a signature. If the correlation exceeds a threshold a detection may be flagged. The threshold may be set based on the detection and false alarm requirements of the application. Signature library 205 may contain multiple signatures that may be tested against measurement data. The signature having the greatest similarity with the measurement may also be used to size a detected defect. For example, the defect size may be estimated to be the same as the size of the defect the signature.

Module 260 may also be used to suppress features that are not of interest such as fasteners or through holes. For example, a through hole in a plate typically has a significant effect on the estimated electrical conductivity of the substrate material if a planar model is used to estimate conductivity. The shape of the conductivity response with respect to position as the sensor is scanned over the hole depends upon the actual electrical conductivity of the substrate material, the excitation frequency, and the geometry (e.g., sense element size and spatial wavelength) of the sensor. However, for a given sensor array, because the conductivity response of the through hole is consistent, it may be removed from the conductivity estimate. For example, module 260 may identify a highly correlated through hole signature with the conductivity response from measurement. The conductivity response may then be updated to remove the signature. This will flatten the conductivity response and may also allow for the hole location to be accurately estimated from the measurement data. While this example discussed suppressing the response for processed data such as the estimated conductivity of the material

this approach can also be used for unprocessed data such as the sensor impedance or transinductance.

Graphics generation module 270 may provide a graphical representation to the user to assist the user in the data collection and/or analysis process. Module 270 may present such a graphical presentation on a video display integral to and/or separate from instrument 110. Information may be presented as tables, A-scans, B-scans, C-scans, or any suitable way. In some embodiments, module 270 configures the graphical environment based on instructions 212. In this way a consistent presentation of information can be provided to the user.

Report Generation Module 280 may be included to facilitate review of measurement results outside of the graphical environment of instrument 110. For example, report generation module 280 may produce a report of measurement data in pdf, docx, rtf, xlsx, or other suitable format. Session file 210 may specify the report format which may be used by module 280 to generate reports for measurement data.

In some embodiments, the output includes a decision with regards to the future disposition of the test object. Modules 270 and/or 280 may present such a decision. Examples include pass/fail decisions on the quality of a component, or the presence of flaws. As another example, it may be determined whether the test object may be returned to service, repaired, replaced, scheduled for more or less frequent inspection, and the like. If it is determined that the application was not determinative, instrument 110 may re-perform the procedure(if automated), or advise the user to re-perform the procedure. A procedure may need to be re-performed, for example, if all requirements of the procedure were not met. For example, the procedure may require the liftoff of the sensor to be below a threshold amount over the inspection surface and require re-performance if the liftoff requirement is not met.

In some embodiments the measurement results are used to control a process. For example, a property measurement may be fed back into a control circuit that controls a process.

Section II - Sensor

An ET-Array sensor 400 is shown in FIG. 4. Such a sensor is one example embodiment of an ET sensor that may be used for inspection of risers or other test objects. Sensor 400 comprises a drive winding 410, a plurality of sense windings 420, and a mechanical support system 430. Drive Winding 410 for sensor 400 has a dual-rectangle (“double-D”) configuration, similar to that discussed in connection with FIG. 1D. An advantage of the dual rectangle drive winding configuration is that semi-analytic models typically provide greater modeling accuracy of double-D drives compared to the single rectangle drive winding models. Also, the sensor footprint may be smaller under certain circumstances allowing the sensor response to more

accurately reflect the precise location of the sensor. An advantage of single rectangle (“single-D”) drive winding is that the axial width of the scanner can be reduced.

The double-D arrangement comprises two substantially rectangular loops adjacent to one another and connected in series such that current between the adjacent portions of the loops (in the middle) will run in the same direction when drive winding 410 is excited. In some embodiments, drive winding 410, including both rectangular loops, are wound from a single insulated conducting wire. In some embodiments each of the two “Ds” is wound individually from a single insulated conducting wire and electrically connected together to form a single current path. The insulated conducting wire may have any suitable cross section, for example, substantially circular, rectangular, or square. Each loop in the double-D may have a single turn or multiple turns. For example, each loop may have, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 35, 50, 75, or 100 turns. Though any suitable number of turns may be used. In some embodiments, both loops have the same number of turns and in other embodiments the loops each have a different number of turns. The terminals of drive winding 410 may be connected to the drive portion of the instrumentation shown in FIG. 1A.

Drive Winding 410 may be manufactured in any suitable way. In some embodiments, drive winding 410 is wound on a set of tooling that holds the corners of the loops in place and confined the vertical extent of the sensor. Such tooling may permit manual winding of the sensor or an automated or semi-automated system to wind the sensor. Once the mechanical support system 430 is firmly in place, the tooling may be separated from the sensor such that the tooling may be reused for subsequent manufacturing. Manufacturing of the sensor is discussed further in Section III, below.

In some embodiments, drive winding 410 includes a current sense portion and a dedicated sense winding for measuring the current in the drive winding 410. Such a current sense may be formed in ways described in PCT Application No. WO2023192887A1 published on October 5, 2023 (the entirety of which is hereby incorporated by reference), in ways analogous to those described therein, or in any suitable way.

The sense windings 420 may be one or more sense windings; if more than one, the sense windings 420 may be formed into an array. In some embodiments, the array is a linear array as shown in FIG. 4. In some other embodiments multiple linear arrays are formed. Though the position of the one or more sense windings 420 may be selected in any suitable way. In some embodiments, the sense windings 420 may be positioned as a linear array along a centerline of one of the double-D loops of the drive winding 410 (i.e., along an axis of symmetry of the loop). In some embodiments, the sense windings 420 may be positioned as a linear array in one of the double-D loops of the drive winding 410 but offset from the center line. In some embodiments, a

linear array of sense windings 420 is positioned outside of the double-Ds, for example, along a long-side of one of the loops. In some embodiments, multiple arrays of sense windings 420 are positioned at multiple such positions (e.g., centered in both loops of the drive).

Each sense winding 420 may be formed by winding an insulated wire with one or more turns. The terminal ends of the wire may be connected to the instrument 110 shown in FIG. 1A. Each sense winding 420 may be individually and simultaneously measured by instrument 110.

In some embodiments a bobbin 421 is used to provide mechanical support and/or facilitate manufacturing of each sense winding. The bobbin 421 may be part of the tooling and removed after fabrication or may be part of the sensor 400. The size and dimensions of the bobbin 421 should be suitable to support the number of turns of the sense winding wire desired for the particular sense winding given the intended gauge, cross section and other relevant properties of the insulated wire. For example, in some embodiments, the wire is wound with 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 35, 40, 50, 60, 70, 80, 90, 100, 110, or 120 turns, or any suitable number of turns.

Sense windings 420 may be wound in any suitable way. For example, the wire may be wound about bobbin 421 by hand, or by using automated or semi-automated systems (e.g., using a lathe). Once the individual sense windings 420 are wound, they may be positioned as desired relative to drive winding 410. Appropriate tooling may be used to hold the sense windings 420 in place. In some embodiments a support is interfaced with the bobbin 420 to maintain the desired position. Though it should be appreciated that the sense windings may be wound already in place.

The mechanical support system 430 provides mechanical support to the sensor 400 holding the drive winding 410 and the sense windings 420 in the desired relative positions. Any suitable mechanical support may be used as mechanical support system 4230. In some embodiments a rigid mechanical support system is used. Mechanical support system 430 may be made, for example, substantially or entirely out of non-conducting or low conducting materials. In some embodiments a rubber-like material is used. Such a material may initially be in a liquid form that is held by the tooling until solidified into a rubber-like state. In one embodiment the mechanical support may include performance enhancing layers such as conducting layers for shielding, high magnetic permeability layers for enhancing the flux into the material under test and reducing the field that is not interrogating the material under test, where in one embodiment the material under test is the riser armor wires and the detection of wire failures is the objective. In other embodiments, the mechanical support is simply designed to limit the conducting or magnetic material that is close to the sensor and to hold such materials stationary relative to the sensor to limit the impact on sensor response.

The leads 440 to drive winding 410 and sense windings 420 may be bundled into a sheath terminated with an electromechanical connector to the instrument 110 of system 100 of FIG. 1A.

In some embodiments, sensor 400 has mounting holes 431. Such holes may be used, for example, to secure sensor 400 to a scanner. Scanners that may be used in combination with sensor 400 are further discussed in Section IV.

Section III - Sensor Manufacture

A discussion of the manufacturing method of fabricating the sensor is now presented in connection with reference to FIGs. 5A - 5AG. This fabrication method is simply one exemplary embodiment, and those of skill in the art will appreciate various alternative fabrication steps. The fabrication steps described could be performed in alternative ways including greater or complete automation of the fabrication step or, if applicable, performing the step by hand. Each bobbin is fabricated in any suitable way such as using an additive manufacturing technique as is illustrated in the present example. A counter may be used to count the turns during wrapping of the bobbin with an appropriate wire and ensure the correct number of turns is achieved. As shown in FIG. 5A, a fixture 422 is used to connect bobbin 421 temporarily to a lathe-type tool. One end of the sense element wire 423 is tied off to the bobbin after setting it up appropriately and then the correct number of turns is achieved by turning the lathe while working wire 423 laterally across bobbin 421 as necessary to achieve a relatively uniform distribution of the wire across the width of bobbin 421 over the entire number of turns.

Once the desired turn count has been achieved, the terminal end of wire 423 is placed appropriately as shown in FIG. 5B and bobbin 421 is wrapped with a tape 424 to secure the coil and to prevent the coil from unwinding. The wire ends 425 and 426 (FIG. 5C) at the terminal of bobbin 421 are now prepared for connection to an insulated wire 427 that will connect the individual sensing element to the instrumentation 110. Once soldered as shown in FIG. 5D, these solder connections are placed inside a cavity of bobbin 421 and then filled with an epoxy to secure both the cabling and the solder in a way that provides suitable strain relief. Care should be taken to ensure that epoxy used is insulating and that the solder points are separated within the cavity of bobbin 421 so that a short between wire ends 425 and 426 is avoided. FIG. 5E shows a bobbin 421A prior to filling with epoxy and another bobbin 421B filled with epoxy 428. Filling with epoxy may be performed in several pours.

In some embodiments, a coil bracket 432, shown in FIG. 5F, is used to provide structural support for the array of sense windings 420. The bobbins 421 may be connected to bracket 432, for example, via screw 429 (FIG. 5E). In some embodiments, the materials used for sensor fabrication are modified to select materials that can survive in deep water.

FIG. 5G shows tooling 510 for fabrication 1/2 of a double-D drive winding. Specifically, tooling holders 411 for the four corners of the drive winding as well as the winding wire 412 and support screws 413 are visible in the figure. A dam may be formed around the winding such that an epoxy fill can be poured into and confined to support the winding wire 412. Note that the
5 pegboard has a clear sheet on top of it so that when the epoxy is poured it does not enter the holes of the pegboard.

FIG. 5H shows a photograph of two drive winding loops removed from tooling 510 after the epoxy has hardened. These drive winding portions have been carefully trimmed of any excess epoxy that escaped the dam. The winding leads (not easily visible) come off the structure
10 at right and will be connected to drive cabling for the sensor.

FIG. 5I shows additional rubber material removal from the Double D drive winding for the sensing element bobbins and additional hardware.

FIG. 5J shows the wiring of the drive winding Double D's together to form a single Drive winding. Note that the direction of the current of the adjacent center portions of the drive
15 winding are in the same direction. FIG. 5K shows a photograph of the wired drive windings. A cable is connect to the terminals of the drive winding. In this example, the cable has six strands of insulated wire, three of which are used to connect to each terminal of the D drive winding. In anticipation of relatively high frequency operation of the drive, these six wires may be wound within the sheath in such a way as to equalize the amount of linear distance each wire spends
20 along the length of the cable along the exterior of the bundle. This will allow for each of the wires to carry approximately the same current, even at high frequency. (It is noted that if these wires were simply bundled within the cable, the outer wires would carry more current than the inner wires at higher frequency operation due to the skin effect.

FIG. 5L shows tooling for assembling the components thus far described into the
25 inductive sensor. The figure shows a pegboard with a clear covering over all unused holes of the pegboard. the exterior perimeter edge defines the edge of the sensor. There is also a component for screwing the bobbins in place. There are several screws to hold holes in the sensor for later use with securing the sensor to a scanner or other hardware for measurement applications. Finally, several pins are provided to align the drive windings precisely in the correct location.

FIG. 5M shows a first fabrication step of flooding the tooling with a small amount of
30 rubber compound. This sets a base before any of the hardware already fabricated is installed the locations for the bobbins are noted to be accessible.

FIG. 5N shows attachment of the bobbins to the tooling. A screw through the bobbin is used to attach the bobbin to the tooling and secure its location. In FIG. 5O, note the complete set
35 of sensing elements have been secured and their cables are let out of the tooling area off the edge

of the sensor. In this example, the sensing elements are all located within one of the double D loops of the drive winding. After affixing the bobbins in place another layer of the liquid rubber compound is poured into the tooling.

FIG. 5P shows the leads for the sensing elements passed through the Double D that will have the sensing elements within its loop. FIG. 5Q shows the drive and sensing elements placed in the fixturing on top of the uncured liquid rubber. The drive and sense cables are lead off the edge of the sensor in appropriate grooves or holders in the tooling.

FIG. 5R shows the use of weights to assist in keeping all of the components of the sensor in place and pressing them into the epoxy to firmly secure the components. Weights may be used to make sure that the drive winding is well affixed to the lower epoxy. After a couple hours the weights may be removed and the remaining epoxy for the sensor is flooded into the fixturing covering the cables and firmly embedding all components. FIG. 5S shows the sensor after this final layer of epoxy is poured.

Allowing for 24 hours for the epoxy to cure, FIGs. 5T and 5U show the bottom and top of the sensor after removal from the fixturing.

FIG. 5V shows the assembly of the cabling that will be used to attach the sensor to a sensor connector that is compatible with the instrumentation being used. Tie wraps are used initially to bundle the cables for the sensing elements. FIG. 5W shows the cable bundled and covered with a sleeve.

FIG. 5X shows a tong circuit board compatible with JENTEK Sensors, Inc. GridStation 8200 product line. The ends of the cable are connected to the board as follows. Each sense cable has three wires: the two wires that connect to the wound bobbin and a sheath. Each sense cable has three holes associated with the tong board that will be used for attachment. The large hole is used to secure the sheathing; the two smaller holes are used to connect the two ends of the wire for the sense element. Once all of the wires are connected on one side of the tong circuit the tong circuit is clean up by clipping and then grinding down excess wire and solder on the far side of the board (e.g., using a file). Appropriate tooling may be used to prevent filing too low. This clipping/filing/grinding step is done to ensure that the sense wires that will be pulled over this region of the tong board are not damaged or electrically interfered with by the wires on the other side of the tong board. FIG. 5Y shows all of the wires connected now on both sides of the tong circuit. Note that the drive winding is connected away from the sensing element connections.

A cable separator as shown in FIG. 5Z is inserted to support each of the wires with a separate larger groove for the drive cable. A heat shrink is placed on the cables and sheath near the top of the tong board. The heat shrink is shrunk to hold the sheath in place as shown in FIG. 5AA. FIGs. 5AB and 5AC show a clamshell used to protect this connection. The clamshell is

essentially a box that is secured over the electrical connections between the cable and the tong circuit board. FIGs. 5AD and 5AE show the clamshell secured to the connector.

FIGs. 5AF and 5AG show the top and bottom of the completed sensor.

Section IV - Scanner

5 A scanner may be used to scan an ET array sensor along a test object such as riser 300. The scanner may be adapted to scan circumferentially, axially, helically, or in any suitable scan pattern. (Further discussion of the inspection procedure may be found in Section V.) The scanner may utilize one or more sensors. In some embodiments, the sensor(s) provide full circumferential coverage for performing a complete scan in one axial movement. In some
10 embodiments, 4 sensors are utilized each providing coverage of at least 90 degrees of the circumferential surface. In some other embodiments, 2 sensors are used, each sensor providing coverage of at least 180 degrees of the circumferential surface. These are simply examples, and any combination of n sensors to cover the circumference may be used in such full coverage embodiments.

