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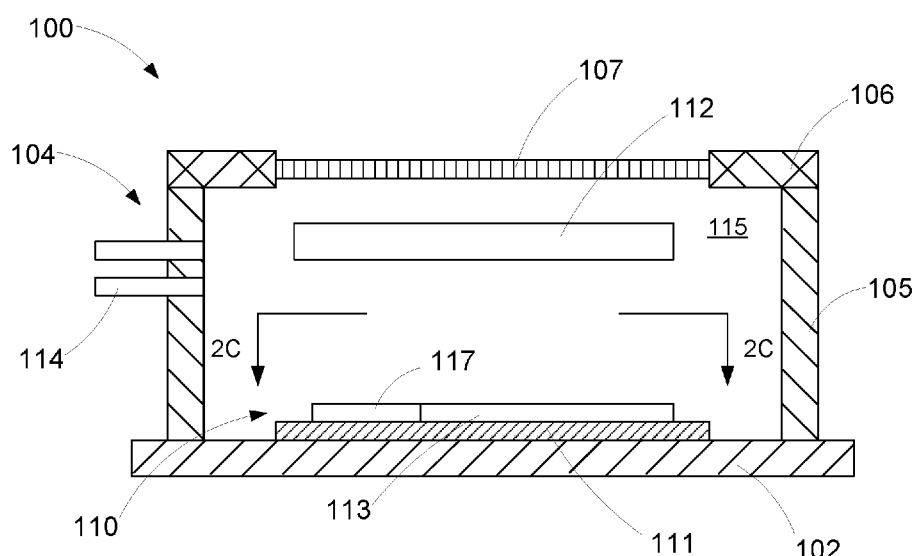


Figure 2B

(57) Abstract: A system for measuring fatigue stress on an item of equipment/structure (121), comprising a fluid tight cavity (115) defined at least partially by sidewalls (105), a lid (106) and at least one of a lower plate (102) or an outer surface (121A) of the equipment/structure (121), a crack-type sensor (110) positioned in the fluid-tight cavity (115), the crack-type sensor (110) comprising a foil fracture piece (113), and a crack image sensor (112) that is positioned in the fluid-tight cavity (115) and oriented such that, when actuated, the crack image sensor (112) is adapted to obtain a non-contact image of the foil fracture piece (113).

REMOTELY ACCESSIBLE FATIGUE ACCUMULATION SENSOR AND METHODS OF ACCESSING AND USING SUCH A SENSOR

TECHNICAL FIELD

The present disclosed subject matter generally relates to the field of fatigue sensing and evaluation of equipment or structures and, in one particular example, to a novel remotely accessible fatigue accumulation sensor that may be installed on such equipment and structures, methods of accessing such a sensor and methods of using the data obtained from such a sensor.

BACKGROUND

In many situations, sensing of stress or fatigue on various items of equipment, such as pressure vessels, pumps, compressors, etc., or structures such as dynamic risers, tension legs, a subsea wellhead/system connection, etc., is very desirable and sometimes required to determine the present condition or the equipment or structure and/or its remaining useful life. In one particular application, sensors installed on the equipment/structure may be periodically accessed and data obtained from accessing such a sensor may be evaluated for purposes of determining fatigue accumulation effects, high pressure-high temperature (HPHT) auto-frottage effects, etc.

One prior art method (by Kawasaki) involved use of a foil crack-type fatigue damage sensor (FDS) to determine stress profiles on various items of equipment/structure. See, for example, US patent number 6,520,024. Figures 1A-1B simplistically depicts one illustrative example of where such an FDS sensor might be employed. In the depicted example, the FDS sensor 16 was positioned on the outer surface 12A of a vessel 12 at a location adjacent a nozzle 14 that penetrates the wall of the vessel 12 and was secured in position by one or more weld joints (not shown). In the depicted example, the FDS sensor comprises a foil substrate 16A and a foil fracture piece 16B. A notch or slit 18 of a known size and length was initially formed in the foil fracture piece 16B. The shape, thickness and configuration of the FDS sensor 16 and the notch or slit 18 could vary depending upon the particular application. In some cases, the thickness of the foil fracture piece 16B as well as the notch geometry may be governed by certain industry standards such as ASTM E1457 and 1820.

In one example, the foil fracture piece 16B was attached to the foil substrate 16A by tack welding or by use of adhesives. The foil substrate 16A of the FDS sensor 16 was physically attached to the outer surface 12A of the equipment/structure under investigation (e.g., the vessel 12) by tack-welding or gluing at the time the equipment/structure was manufactured and before it was placed in service, e.g., before the equipment/structure was installed in a subsea application. In some

applications, after the FDS sensor 16 was attached to the equipment/structure, insulation and/or fireproofing were placed around the equipment/structure and over the installed equipment.