15 Other embodiments may provide less than 360 degree coverage. In some such embodiments the scan plan is such that multiple passes are used to provide full coverage. For example, a scanner for an out-and-back scan may provide less than full coverage in each pass but full coverage between the two passes. Scanners may also be designed for scan plans requiring more than two passes.

20 FIG. 6A shows a riser 300 with two double-D ET array sensors 610 and 620 providing 360 degree coverage about the circumference. FIG. 6B shows the sensors 610 and 620 “unwrapped” from the riser 300.

FIG. 6C shows a riser 300 with two single-D ET array sensors 630 and 640 providing 360 degree coverage about the circumference. FIG. 6B shows the sensors 630 and 640
25 “unwrapped” from the riser 300.

In one embodiment the instrumentation is designed so that the impedance instrument and any additional electronics can be placed in a vessel that enables survival in deep water. In one such embodiment cables are used between the instrument to provide support for sensor data acquisition, encoder position recording and power for instrumentation and motors as needed. In
30 one such embodiment dedicated electronics is included for each sensor drive to provide the current or voltage needed to create a magnetic field at one or more frequencies and dedicated electronics is provided to measure a response at each sensing element simultaneously. In one such embodiment the drive electronics enables data acquisition from four MWM-Array inductive sensors simultaneously as they are scanned in the axial direction.

In one embodiment the axial separation of the two or four sensors and arcs is at least far enough to reduce the interference between sensors below a prescribed acceptable level, but not so far that the total length of the scanner is too large to be carried by an appropriate vehicle needed to install the scanner on the riser to allow inspections to be performed.

5 In the embodiment shown in FIG. 6E, the scanner 600 has four sensors (sensors 601, 602, 603, and 604). A corresponding top down view is shown in FIG. 6H. Each sensor provides coverage of at least 90 degrees with the sense elements. The drive windings have at least the same extent as the sense elements. In some embodiments the drive windings do not exceed 180 degrees. Increasing the lateral extent of the drive winding improves the uniformity of sense
10 element responses, but increases the size of the sensor. While sense element specific grid databases may be used, it may be preferred to use a single grid database for all sense elements of a sensor. The sense element specific grids provide improvements by accounting for the finite size of the drive and other such constraints to improve the accuracy of the models.

The sensors may be rigidly supported by sensor supports (mounting arcs 605 and 606)
15 that hold the sensor in an arc. During the inspection procedure this will allow the sensor to be concentric to the riser. In some embodiments, the four sensors are arranged in pairs so that two sensors at a single axial location (e.g., sensors 601 and 603, rigidly supported by mounting arc 605) would cover more than 180 degrees with their combined sense elements. With two sensors at the same axial position (but different circumferential positions) the drive windings may be
20 limited to 180 degrees to avoid overlapping. In one embodiment the sensor is flexible but it is mounted onto a rigid arc. The use of rigid arcs with fixed radial positions allows the use of precomputed databases that assume this radial position with relatively small variations in liftoff relative to the riser wires. In another embodiment the sensor is rigid and made from materials that can tolerate deep water operation. In another embodiment, confirmable sensor mounting
25 arcs are used to support the sensors allowing the flexible sensors to dynamically conform to the test object.

The mounting arcs 605 and 606 may be hinged at the edges (i.e., between sensors) so that they may be inserted onto riser 300 without changing the shape of the sensor. FIG. 6F shows scanner 600 with mounting arcs 605 and 606 opened at hinges 607 and 608, respectively. A
30 corresponding top down view is shown in FIG. 6I. The second pair of sensors at the second axial location (e.g., sensors 602 and 604, supported by mounting arc 606) is rotated 90 degrees compared to the first axial location in order to provide full circumferential coverage.

FIG. 6G shows sensors 601, 602, 603, and 604 on riser 300 with other elements of the scanner not shown for clarity.

The scanner moves the sensors in the axial direction to scan the flexible (or rigid) pipe and measure the properties with the goal of monitoring stress and detecting riser wire failures or degradation.

The scanner for holding the arrays against the riser will not rely on the diameter of the riser being constant. Wheels, tracked treads or mechanism of locomotion may be connected to the sensor supports to allow the scanner to move over the surface of the riser. FIG. 6J shows an example embodiment with wheels 650, according to some embodiments. While wheels are discussed herein, it should be appreciated that any other suitable mechanism of location or combination may be used. The wheels (for motion and encoding position) are the only parts of the scanner that touch the riser. The wheels are connected to the sensor supports via a suspension 651 that allows the wheels to move radially to account for variations in the diameter of the riser. Multiple wheels are used to allow the scanner to remain concentric with the riser. In some embodiments a set of three or more wheels are used at a single axial location with additional sets of three or more wheels provided at one or more additional axial locations. The wheels may have an additional mechanism that forces them to move radially at the same time so that the scanner remains concentric with the riser. One or more wheels may have a position encoder installed. Such mechanisms may be purely mechanical or include a form of electronic feedback control.

The sensors are flexible but are mounted to rigid sensor supports. The scanner can be used with different sensor supports that have a different curvature in order to inspect risers with different diameters and with different insulation or other protective layer thickness.

In order to reduce the axial length of the scanner, the sensor may have a single drive loop. Two or more drive loops may be used, which may improve performance.

In order to reduce the axial length of the scanner, all of the sense elements may be placed on a single, long sensor. The sensor may have two drive loops or 4 drive loops. Two rows of sense elements are used that each cover more than 50% of the riser circumference.

In one embodiment there are five fixed radius arcs to cover a range of insulation thickness for one flexible pipe diameter. In one such embodiment the adjustable wheels allow for continuous adjustment of the distance between the outer insulation surface and the fixed diameter arcs to hold the position of the arcs at the prescribed distance from the center of the riser. This allows the use of five precomputed databases that accurately represent the position of the arc and sensor relative to the outer flexible pipe (wire) surface and the center of the pipe. In one such embodiment the wheel motion can be adjusted to take reference calibration data at two or more liftoffs to improve the alignment of the sensor response with the liftoff lines in the database. In another such embodiment more than five arcs might be used to provide more accurate positioning and a wider range of insulation thickness or other protective layer thickness

support. Note that the sensor does not touch the surface, it rides at an approximately fixed distance from the outer riser insulation surface to avoid wear. This separation is provided by fixed or adjustable wheels. The sensor, arc and other system materials are selected to provide sustainable performance at the depth of the planned inspection.

5 In some embodiments a fixed number of mounting arc diameters are provided as part of a sensor kit to facilitate inspection of risers having varying diameters or insulation thicknesses. For example, mounting arcs may be defined based on the outer insulating layers thickness. A set of arcs may be build for insulation thicknesses of 15, 25, 35, 45, 55, 65, 75 mm. Thought this is just an example, and any suitable number of rigid mounting arcs may be used to provide
10 coverage for a riser or set of risers of interest. In some embodiments the system is adapted for inspection of risers in deep water environments.

In some embodiments a single sensor covers the entire circumference of the riser. This design reduces the axial length of the scanner. Since drive returns prevent a single row of sense elements, two rows of are used, one in each of two drive loops. The drive loops are staggered to
15 allow the end turn to come together away from the sense elements. A problem is that the end turns from one loop are close to the sense elements in the other loop when wrapped onto the riser. An alternative design uses two drive loops in order to protect the sense elements from the end turns. Advantages of such a design include one sensor versus 4, reduced axial length, and a larger distance from the last sense element to the end turns. A challenge is that the sensor needs
20 enough flexibility to open and allow the riser to fit inside. It then needs to close and form a complete circle.

For risers it is possible that the diameter and insulation thickness will be known and constant for a targeted riser (up to 1.2km long). Also, since there is no metal outer layer, the sensor can be kept “floating” above the insulation at fixed diameters, just centered by adjustable
25 wheels. The insulation thicknesses range is from 10 mm to 75 mm. We could, for example, have 15, 25, 35, 45, 55, 65, and 75mm versions of sensors that are selected topside before submerging to inspect a riser with known thickness.

In one embodiment of a magnetic material (non-conducting or conducting) is added behind the sensor at a larger radial position to shield and possibly enhance the field so that the
30 applied magnetic field is primarily projected in the direction of the center of the cylindrical part. The purpose of this is to have a larger fraction of the field inducing eddy currents or flux in the target conducting material. In one such embodiment the area covered by the magnetic material is adjusted to maximize the sensitivity to wire failures for flexible pipes. In another embodiment the arcs and supports are designed to avoid motion of conducting or magnetic materials relative
35 to the sensor within the physical distance of sensor sensitivity to avoid affecting the sensor

response. In one such embodiment the sensors are primarily sensitive to changes in the armor wire properties. In one such embodiment the sensor geometry, supports, arcs and instrumentation is designed to sense wire failures in the inner and outer armor wire layers. In one such embodiment scans are performed on wire failure samples to capture signatures at multiple arc liftoffs to build a signature library that can be used to detect similar wire failures. In one such embodiment the liftoff is varied for each of the fixed arcs by adjusting the wheels that change the radial arc position. Note that the precomputed databases for permeability, liftoff and other unknowns are specific to each of the fixed arcs and assume the arc radius is fixed at a nominal value. Thus, small changes in liftoff can be corrected for, while large changes in liftoff require changing the arc radius. In one embodiment the precomputed database is computed using a cylindrical coordinate model that assumes the arc radius is concentric with the armor wire layer radius to achieve reliable liftoff compensation.

Section V: Inspection Procedure

This section describes the procedure for inspecting test objects, such as risers, according to some embodiments. The system, sensor, and scanner discussed above in Sections I, II, and IV may be used, though the inspection procedure is not so limited.

As discussed in Section I, precomputed databases may be generated prior to analyzing the inspection data. Such a grid database may be specific to a sensor geometry and thus assists in selecting an appropriate sensor. As ET sensor liftoff may have a significant impact on performance, the nominal liftoff should be determined from the target test object and scanner being used. Sensor parameters such as the drive geometry and drive-sense gap will likely affect the sensor response. For risers, a cylindrical coordinate layered media model assuming uniformity in the axial and angular direction and layers in the radial direction may be used. The model layers may model some or all of the layers of the riser. The model may define each layer by three properties - electrical conductivity, magnetic permeability and thickness. Each property may be treated as “known” (i.e., the value is fixed in the model) or “unknown” (i.e., the value is iterated over by the model). The database is generated by iterating each of the unknowns over a respective set of fixed values.

In some embodiments, the model is used to generate a two-unknown database to measure liftoff (first unknown) and magnetic permeability (second unknown) at one or more frequencies. The liftoff may be used to verify inspection quality (“Was the sensor close enough to the riser to perform an acceptable inspection?”) and the magnetic permeability may be used to identify defects of interest (“Does the local magnetic permeability response indicate a defect of interest?”). For example, the absolute magnetic permeability and the shape of its response may be used for defect detection. In some embodiments the liftoff can also be indicative of a defect.

For example, if the wire has broken and separated so that an appreciable gap exists, a higher liftoff may be measured when scanning over the gap. This may be distinguishable from other liftoff variation, for example, if it is localized to only one or a few channels of the ET array.

Properties that are not being measured (“knowns”) but that also affect the sensor response should be suitably set in the model. For example, the electrical conductivity and thickness of the wire layer may be fixed in the model. Alternatively a higher number of unknowns may be modeled in the database (e.g., three unknowns - liftoff, electrical conductivity, magnetic permeability) than will be actually measured. Prior to data analysis an unknown can be fixed by setting its value. In this way a database can be simplified to a fewer number of unknown properties. As a practical example, the electrical conductivity may be measured on the test object at one location and then fixed to that value for further measurements. A liftoff test may be performed on the test object prior to data collection to determine the electrical conductivity value. Specifically, the conductivity is selected such that the liftoff response follows a line of constant permeability in a permeability-liftoff grid. In another embodiment, a different parameter than conductivity is adjusted so that the response with varying liftoff follows a constant permeability line.

In some embodiments a three-unknown method is used. For example, the model may take the liftoff, an electrical property of the outer layer of tensile armor (e.g., electrical conductivity or electrical permeability), and an electrical property of the inner layer of tensile armor, as unknowns. The liftoff may be used to validate measurement quality (e.g., confirm the sensor was adequately positioned relative to the riser), and the estimated electrical property of the outer and inner tensile armor may be used to determine if a defect is present in the applicable layer. For example, a broken wire in a tensile armor may appear as a localized change in the electrical property. A threshold may be used to control false calls.

Sensor 400 may be scanned along a riser while exciting the drive winding 410 and measuring the responses of sense windings 420 using instrumentation 110 of FIG. 1A, or any other suitable instrumentation. In some embodiments, a layered media model is used to estimate properties from the measurement data and these properties may be analyzed to determine if a defect is present.

The precomputed database and multivariate inverse method may be used to convert the measured transimpedance into liftoff and magnetic permeability. In some embodiments either the liftoff or magnetic permeability is used as a means to detect damage in the electrically conducting component.

In one embodiment the electrical component is metal flexible pipe wire (also called armor) and the damage is either cracking or wire failure or stress change in the wire. In some

embodiments the goal is to measure stress in the electrical conducting material by monitoring changes in the magnetic permeability while assuming the conductivity is constant. In some embodiments, temperature is monitored separately to enable correction for temperature effects on the magnetic permeability.

5 Normalization & baseline subtraction provide powerful methods for wire failure detection improvements. Baselines can be estimated from scans on risers without defects and signatures of wire failure can be extracted from seeded faults/wire failures in actual flat or cylindrical samples.

10 In some embodiments, permeability / liftoff grids (1 or more frequency) with the lowest frequency selected to have sensitivity to the second armor layer. Multiple frequency grids may be used to improve performance. Air calibration or reference calibration may be used, for example, in accordance with ASTM standards 2884 and/or E2338.

15 In some embodiments artificial intelligence (AI) is used for pattern recognition for categorization of defects and/or background anomalies. In one embodiment, common AI methods such as neural networks in python are used alone or in addition to signature library approaches.

20 Testing of the sensing method can be performed on riser samples or on simplified samples that have similar electromagnetic properties. FIG. 7A shows an example of a simplified sample 700. The sample is flat rather than a cylinder in order to reduce cost and simplify construction. The top layer 701 consists of steel bars positioned side-by-side to simulate one layer of wires similar to tensile armor layers 302 (FIG. 3). In this example, the steel bars are 0.625 inches by 0.188 inches. The next layer 702 is an insulator made from any non-conductive and non-magnetic material such as plastic similar to anti-wear layer 303. In this example, the insulator is 0.063 inches thick and made from PVC. The next layer 703 is another layer of steel bars the same as the first layer and similar to tensile armor layers 304. The next layer 704 is another insulating layer the same as layer 702 and similar to second anti-wear layer 305. The final layer 705 is a steel plate. In this example, the steel plate is 0.250 inches thick. This layer is designed to represent the remaining conductive layers similar to interlocked pressure armor 306 and carcass 308. It is expected that the inner layers have a higher effective conductivity and that the sensor will not be sensitive to any other layers.

30 In risers, the armor layers are at an angle relative to the axis of the riser. In one example, the first armor layer is at +30 degrees and the second armor layer is at -30 degrees. However, any number of layers can be used. The number of layers and the composition of the layers should be close to the riser that is to be inspected. The simplified sample may have the wire layers at the same angle as the layers in the risers. In order to reduce cost and complexity, the

35

simplified sample may have the steel bars straight and at the sample angle. The effect of the angle of the bars is expected to be small compared with other effects.

In some inspection applications the riser is constructed using steel “wires.” A wire in this context is rectangular in cross-section. A typical riser wire dimension is 5mm x 15mm. Two layers of wire may be wrapped around the riser in a helical pattern. Each layer is at an angle to the axis of the riser. A typical angle is 30 degrees. Since there is little electrical conductivity between the wires, the “effective” electrical conductivity of the armor layers (formed by the wires) as measured by the sensor at a distance from the armor layers is substantially lower than the electrical conductivity of the wire material itself. The term “effective” is used to indicate that the measurement is based on analysis using a planar layered media model. A typical effective conductivity estimated using data collected from a sensor and processed using a layered media model is about 0.25% IACS. For comparison, the conductivity of the steel is approximately 8% IACS. FIG. 7B shows a depth of penetration chart for a representative sensor and a uniform layer of material that has an electrical conductivity of 0.25% IACS and a relative magnetic permeability of 80. The plot shows that the depth of penetration is on the same order as the thickness of the first armor layer (example: 5mm) when the sensor is driven at a frequency between 100Hz and 10kHz. Note that the sensor is sensitive to material that is beyond the depth of penetration, so physical testing is useful for determining the actual depth of sensitivity.

The raw sensor data is converted to estimated properties using a measurement grid. The measurement grid is a database of sensor responses predicted using a computation model. The model includes the geometry of the sensor and multiple layers of material that the sensor will interact with. The simplest model includes the sensor, a non-conductive layer, and a single material that is assumed to be infinitely thick. Note that “infinite” in this case is a mathematical limit and that a model that assumes a large but finite thickness would produce a similar result. This type of model could be used for the riser. Another method would be to model the layers of the riser individually. For example, the model can include the sensor, a non-conductive layer, an armor layer, a non-conductive layer, an armor layer, a non-conductive layer, and one or more inner layers. In this example, the armor layers are assumed to have a uniform effective conductivity, such as 0.25% IACS. The inner layer can be modeled as a single layer with a higher effective conductivity (8% IACS). The number of layers and the properties of the layers do not need to be identical to the riser in order to usefully predict the sensor response. Also, the layers can be assumed to be flat or cylindrical.

FIG. 7C shows data on a measurement grid. The measurement grid is a database of predicted sensor responses at different liftoff and magnetic permeability of the material under test. In this case, the material under test is the first armor layer. The second armor layer and one

internal layer are also included in the model used to construct the grid. The axes represent normalized sensor transimpedance values; the values are normalized by dividing the raw measurement by the measurement in air, far from the test object. The point (1, 0) thus represents the response in air. The thick line shows sensor data acquired on a simplified test sample. The
5 liftoff is varied during data acquisition. The goal of this type of test is to demonstrate that the model is a good representation of the actual behavior of the sensor and the material by showing that measurements where only the liftoff changes show the other estimated properties are unchanging. The data follows the lines that represent constant magnetic permeability.

FIG. 7D shows the sensor response for two measurement channels using a simplified flat
10 sample. For this test, a wire break was simulated by placing a 1mm gap between two of the steel bars and pushing the bars so that the gap passed under the sensor during data acquisition. The sensor remained stationary relative to the sample. One of the channels was directly over the gap and one of the channels was far enough away from the gap that the sensor response did not change significantly.

FIG. 7E shows the sensor response for two measurement channels using a simplified flat
15 sample. For this test, a wire break was simulated by placing a 1mm gap between two of the steel bars and moving the sensor over the sample. One of the channels passed over the gap and one of the channels was far enough away from the gap that the sensor response did not change significantly due to the gap. The signal varied over the duration of the scan due to the movement
20 of the sensor relative to the sample. This variation is primarily due to the changing distance of the sensor relative to the edges of the sample. The effect can be ignored since all of the channels in the array experience a similar change, but only a few of the channels are sensitive to the gap.

Section VI: Closing Discussion

Having thus described several aspects of at least one embodiment of this invention, it is
25 to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art.

Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Accordingly, the foregoing description and drawings are by way of example only.

30 The above-described embodiments of the present invention can be implemented in any of numerous ways. For example, the embodiments may be implemented using hardware, software or a combination thereof. When implemented in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single computer or distributed among multiple computers.

Further, it should be appreciated that a computer may be embodied in any of a number of forms, such as a rack-mounted computer, a desktop computer, a laptop computer, or a tablet computer. Additionally, a computer may be embedded in a device not generally regarded as a computer but with suitable processing capabilities, including a Personal Digital Assistant (PDA),
5 a smartphone or any other suitable portable or fixed electronic device.

Also, a computer may have one or more input and output devices. These devices can be used, among other things, to present a user interface. Examples of output devices that can be used to provide a user interface include printers or display screens for visual presentation of output and speakers or other sound generating devices for audible presentation of output.

10 Examples of input devices that can be used for a user interface include keyboards, and pointing devices, such as mice, touch pads, and digitizing tablets. As another example, a computer may receive input information through speech recognition or in other audible format.

Such computers may be interconnected by one or more networks in any suitable form, including as a local area network or a wide area network, such as an enterprise network or the
15 Internet. Such networks may be based on any suitable technology and may operate according to any suitable protocol and may include wireless networks, wired networks or fiber optic networks.

Also, the various methods or processes outlined herein may be coded as software that is executable on one or more processors that employ any one of a variety of operating systems or
20 platforms. Additionally, such software may be written using any of a number of suitable programming languages and/or programming or scripting tools, and also may be compiled as executable machine language code or intermediate code that is executed on a framework or virtual machine.

In this respect, the invention may be embodied as a computer readable medium (or
25 multiple computer readable media) (e.g., a computer memory, one or more floppy discs, compact discs, optical discs, magnetic tapes, flash memories, circuit configurations in Field Programmable Gate Arrays or other semiconductor devices, or other tangible computer storage medium) encoded with one or more programs that, when executed on one or more computers or other processors, perform methods that implement the various embodiments of the invention
30 discussed above. The computer readable medium or media can be transportable, such that the program or programs stored thereon can be loaded onto one or more different computers or other processors to implement various aspects of the present invention as discussed above.

In this respect, it should be appreciated that one implementation of the above-described embodiments comprises at least one computer-readable medium encoded with a computer
35 program (e.g., a plurality of instructions), which, when executed on a processor, performs some

or all of the above-discussed functions of these embodiments. As used herein, the term “computer-readable medium” encompasses only a computer-readable medium that can be considered to be a machine or a manufacture (i.e., article of manufacture). A computer-readable medium may be, for example, a tangible medium on which computer-readable information may be encoded or stored, a storage medium on which computer-readable information may be encoded or stored, and/or a non-transitory medium on which computer-readable information may be encoded or stored. Other non-exhaustive examples of computer-readable media include a computer memory (e.g., a ROM, a RAM, a flash memory, or other type of computer memory), a magnetic disc or tape, an optical disc, and/or other types of computer-readable media that can be considered to be a machine or a manufacture.

The terms “program” or “software” are used herein in a generic sense to refer to any type of computer code or set of computer-executable instructions that can be employed to program a computer or other processor to implement various aspects of the present invention as discussed above. Additionally, it should be appreciated that according to one aspect of this embodiment, one or more computer programs that when executed perform methods of the present invention need not reside on a single computer or processor, but may be distributed in a modular fashion amongst a number of different computers or processors to implement various aspects of the present invention.

Computer-executable instructions may be in many forms, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Typically the functionality of the program modules may be combined or distributed as desired in various embodiments.

Also, data structures may be stored in computer-readable media in any suitable form. For simplicity of illustration, data structures may be shown to have fields that are related through location in the data structure. Such relationships may likewise be achieved by assigning storage for the fields with locations in a computer-readable medium that conveys relationship between the fields. However, any suitable mechanism may be used to establish a relationship between information in fields of a data structure, including through the use of pointers, tags or other mechanisms that establish relationship between data elements.

Various aspects of the present invention may be used alone, in combination, or in a variety of arrangements not specifically discussed in the embodiments described in the foregoing and is therefore not limited in its application to the details and arrangement of components set forth in the foregoing description or illustrated in the drawings. For example, aspects described

in one embodiment may be combined in any manner with aspects described in other embodiments.

Also, the invention may be embodied as a method, of which an example has been provided. The acts performed as part of the method may be ordered in any suitable way.

5 Accordingly, embodiments may be constructed in which acts are performed in an order different than illustrated, which may include performing some acts simultaneously, even though shown as sequential acts in illustrative embodiments.

For the purposes of describing and defining the present disclosure, it is noted that terms of degree (e.g., “substantially,” “slightly,” “about,” “comparable,” etc.) may be utilized herein to
10 represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. Such terms of degree may also be utilized herein to represent the degree by which a quantitative representation may vary from a stated reference (e.g., about 10% or less) without resulting in a change in the basic function of the subject matter at issue. Unless otherwise stated herein, any numerical values appeared in this
15 specification are deemed modified by a term of degree thereby reflecting their intrinsic uncertainty. The “substantially simultaneous response” means responses measured within 1 second of one another.

Use of ordinal terms such as “first,” “second,” “third,” etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element
20 over another or the temporal order in which acts of a method are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of “including,” “comprising,” or “having,”
25 “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

Any materials that have been incorporated by reference are incorporated by reference herein in their entirety except as otherwise indicated specifically with respect to such material and only to the extent that the incorporated materials are not inconsistent herewith. As such, and
30 to the extent necessary, the disclosure as explicitly set forth herein supersedes any conflicting material incorporated herein by reference. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosure material set forth herein will only be incorporated to the extent that no conflict arises between that incorporated material and the existing disclosure material.

CLAIMS

What is claims is:

1. A system comprising:

- 5 a first sensor;
 a second sensor;
 a first mounting arc rigidly holding the first sensor at a first radius;
 a second mounting arc rigidly holding the second sensor at the first radius, wherein the
first and second mounting arcs are concentric about an axis, and a first center of the first sensor
10 is at a different angular position about the axis relative to a second center of the second sensor;
and
 a scanner, holding the first and second mounting arc, having a plurality of wheels, at
least one wheel having a suspension for moving the wheel radially relative to the axis.

15 2. The system of claim 1, wherein the first sensor is an eddy current array sensor having a drive
winding common to an array of sensing elements.

3. The system of claim 2, wherein each sensing element in the array of sensing elements is at a
same distance from the drive winding.

20 4. The system of claim 2, wherein the second sensor is also an eddy current array having a same
design as the first sensor.

5. The system of claim 4, wherein an angular extent of the array of sensing elements of the first
25 sensor overlaps with an angular extent of the array of sensing element of the second sensor.

6. The system of claim 2, further comprising an instrument for providing power to the drive
winding and measuring electrical responses from the array of sensing elements.

30 7. The system of claim 1, wherein the first and second mounting arcs form a first set, the system
further comprising:
 a second set of mounting arcs having a second radius different from the first radius,
wherein the second set is interchangeable with the first set.

8. A method of inspecting a cylindrical test object having an electrically insulating exterior surface layer and an electrically conducting interior layer, the method comprising acts of:

(i) providing a system having

a first sensor;

a second sensor;

a first mounting arc rigidly holding the first sensor at a first radius;

a second mounting arc rigidly holding the second sensor at the first radius,

wherein the first and second mounting arcs are concentric about an axis, and a first center of the first sensor is at a different angular position about the axis relative to a

second center of the second sensor; and

a scanner, holding the first and second mounting arc, having a plurality of wheels, at least one wheel having a suspension for moving the wheel radially relative to the axis;

(ii) securing the system to the cylindrical test object such that the first second sensors are

concentric with the cylindrical test object;

(iii) moving the scanner in a scan direction along the cylindrical test object;

(iv) during the moving, measuring sensor responses from the sensors; and

(v) characterizing a condition of the electrically conducting interior layer based on the sensor responses.

9. The method of claim 8, wherein the act of characterizing comprises converting the sensor response at each of a plurality of sensing elements into a measure of the properties of the electrically conducting interior layer.

10. The method of claim 8, wherein

the act (v) comprises storing a precomputed database modeling sensor responses over a range of sensor liftoffs; and

the act (ii) the plurality of wheels ride along the surface of the cylindrical test object and the arcs are held at a distance from the cylindrical test object such that the liftoff is within the range.

11. The method of claim 8, wherein

the electrically conducting interior layer of the cylindrical test object is an outer armor layer and the cylindrical test object further comprises an inner armor layer concentric with and nested within the first armor layer;

the act (iv) the sensors are excited at a plurality of frequencies and sensor responses are measured at each frequency; and

the act (v) a sensor response at a higher frequency is utilized to characterize the outer armor layer, and a sensor response at a lower frequency is utilized to characterize the inner armor layer.

12. The method of claim 8, wherein the electrically conducting interior layer of the cylindrical test object is an outer armor layer and the cylindrical test object further comprises an inner armor layer concentric with and nested within the first armor layer, the method further comprising:

generating a precomputed database of sensor responses with a model that accounts for the presence of the outer armor layer, the inner armor layer, and the electrically insulating exterior surface layer.

13. The method of claim 12, wherein the act of generating, the model includes at least one additional electrically conducting layer.

14. The method of claim 8, wherein

the electrically conducting interior layer of the cylindrical test object is an outer armor layer formed by a plurality of helically wrapped riser wires; and

the first sensor is an eddy current array sensor having a drive winding common to an array of sensing elements, the drive winding oriented at a same angle as the helically wrapped riser wires.

15. A system for inspecting a cylindrical test object having an electrically insulating exterior surface layer and an electrically conducting interior layer, the system comprising:

a plurality of conformable sensors;

a plurality of conformable arcs for holding the conformable sensors;

a plurality of wheels for riding along the cylindrical test object, the wheels connected to the plurality of conformable arcs and enabling the plurality of sensors to maintain a shape that follows the curvature of the cylindrical test object, wherein the arcs allow for continuous adjustment to the external shape; and

a data analysis module to characterize the cylindrical test object based on measurements from the plurality of sensors, wherein the data analysis module assumes that the plurality of sensors maintain a concentric shape relative to an axis of the cylindrical test object.

16. A flat riser test bed intended to simulate inspection of cylindrical flexible pipe, the test bed comprising

one layer of riser wire this is long and rectangular in shape in a single plane with minimal gap between riser wires, where the riser wires are cut to a length ending at the edge of a square platform where the platform provides a rigid base for the test bed; and

a means for adding electrically insulating layers above the riser wire layer to simulate electrically insulating material on a flexible pipe.

17. The test bed of claim 16, where a second riser wire layer is included in the same orientation as the first riser wire layer for convenient removal of riser wires.

18. The test bed of claim 16, where a second riser wire layer is included in a different orientation, where the orientation of the two riser wire layers is approximately the same as the armor wire layers in a flexible pipe.

19. The test bed of claim 16, wherein a sensor can be located in the approximate center of the square test bed and a wire failure can be simulated by providing a gap between two rectangular cross section wires, where the gap is moved under the sensor in the first or second wire layer by pushing a second wire in the same location as the first wire keeping the gap approximately constant by the two wires, wherein insulating layers are used between the sensor and the outer wire layer to simulate the thickness of an outer electrically insulating layer on a riser.

20. The test bed of claim 16, wherein a riser wire failure is simulated by using two wires and a small gap located approximately in the center of the test bed in either the outer or inner wire layer, where a sensor is moved from one end of the test bed to the other in a path that includes the simulated wire failure, wherein insulating layers are used between the sensor and the outer wire layer to simulate the thickness of an outer electrically insulating layer on a riser.

21. The test bed of claim 16, where a system is used with software to detect riser wire failures where the system is intended to detect failures on either or flat or cylindrical shaped test objects and the data from the flat test bed is used to validate the intended inspection on a cylindrically shaped test object.