The FDS sensor 16 was placed at one or more locations where high or repeated cyclic stresses or high fatigue stress were expected to occur, e.g., at a structural discontinuity (e.g., the area between the nozzle 14 and the vessel wall 12, a location where an attachment lug or plate is attached to the outer surface of the equipment/structure by a fillet weld, etc.) or at a location where relatively higher temperatures might be expected during operations (adjacent the primary inlet of an item of equipment that is adapted to receive a hot process fluid). The location and placement of such FDS sensors 16 was all based upon sound engineering judgment based upon the particular equipment/structure at issue and its anticipated operating conditions.

Once installed, the FDS sensor 16 is subjected proportionally to the same conditions, e.g., the same number of fatigue cycles, as was the location of interest on the equipment/structure where the FDS sensor 16 was installed. Accordingly, any changes in size of the pre-manufactured notch 18 in the FDS sensor 16 reflect the effects of the accumulated fatigue damage on the adjacent area of interest. Crack growth of the pre-manufactured notch 18 (shown as a dashed line crack 19 in Figure 1B) is a well-known calibrated property of the material of the sensor 16 and its manufactured geometry, and becomes a time-stamped record of the accumulated cyclic loads culminating in the amount of fatigue induced stress. Then by superposition, the useful life of the area of interest on the equipment/structure may be inferred. Accordingly, once the accumulated fatigue stress of the equipment/structure is inferred (by observing changes in the sensor 16) the remaining useful life of the equipment/structure may be determined.

In one illustrative embodiment, determining any changes in the size of the pre-manufactured notch 18 in the FDS sensor 16 was accomplished by performing the following. First, if present, any materials such as insulation and/or fireproofing that was positioned above the FDS sensor 16 was removed so as to expose the FDS sensor 16. Then, a human inspector would physically contact the FDS sensor 16 with inked taped so as to take an impression of the notch 18 at that point in time. The inked tape was then removed and the image in the inked tape was transferred to a data sheet (by pressing the inked tape on the data sheet). At that point, if required, the sensor 16 was re-covered with insulation/fireproofing. The data sheet was then sent to a laboratory where any changes in the size of the notch 18 were measured using a microscope and changes in the size of the notch 18 in the foil FDS sensor 16 (from any or all previous investigations) was determined. Obtaining and updating changes in the size of the notch 18 on the FDS sensor 16 could be done periodically, e.g., monthly, yearly, and continually updated as needed or as required based upon design considerations. Based upon this information about changes in the size of the notch 18 in the FDS sensor 16, the stress

conditions in the FDS sensor 16 were determined, and the stress results determined from analyzing the FDS sensor 16 were assumed to reflect the stress conditions in the area of the equipment/structure associated with the FDS sensor 16. In other applications, the FDS sensor 16 may also comprise a plurality of electrical wires (arranged in parallel) that extend across the FDS sensor 16 in a direction that is substantially orthogonal to a direction in which a crack in the notch 18 propagates. Accordingly, as the size of the notch 18 increases, some of the wires were broken, thereby changing the resistance of the remaining wires. The resistance variation was measured thereby permitting the state of crack propagation to be qualitatively determined. In other applications, where the environmental and space conditions permitted, a fiber scope was used to take an image of the region of the notch 18 (including any region of potential crack propagation) and the resulting image data was used to determine the length of crack propagation.

Unfortunately, the above described process of accessing the Kawasaki FDS sensor presents several problems. First, in cases where an inspector -- a person -- physically accessed the FDS sensor, such sensors were typically only placed in relatively open areas so as to make it easier for the inspector to access the FDS sensor. Second, such sensors were not placed in some harsher environments, e.g., deep subsea locations, desert environments, extremely cold environments such as Alaska or the North Sea, etc. Third, in cases where the FDS sensors had to be located so as to facilitate access by the inspector, such FDS sensors were not placed in inaccessible locations, even though such inaccessible locations on the equipment/structure might have been the location where the highest fatigue stress may have been expected to occur on the equipment/structure during operation. Fourth, in the case where the inspector used inked tape to take an impression of the area of the notch 18, the act of an inspector physically pressing inked tape on the FDS sensor and transferring the impression of the notch 18 in the FDS sensor 16 was subject to human errors as it relates to the repeatedly and reliably obtaining an accurate image of the notch 18 (and any crack propagation) in the FDS sensor 16. However, it should be noted that not all of the problems discussed above are limited to harsh environment concerns as one or more to the problems above may apply to both equipment/structure positioned subsea as well as equipment/structure positioned above the surface of the sea, e.g., a land-based drilling and production site or rig, and offshore drilling or production rig, a drill ship, a drilling and production vessel, etc.