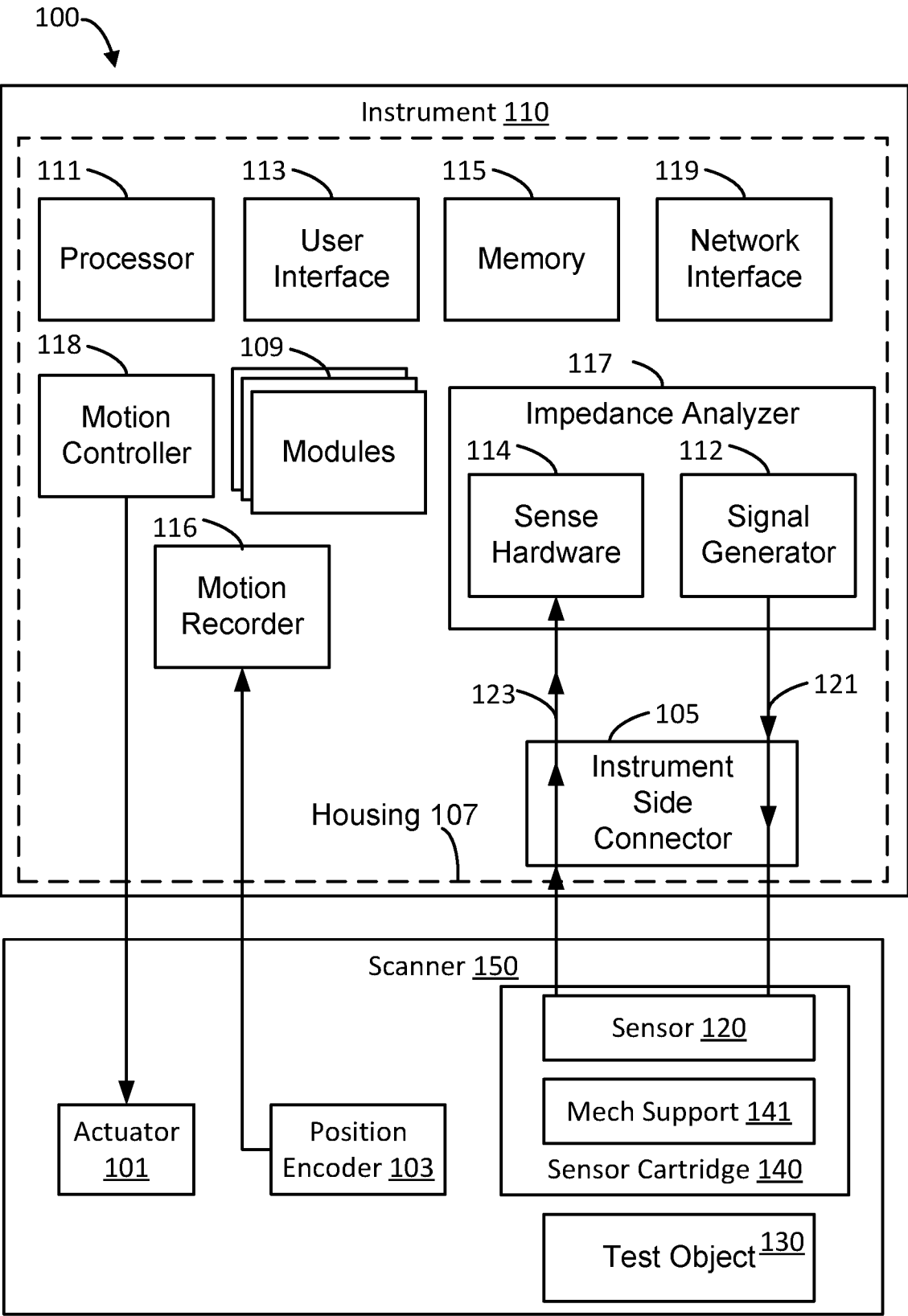


FIG. 1A

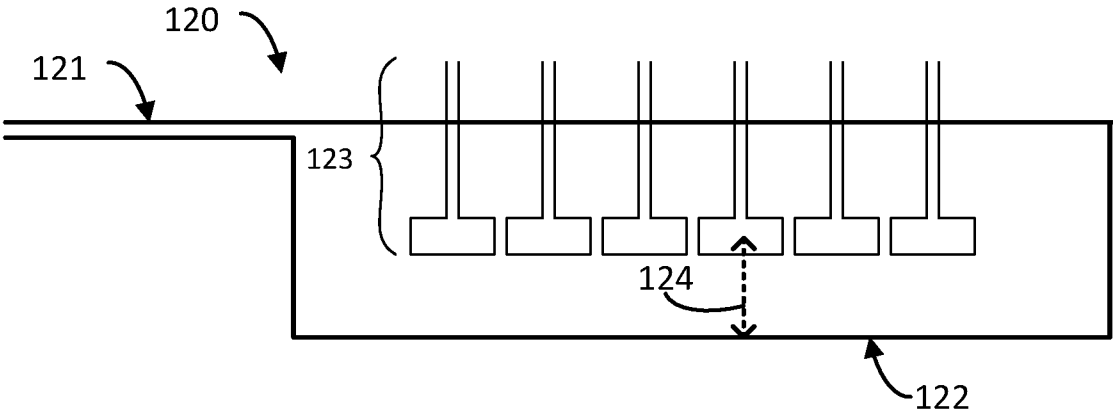


FIG. 1B

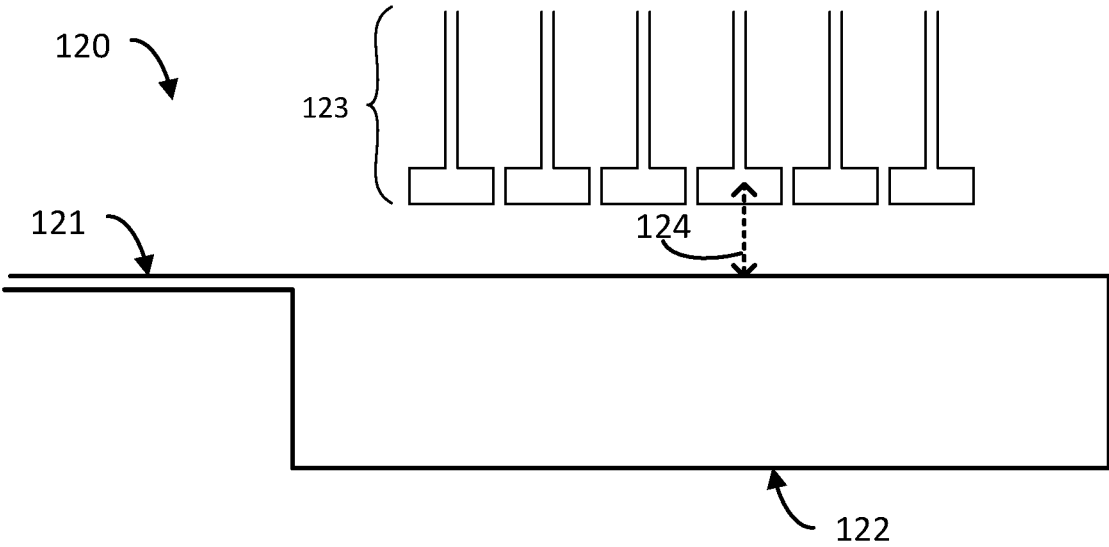


FIG. 1C

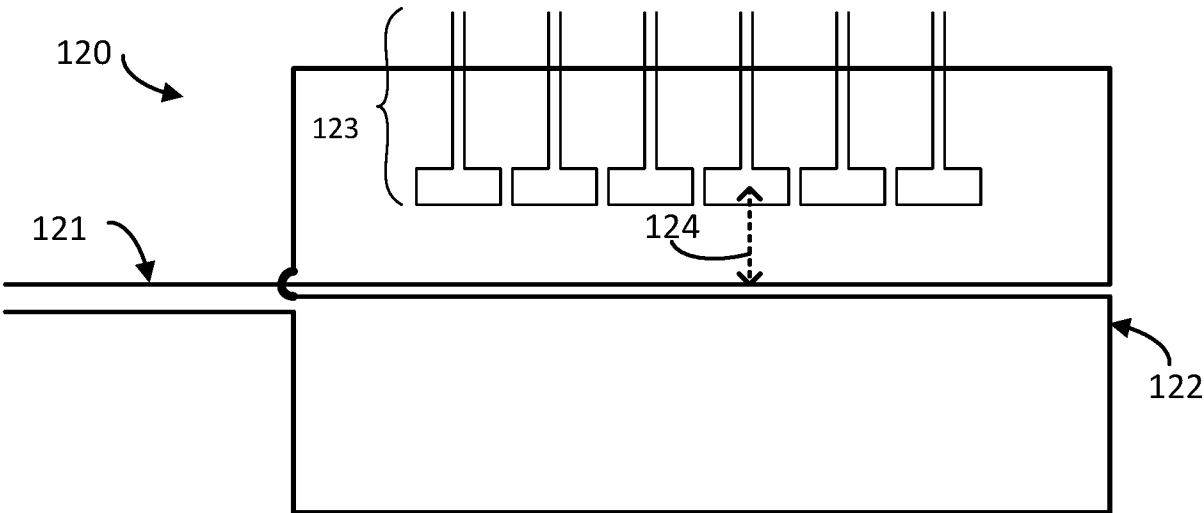


FIG. 1D

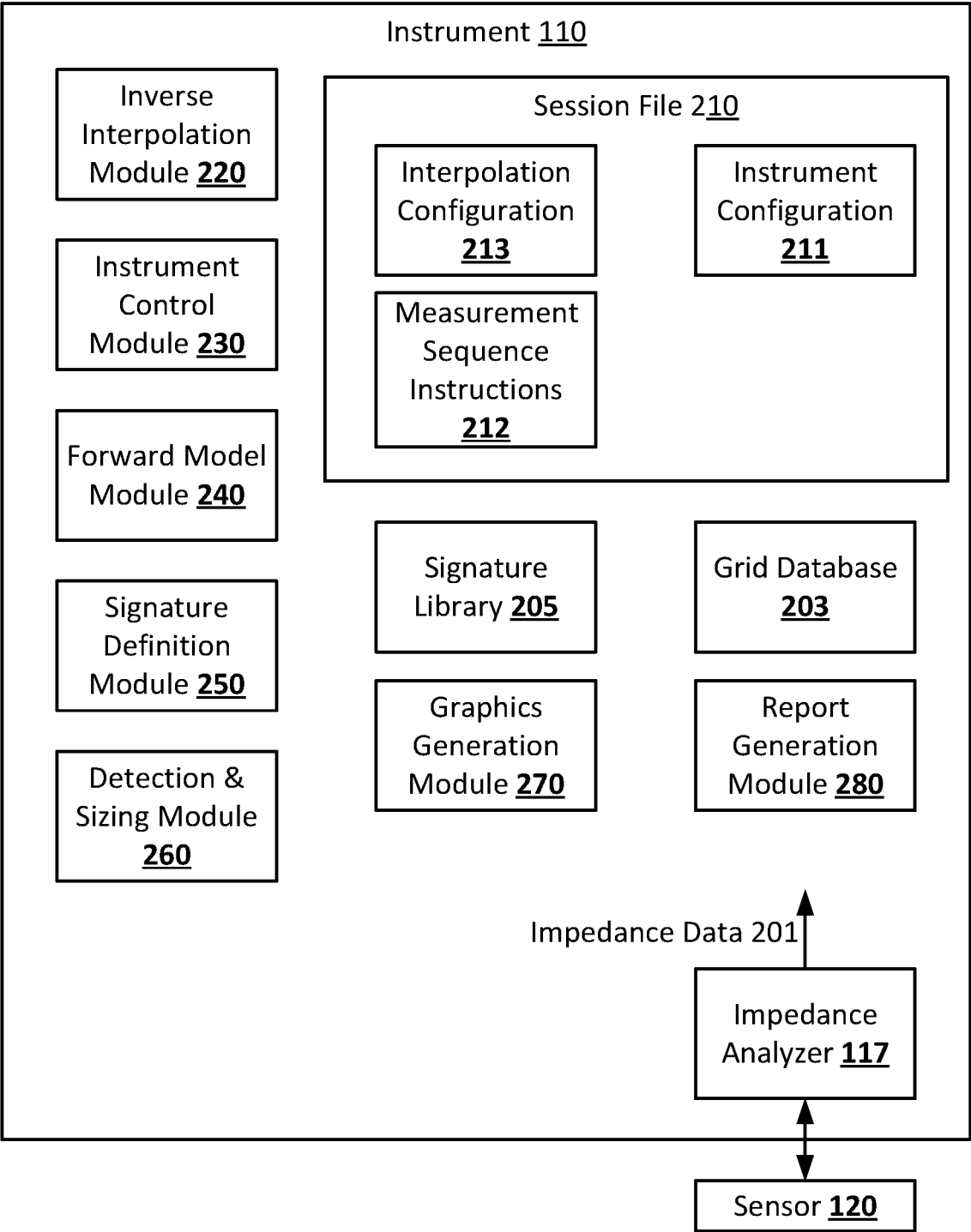


FIG. 2

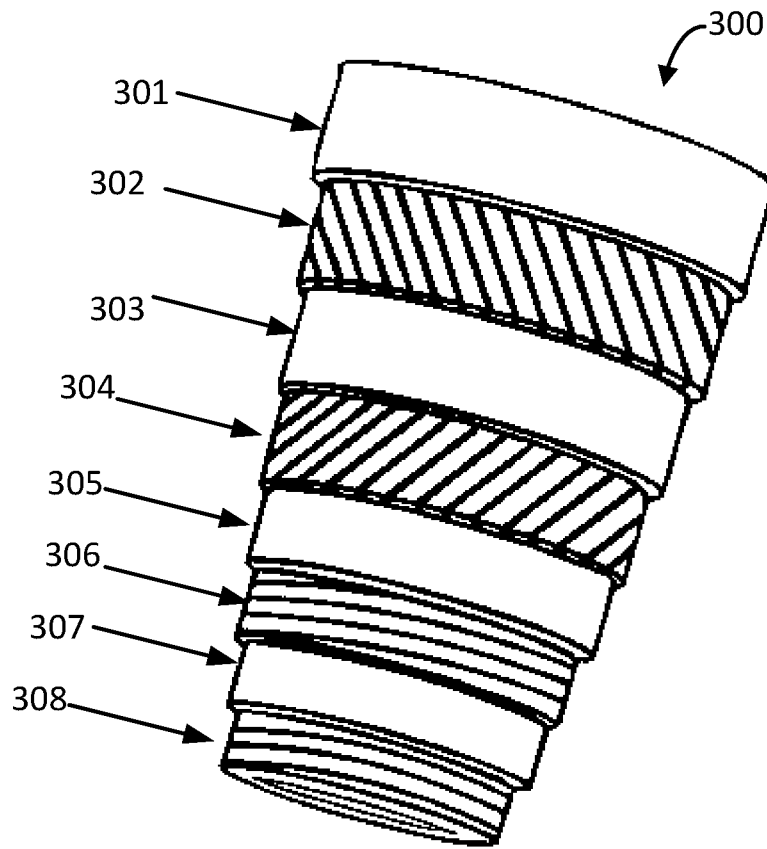


FIG. 3

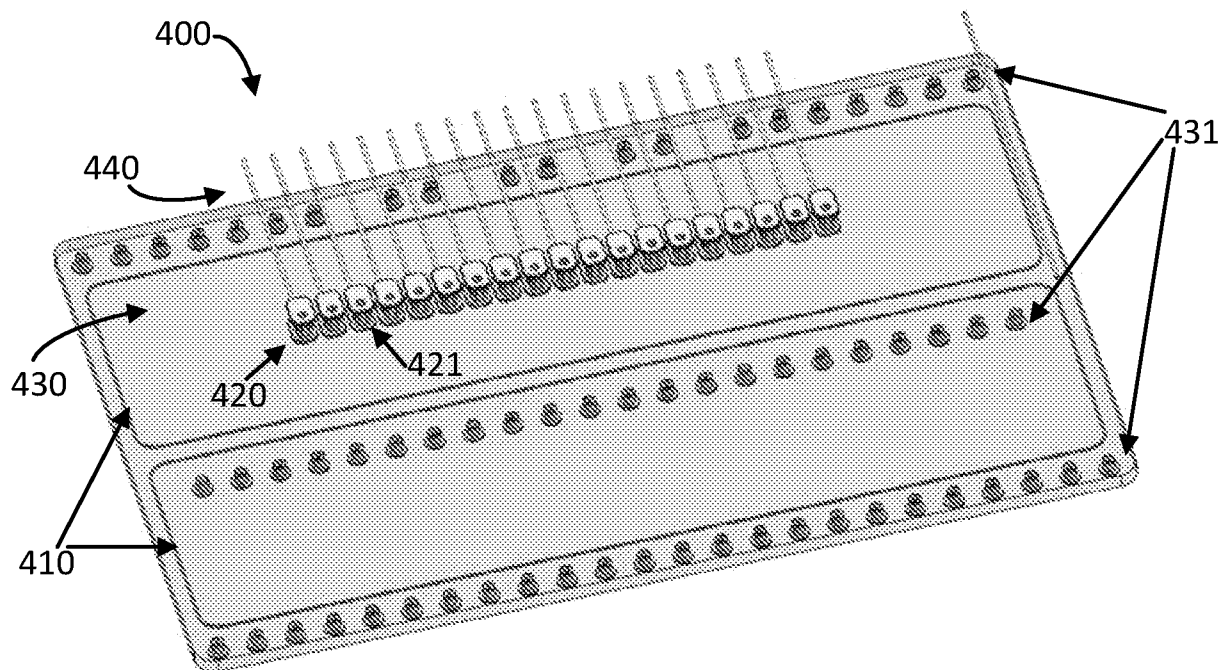


FIG. 4

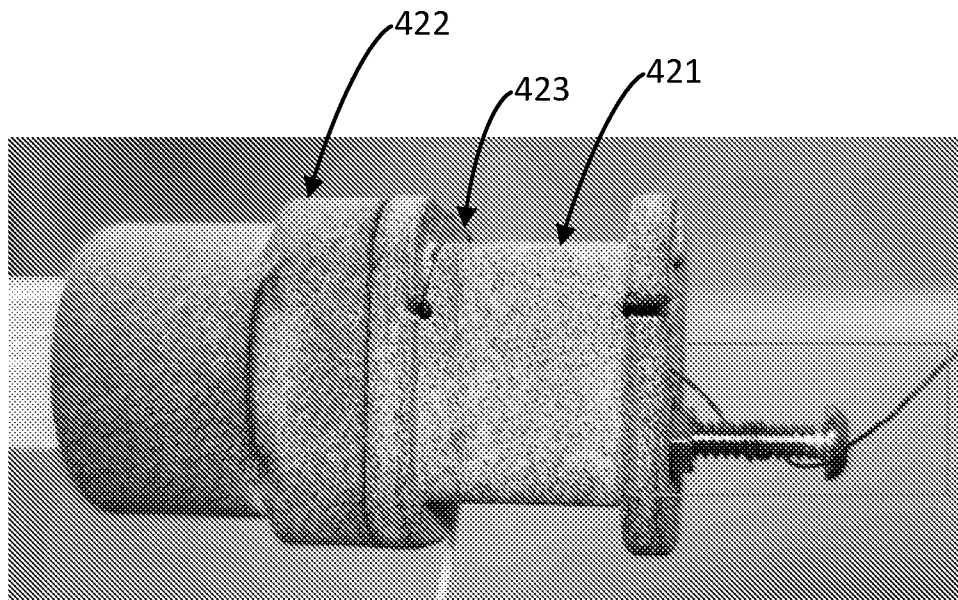


FIG. 5A

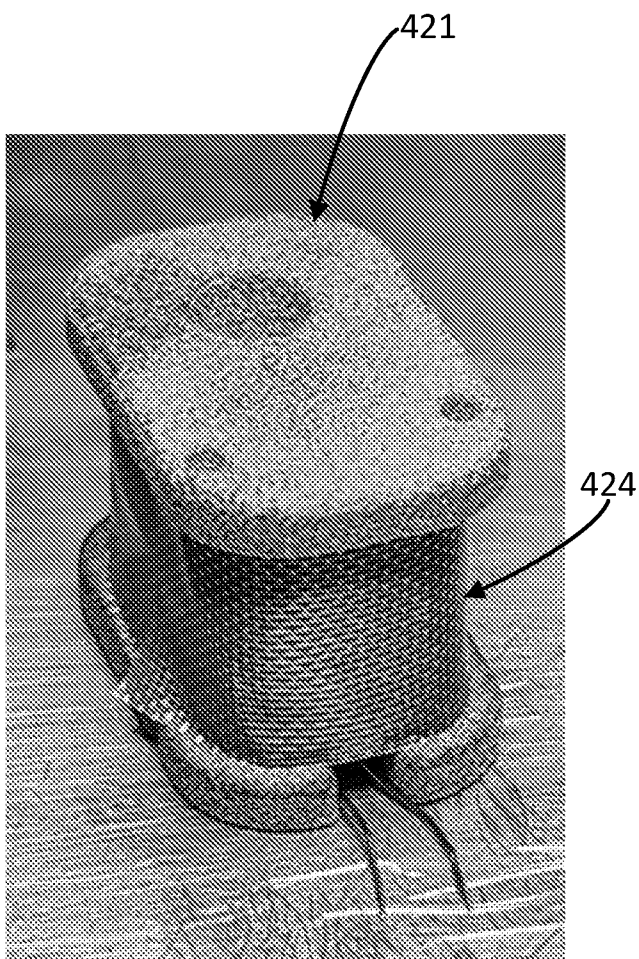


FIG. 5B

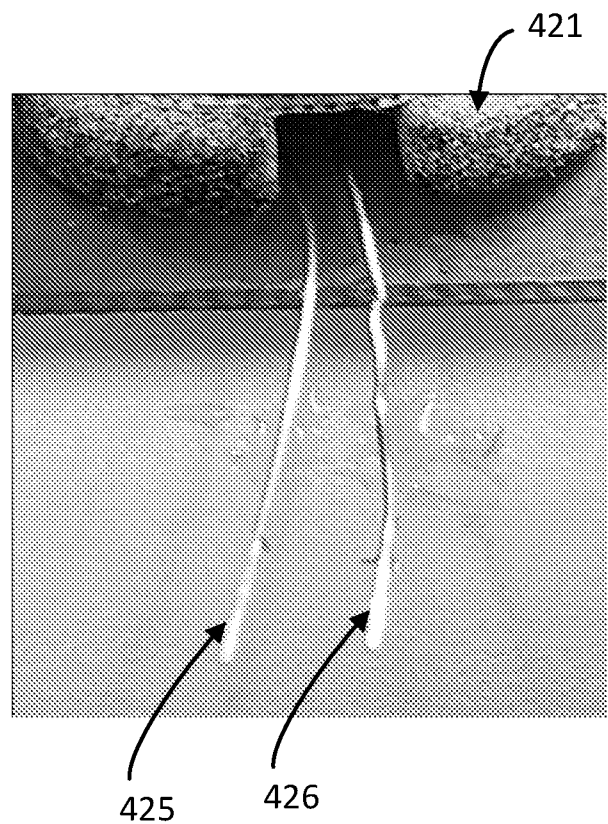


FIG. 5C

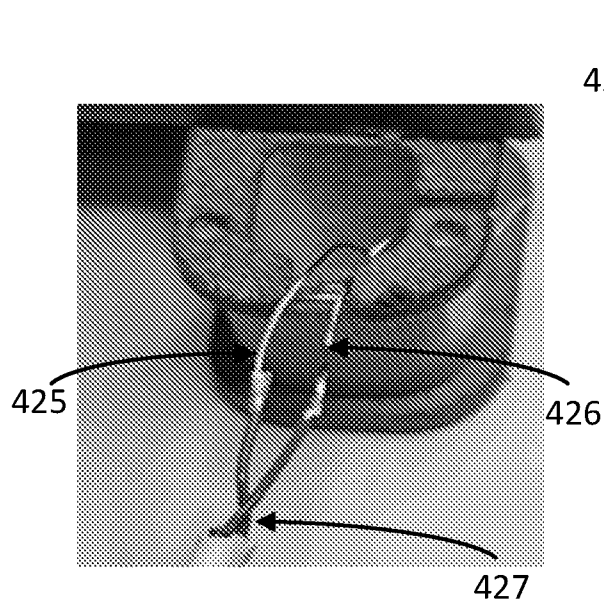


FIG. 5D

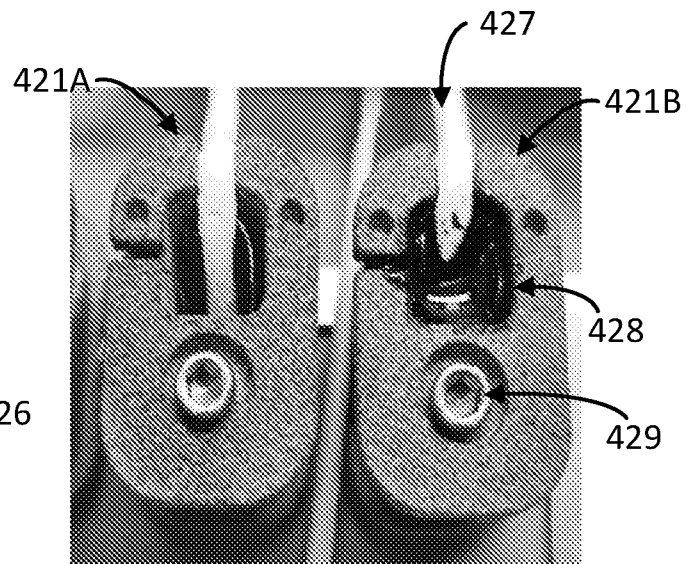


FIG. 5E

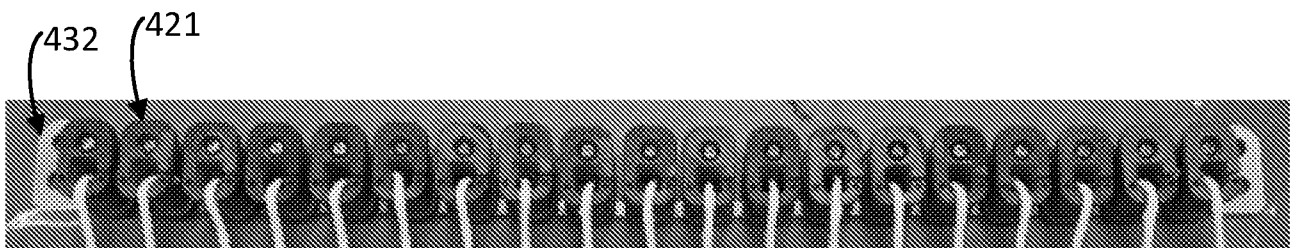


FIG. 5F

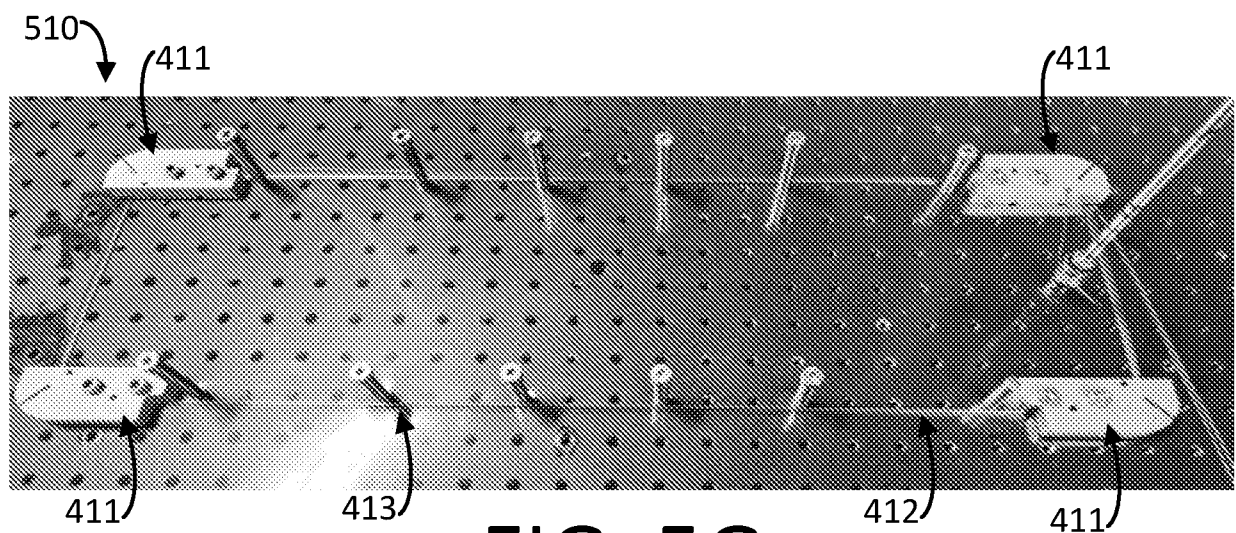


FIG. 5G

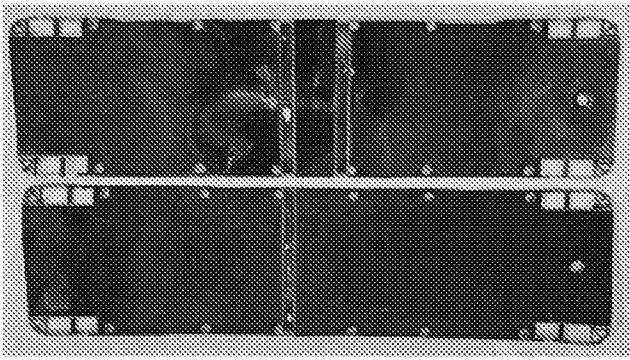


FIG. 5H

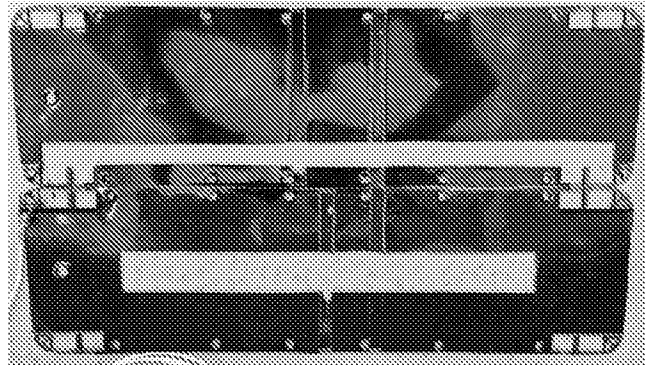


FIG. 5I

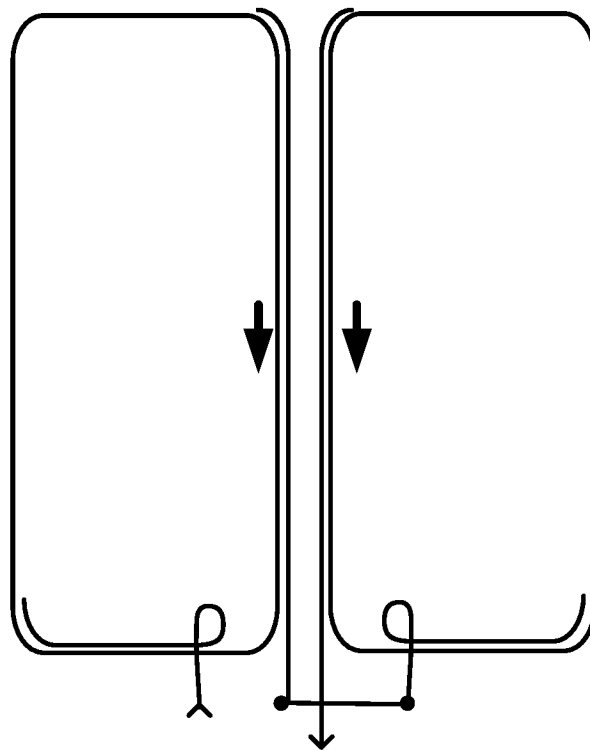


FIG. 5J

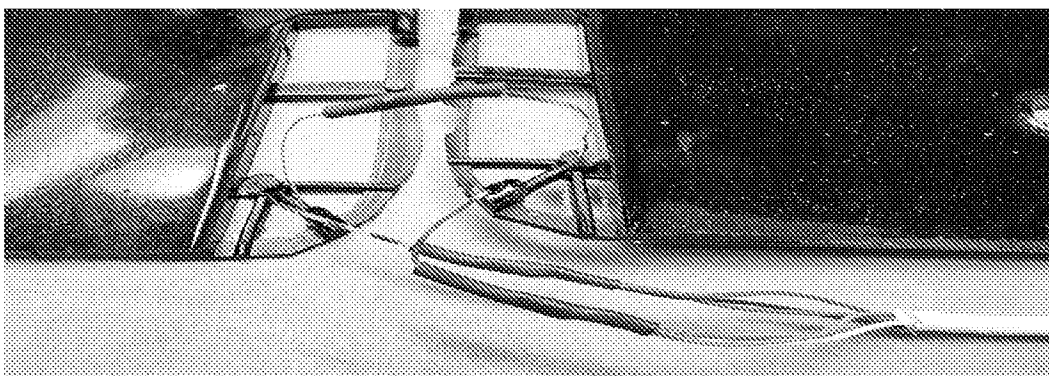


FIG. 5K

FIG. 5L

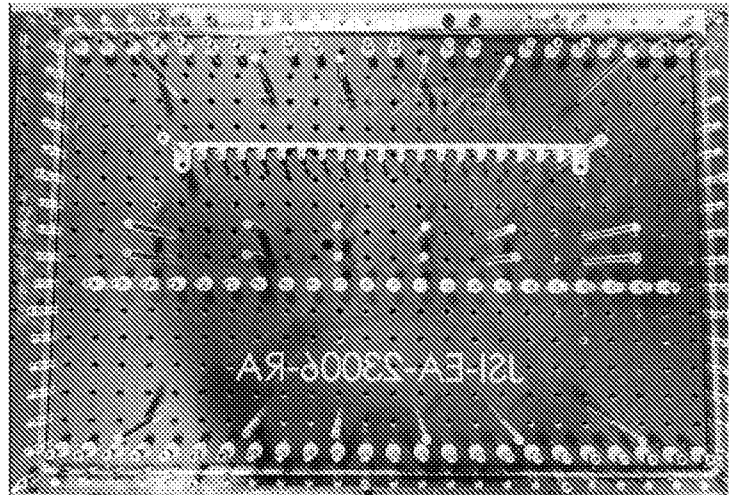


FIG. 5M

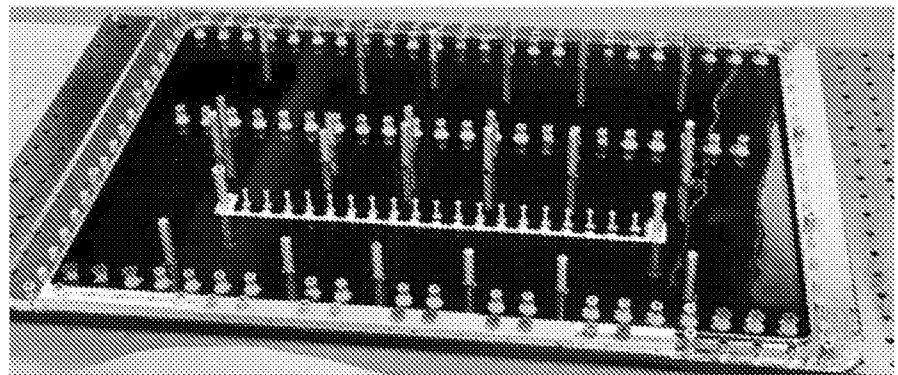


FIG. 5N

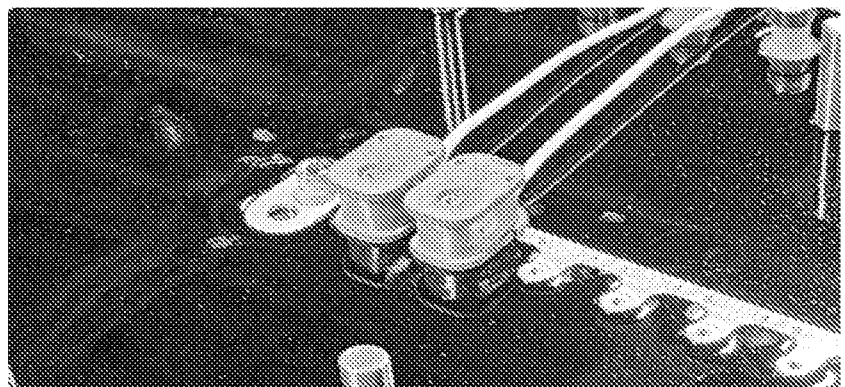
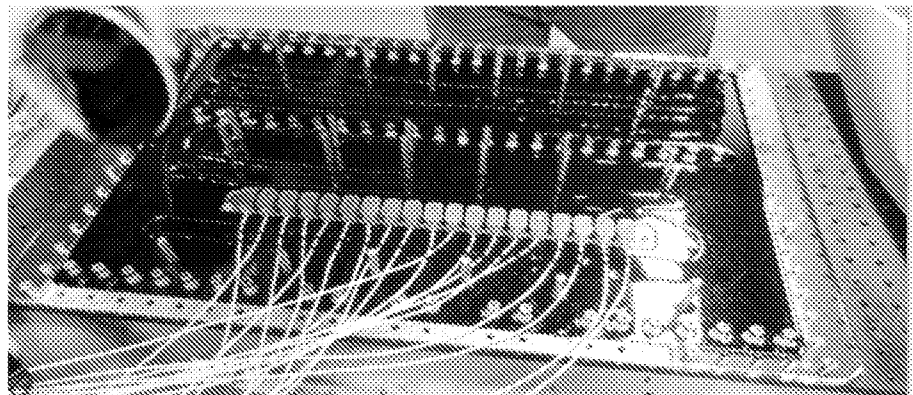