The above-described problems may be even more pronounced in high pressure applications. For example, ASME Boiler and Pressure Vessel Codes (Section VII, Division 2 and 3) state that vessels in high-pressure, cyclic service (i.e., working pressure greater than 68.94 MPa (10, 000 psi) should be evaluated for fatigue damage from the physical expansion and contraction of the vessel from internal pressure and/or elevated temperatures as the vessel is turned on and off during cyclical operations. Periodic inspection of these pressure vessels, looking for crack growth, is required to

make sure that stressed areas (the areas of interest) does not exhibit any fatigue cracks that could compromise the future integrity of the pressure vessel. If no such cracks are found, the pressure vessel may be returned to service until the next inspection cycle. If no inspection is performed, the assumed safety factor used in designing the pressure vessel is raised with the net result being that the pressure vessel must be taken out of service much sooner than its predicted service life.

As a result, standard industry codes governing pressure vessel design typically require a periodic inspection of a pressure vessel to inspect for any cracks in the vessel that may exceed a preselected acceptable size set by the original design parameters for the vessel. In general, under the fracture mechanics approach, should inspection of the vessel reveal that no cracks (or no cracks that exceed a preselected acceptable size) are present on the pressure vessel, the pressure vessel may be put back into service for another period, which is equal to one-half of the duration of the previous inspection period, at which point the pressure vessel must be examined and inspected again. This practice and approach is generally referred to a damage tolerant design practice and the calculated design life is divided by a factor of three. If the pressure vessel cannot be inspected (for whatever reason such as being positioned in a subsea environment) then the overall calculated design life must be divided by a factor of ten, so as to thereby define the remaining operational design life of the pressure vessel. At the end of the determined remaining operation life, the pressure vessel must be taken out of service. Thus, in cases where it is desired or necessary to perform such inspections, and where such inspections are not performed due to a variety of factors (e.g., inaccessibility of the FDS sensor, non-placement of an FDS sensor), the equipment/structure at issue may have to be prematurely retired from service. Such premature retirement of such equipment/structure can be very costly and/or result in mandatory use of expensive intervention activities in an effort to acquire stress data about the vessel so as to extend its useful life.

The present application is directed to a unique remotely accessible fatigue accumulation sensor that may be installed on such equipment and structures, methods of accessing such a sensor and methods of using the data obtained from such a sensor that may eliminate or at least minimize some of the problems noted above.

SUMMARY

The following presents a simplified summary of the subject matter disclosed herein in order to provide a basic understanding of some aspects of the information set forth herein. This summary is not an exhaustive overview of the disclosed subject matter. It is not intended to identify key or critical elements of the disclosed subject matter or to delineate the scope of various embodiments

disclosed herein. Its sole purpose is to present some concepts in a simplified form as a prelude to the more detailed description that is discussed later.

The present application is generally directed to a unique remotely accessible fatigue accumulation sensor that may be installed on items of equipment and/or other structures, methods of accessing such a sensor and methods of using the data obtained from such a sensor. In one example, the sensor comprises, among other things, a fluid tight cavity (115) defined, at least partially, by sidewalls, a lid and at least one of a lower plate or an outer surface of the equipment/structure, a crack-type sensor positioned in the fluid-tight cavity, the crack-type sensor (comprising a foil fracture piece, and a crack image sensor that is positioned in the fluid-tight cavity and oriented such that, when actuated, the crack image sensor is adapted to obtain a non-contact image of the foil fracture piece.

In another example, a method of obtaining data from such a remotely accessible fatigue accumulation sensor includes, among other things, a fluid tight cavity defined at least partially by sidewalls, a lid and at least one of a lower plate or an outer surface of the equipment/structure, a crack-type sensor positioned in the fluid-tight cavity, the crack-type sensor comprising a foil fracture piece and a plurality of conductive electrodes positioned in electrical contact with the foil fracture piece. In this example, the system further comprises a resistance measurement device that is electrically coupled each of the plurality of electrodes wherein the resistance measurement device is adapted to, for each of the electrodes in the plurality of electrodes, measure a resistance between each of the plurality of electrodes and all other electrodes in the plurality of electrodes so as to obtain an image of any crack in the foil fracture piece.