FIG. 5O



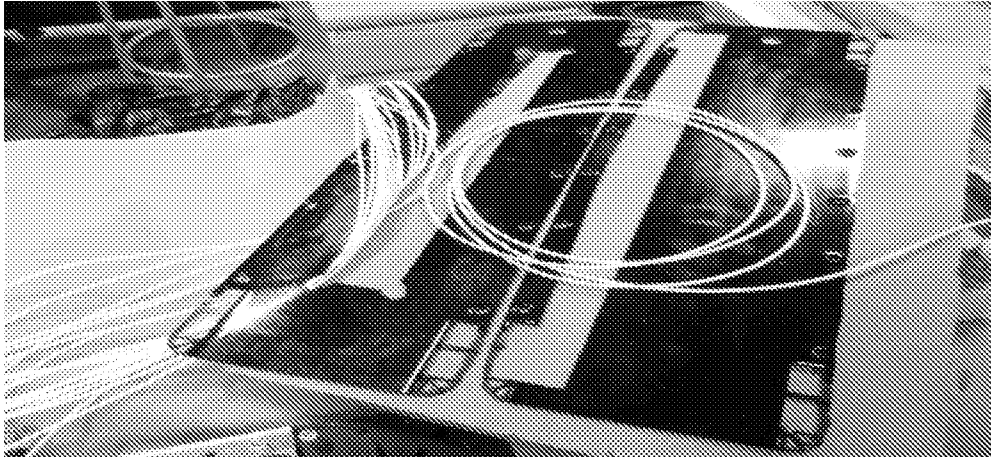


FIG. 5P

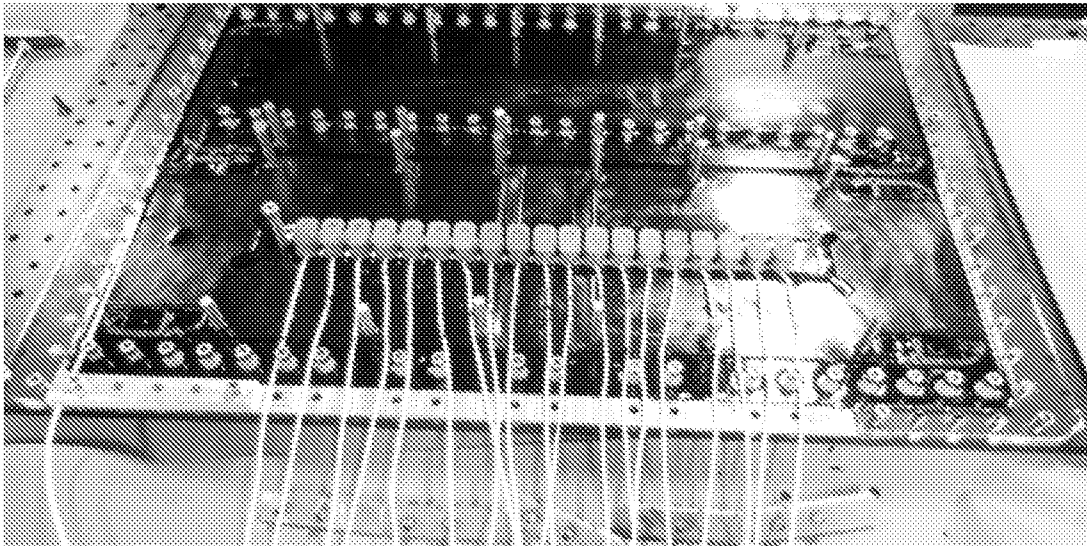


FIG. 5Q

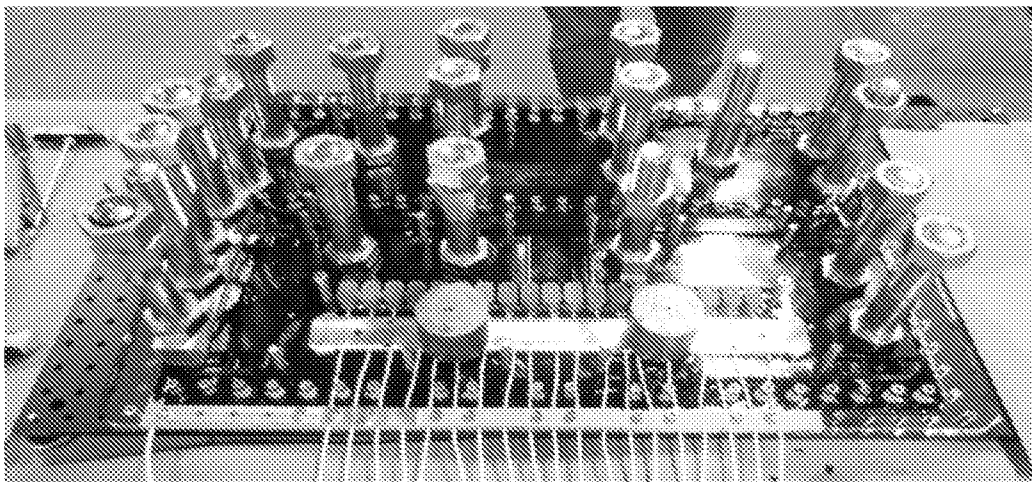


FIG. 5R

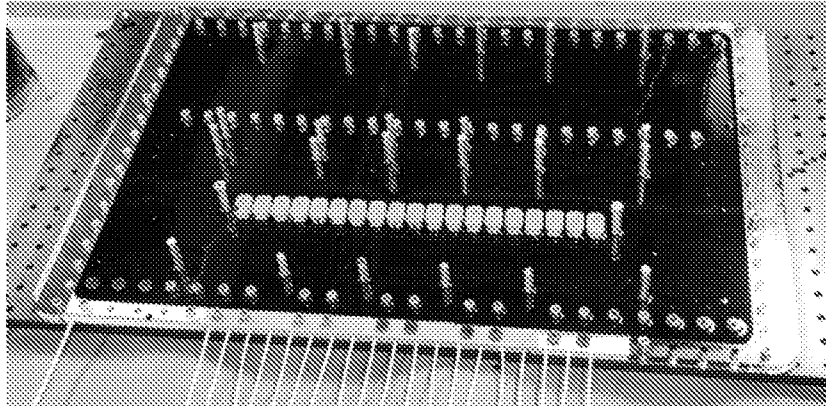


FIG. 5S

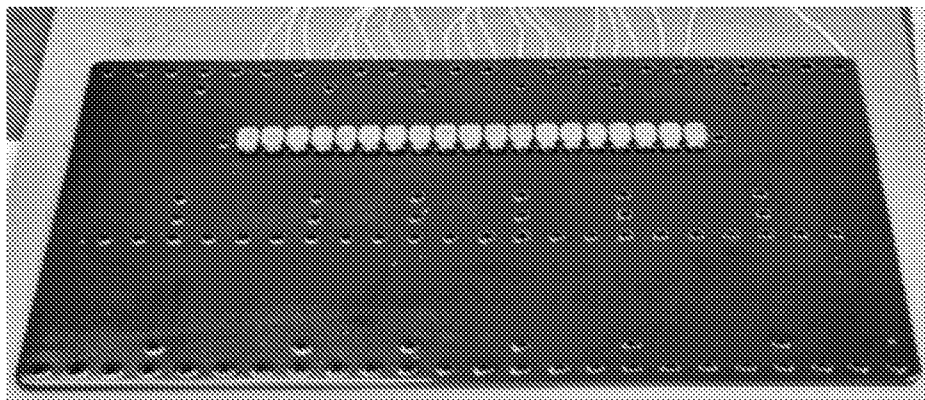


FIG. 5T

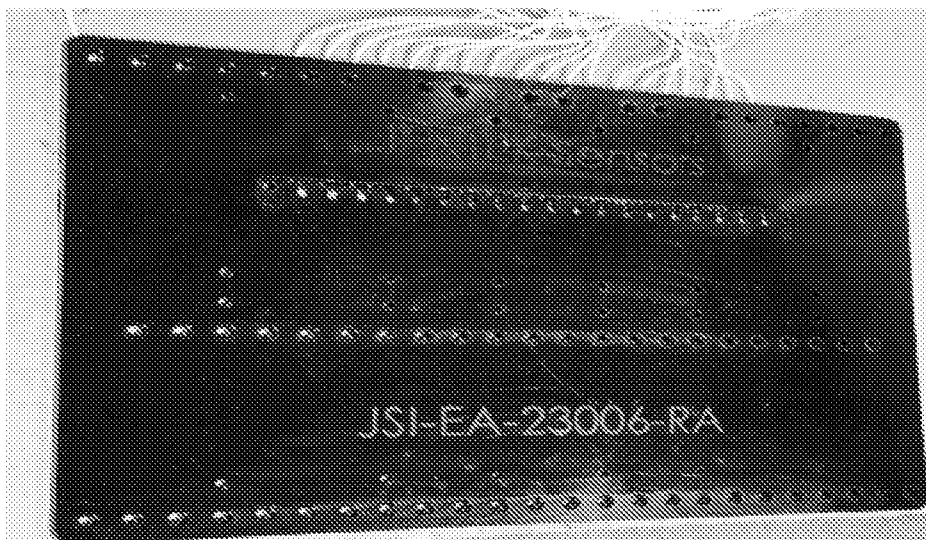


FIG. 5U

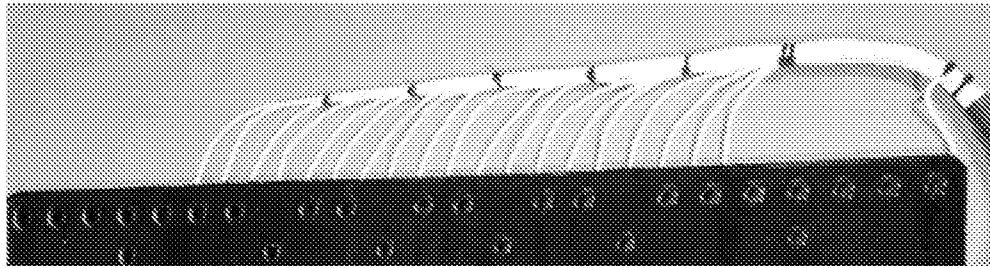


FIG. 5V

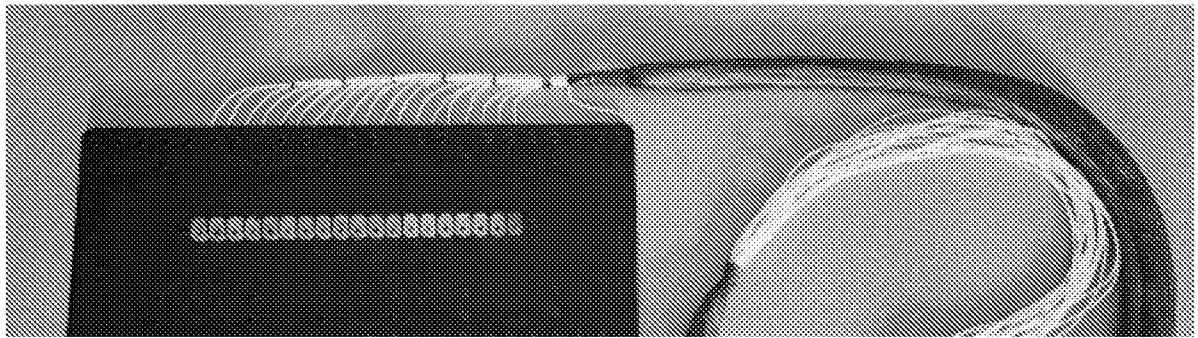


FIG. 5W

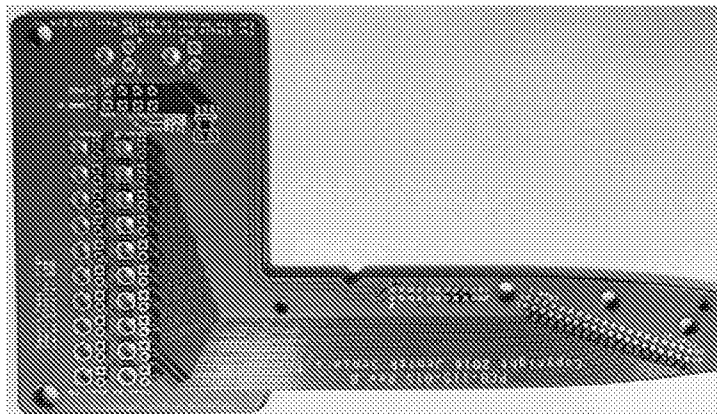


FIG. 5X

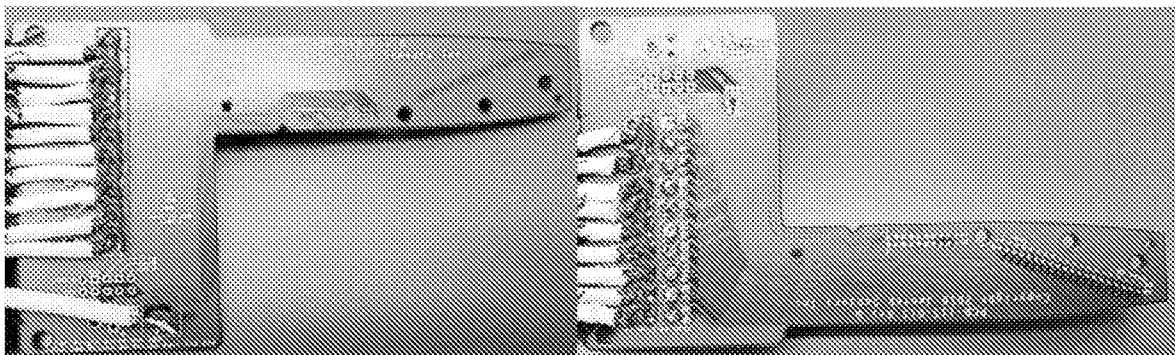


FIG. 5Y

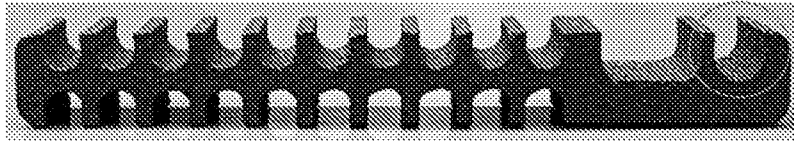


FIG. 5Z

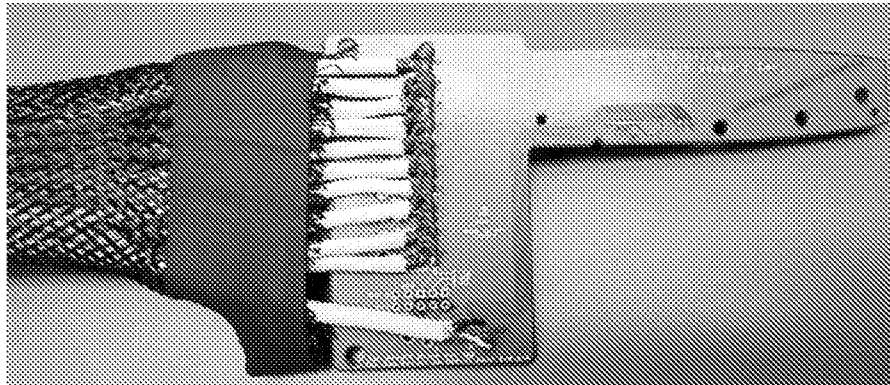


FIG. 5AA

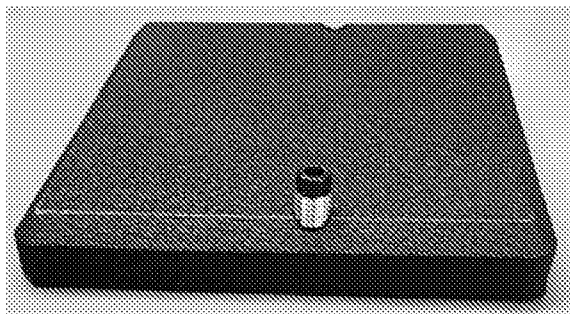


FIG. 5AB



FIG. 5AC

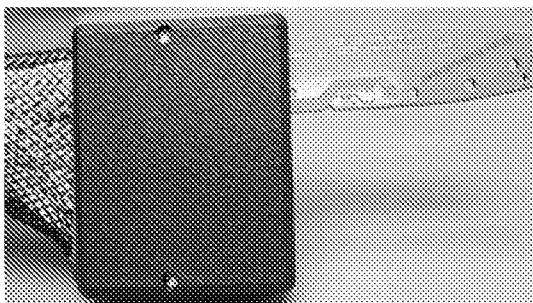


FIG. 5AD

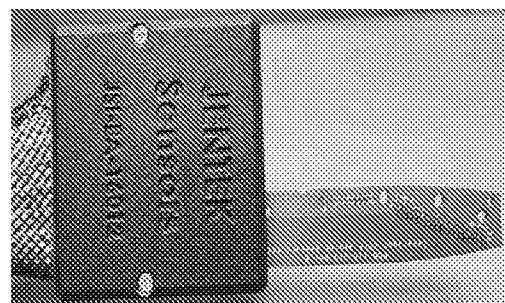


FIG. 5AE

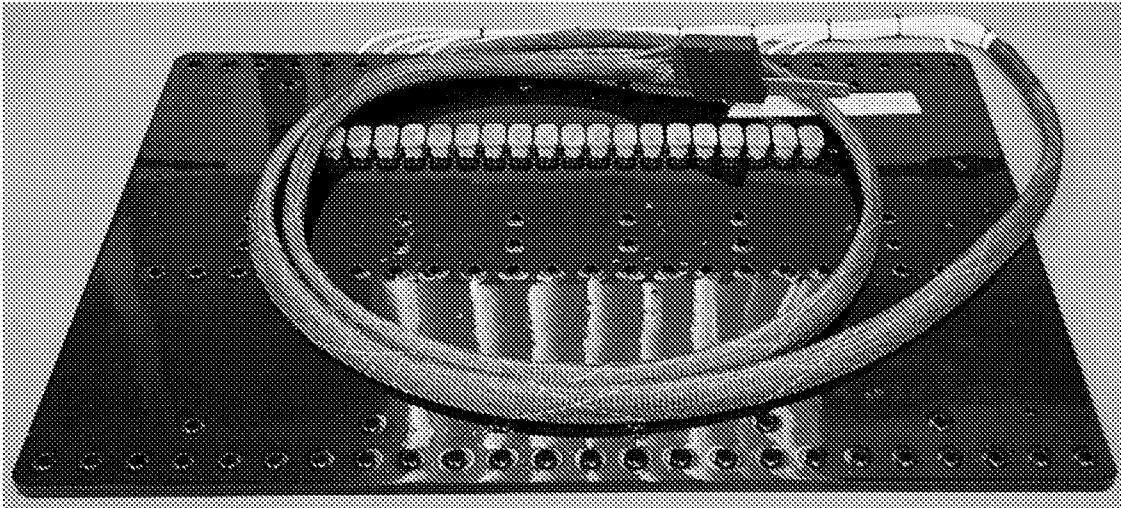


FIG. 5AF

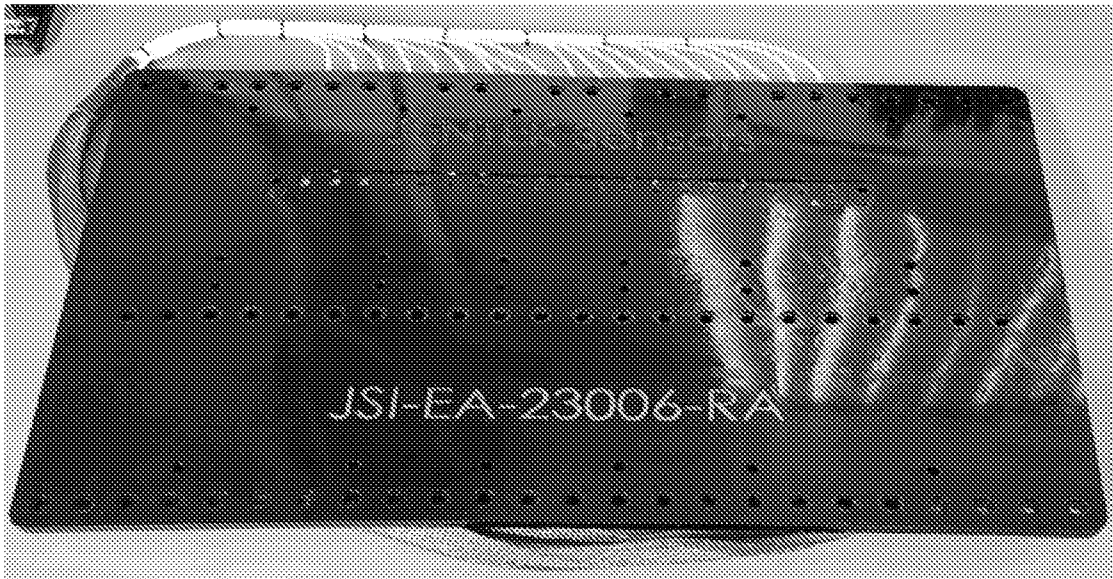


FIG. 5AG

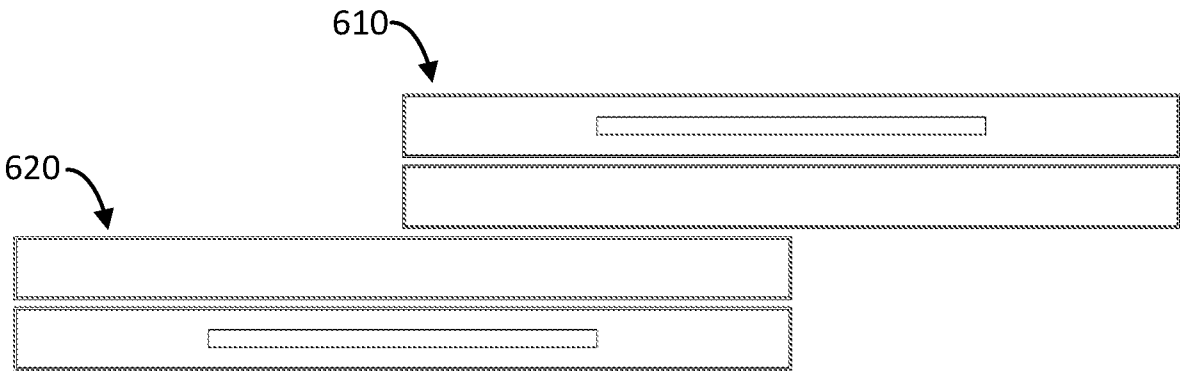


FIG. 6A

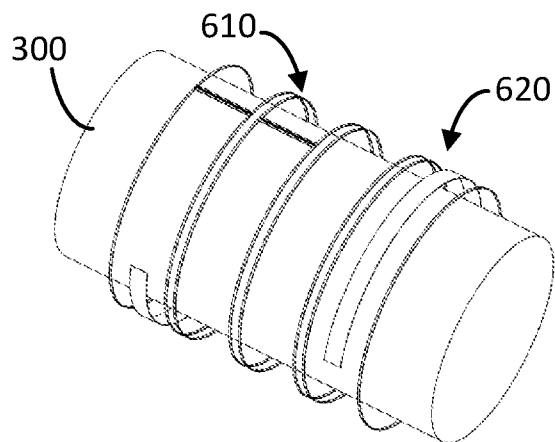


FIG. 6B

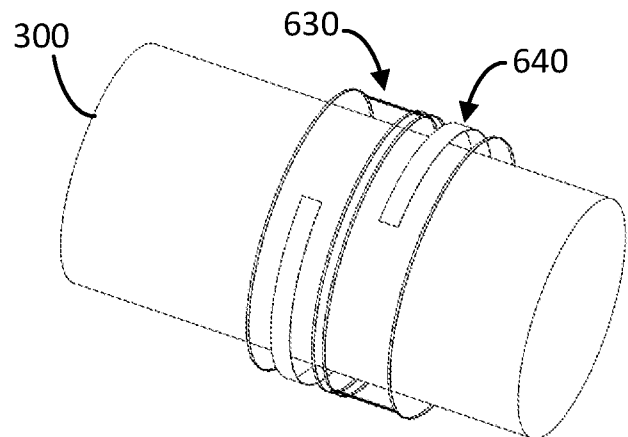


FIG. 6D

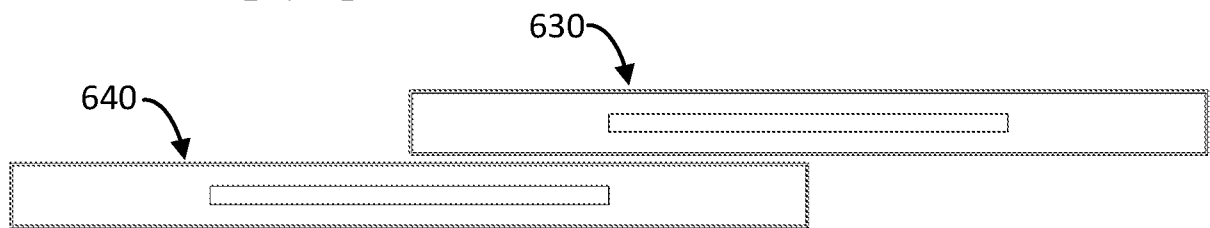


FIG. 6C

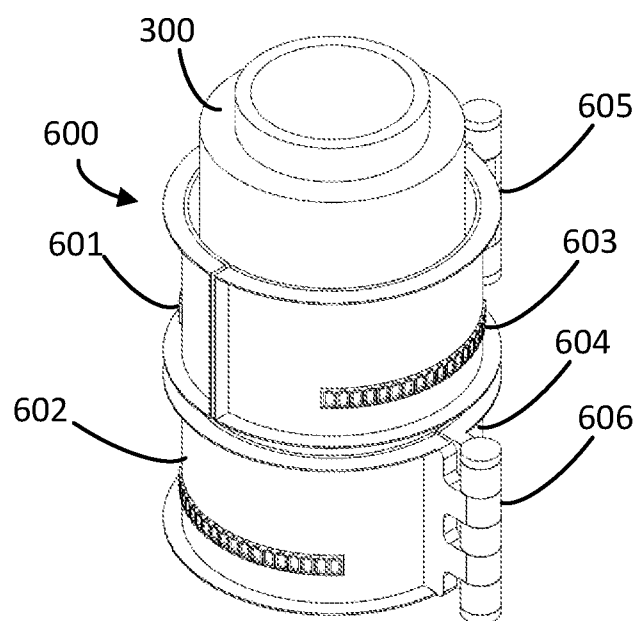


FIG. 6E

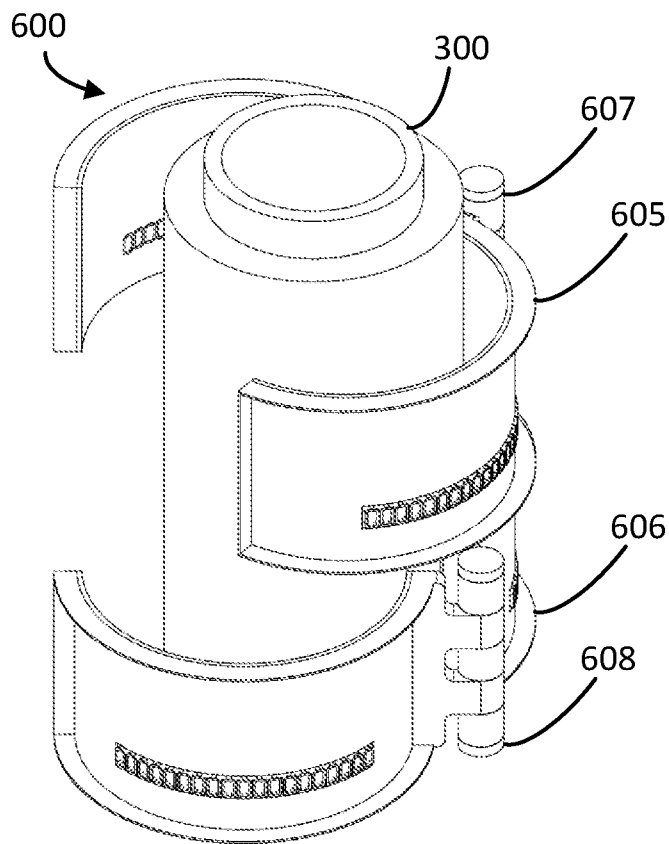


FIG. 6F

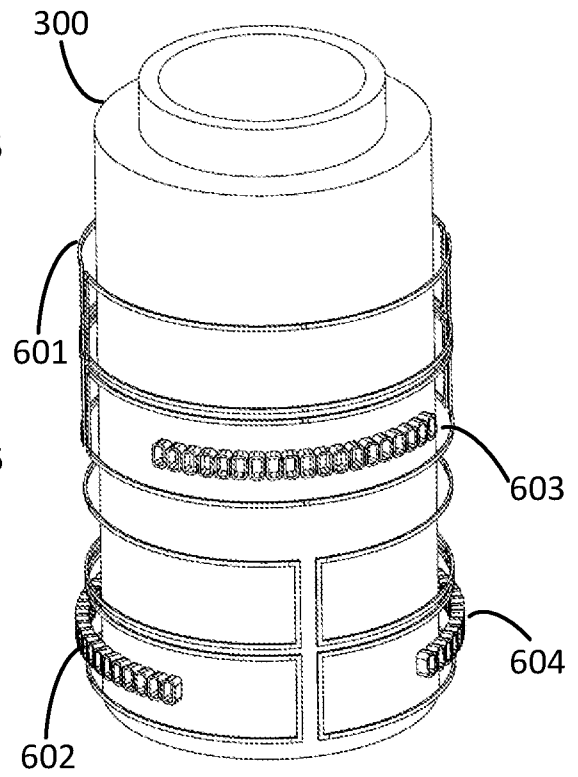


FIG. 6G

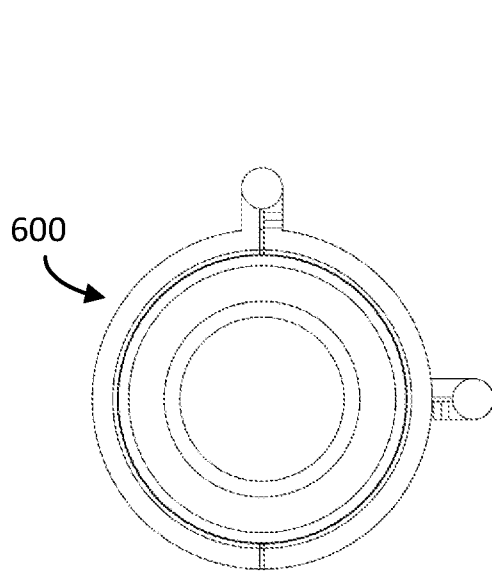


FIG. 6H

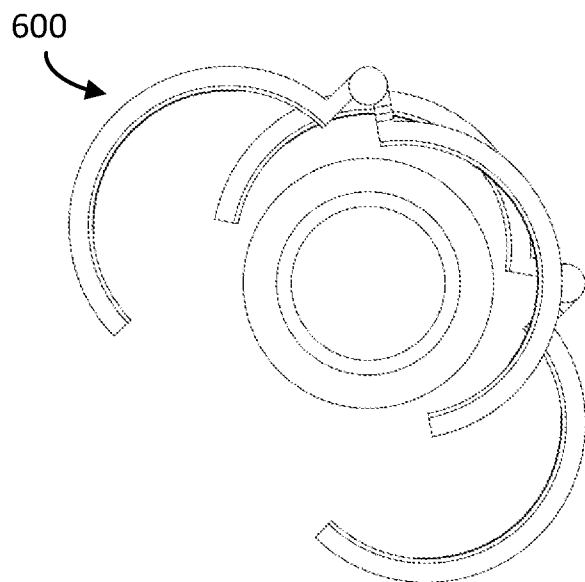


FIG. 6I

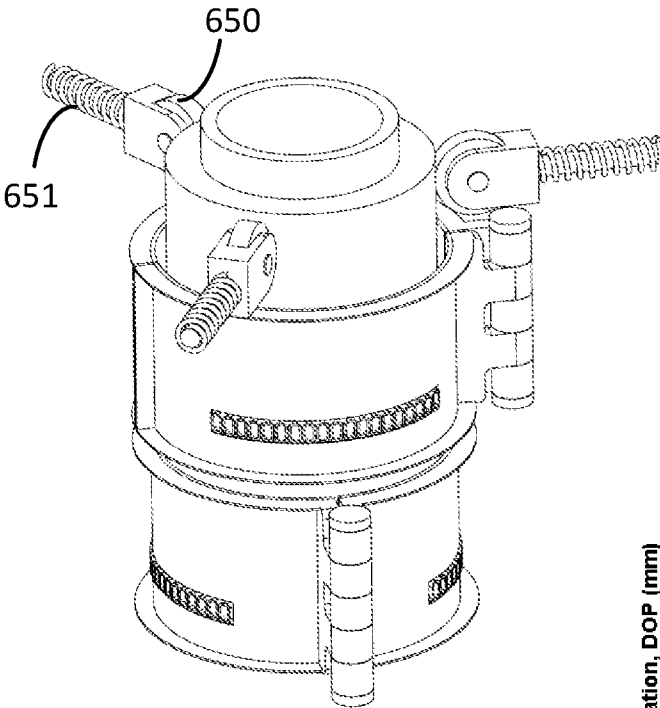


FIG. 6J

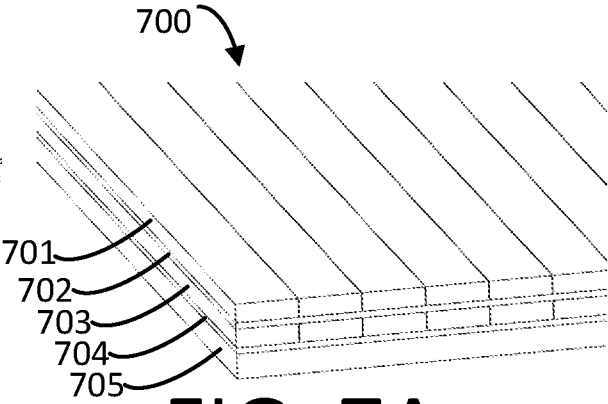


FIG. 7A

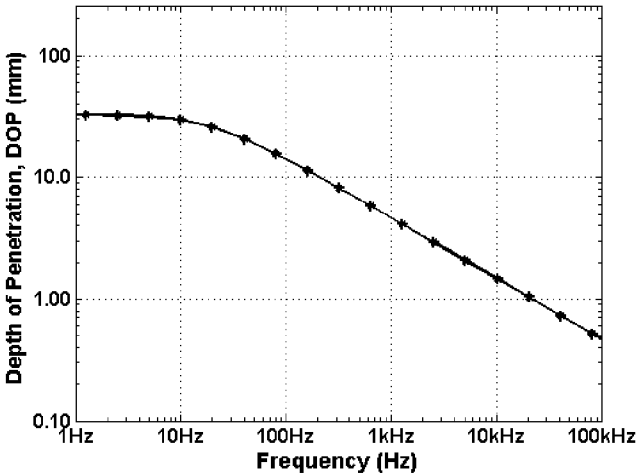


FIG. 7B

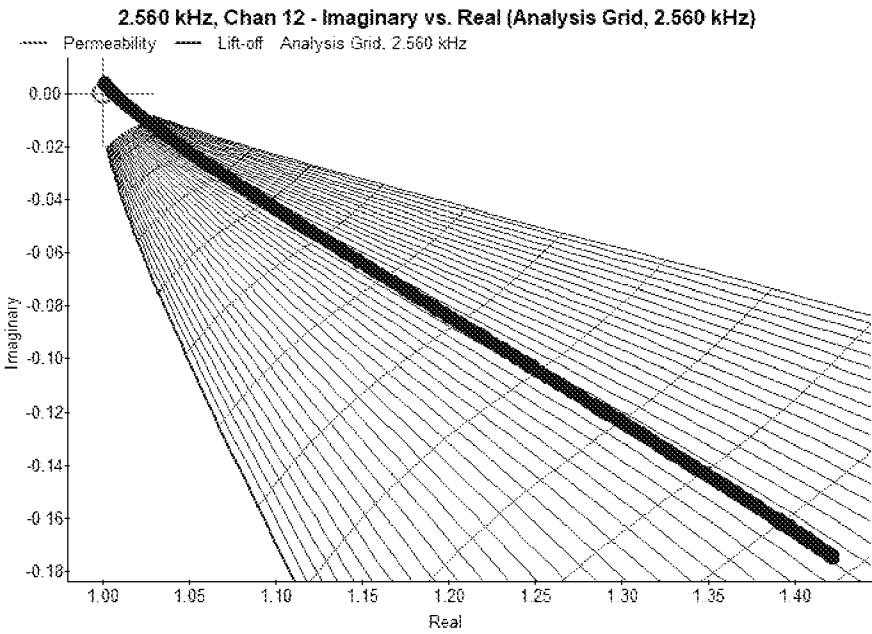


FIG. 7C

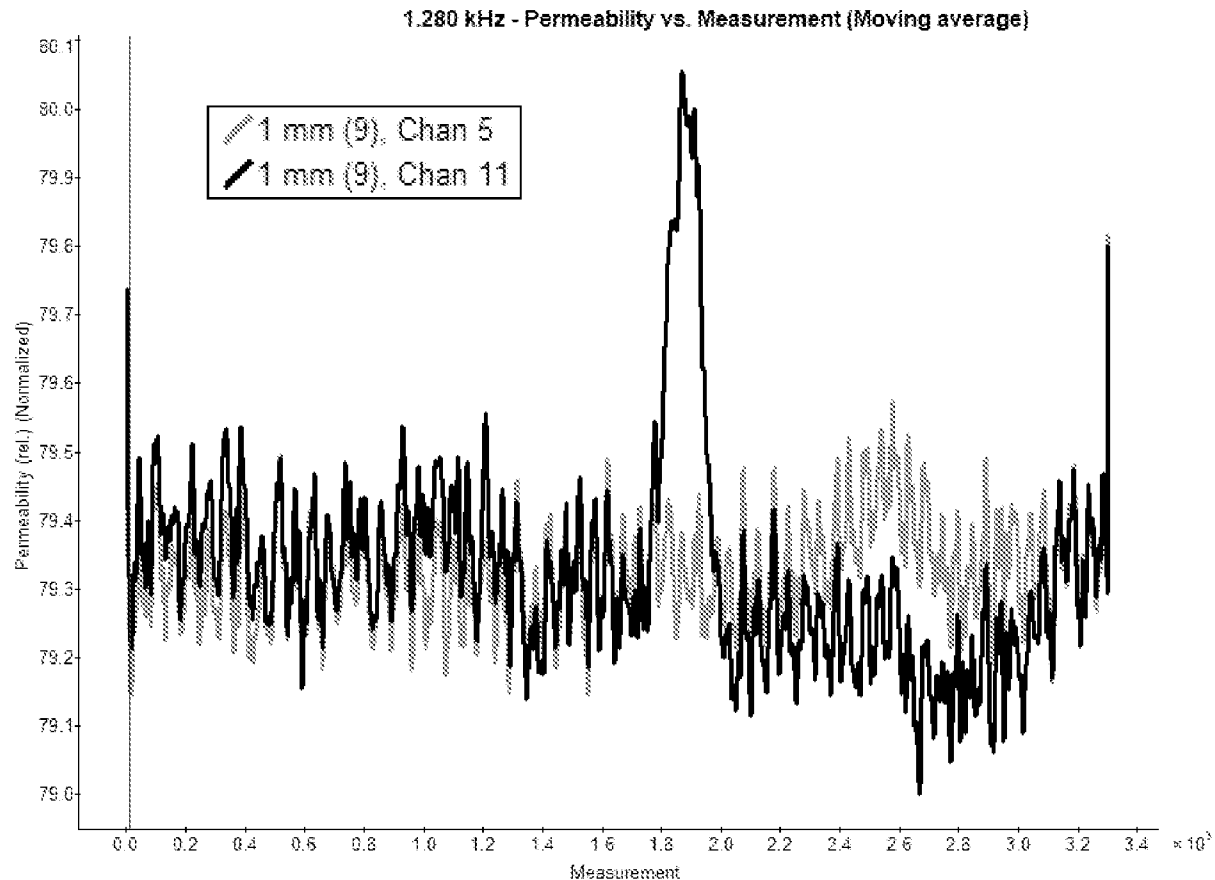


FIG. 7D

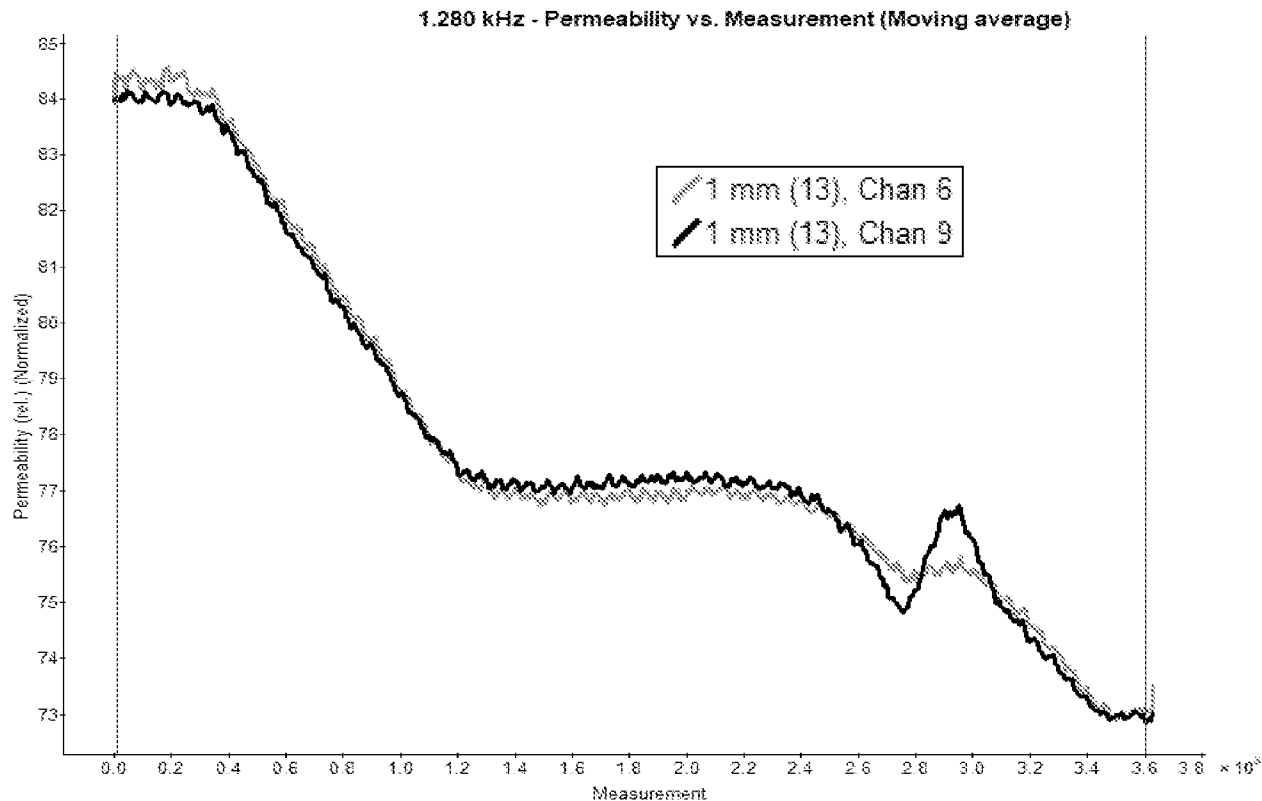


FIG. 7E