BRIEF DESCRIPTION OF THE DRAWINGS

Certain aspects of the presently disclosed subject matter will be described with reference to the accompanying drawings, which are representative and schematic in nature and are not be considered to be limiting in any respect as it relates to the scope of the subject matter disclosed herein:

Figures 1A-1B are various views of an illustrative prior art crack-type fatigue detection sensor;

Figure 2A contains top, side and end views of one illustrative embodiment of a fatigue detection sensor module disclosed herein;

Figure 2B is a cross-sectional view of one illustrative embodiment of a fatigue detection sensor module disclosed herein;

Figure 2C is a plan view of one illustrative embodiment of a crack-type fatigue detection sensor disclosed herein;

Figures 2D-2F depicts illustrative applications where the fatigue detection sensor module disclosed herein may be employed;

Figure 2G depicts, at a systems level, one illustrative embodiment of a fatigue detection sensor module disclosed herein;

Figures 2H-2I depict another illustrative embodiment wherein portions of the fatigue detection sensor module disclosed herein may be positioned in multiple housings;

Figure 2J is a plan view of another illustrative embodiment of a crack-type fatigue detection sensor disclosed herein wherein crack propagation may be determined using electrode tomography principles; and

Figure 2K depicts another embodiment disclosed herein wherein crack propagation may be determined using current injection/voltage measurement techniques.

While the subject matter disclosed herein is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the description herein of specific embodiments is not intended to limit the disclosed subject matter to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosed subject matter as defined by the appended claims.

DESCRIPTION OF EMBODIMENTS

Various illustrative embodiments of the disclosed subject matter are described below. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual embodiment, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking for those of ordinary skill in the art having the benefit of this disclosure.

The present subject matter will now be described with reference to the attached figures. Various structures, systems and devices are schematically depicted in the drawings for purposes of explanation only and so as to not obscure the present disclosure with details that are well known to those skilled in the art. Nevertheless, the attached drawings are included to describe and explain illustrative examples of the present disclosure. The words and phrases used herein should be understood and interpreted to have a meaning consistent with the understanding of those words and phrases by those skilled in the relevant art. No special definition of a term or phrase, *i.e.*, a definition that is different from the ordinary and customary meaning as understood by those skilled in the art, is intended to be implied by consistent usage of the term or phrase herein. To the extent that a term or phrase is intended to have a special meaning, *i.e.*, a meaning other than that understood by skilled artisans, such a special definition will be expressly set forth in the specification in a definitional manner that directly and unequivocally provides the special definition for the term or phrase.

One illustrative example of a novel fatigue detection sensor module 100 will be described with reference to the attached drawings. With reference to Figures 2A-2B, in one illustrative embodiment, the fatigue detection sensor module 100 comprises a housing 104 that comprises a bottom plate 102, sidewalls 105, a lid 106 and a window 107 defined in the lid 106. The housing 104 defines a cavity 115 wherein various components are positioned to permit the fatigue detection sensor module 100 to perform its functions. In the depicted example, the fatigue detection sensor module 100 also comprises a crack-type fatigue damage sensor 110 (see Figure 2C) that is used to determine stress profiles on various items of equipment/structure 121. As will be appreciated by those skilled in the art after a complete reading of the present application, fatigue detection sensor module 100 disclosed herein may be employed on any type of equipment/structure 121 wherein examination of stress conditions on the equipment/structure 121 and, in particular, fatigue damage on the equipment/structure 121 may be important. Such equipment/structure 121 may include, but is not limited to, wellheads, connectors, tubing heads, pressure vessels, marine risers, tension legs, pipelines, compressors, pumps, structures such as on-shore platforms or off-shore platforms, etc.

Figures 2D-2F simplistically depict illustrative example of where the fatigue detection sensor module 100 disclosed herein may be employed. In the example depicted in Figures 2D-2E, the fatigue detection sensor module 100 was positioned on the outer surface 121A of a pressure vessel at a location adjacent a nozzle 123 that penetrates the wall 121 of the vessel and was secured in position by one or more weld joints (not shown). The fatigue detection sensor module 100 may be attached to the equipment/structure 121 using a variety of known techniques, e.g., by welding, by use of an adhesive, by bands that extend around the equipment/structure 121, by a threaded fastener (such as a screw -not shown) that extends openings (not shown) in the bottom plate 102, etc. In the example depicted in Figures 2D-2E, the bottom plate 102 of the fatigue detection sensor module 100 comprises

a metal and it may be attached to the outer surface 121A of the vessel by tack-welding the fatigue detection sensor module 100 to the equipment/structure 121 at the time the equipment/structure 121 was first manufactured or before it was placed in service, e.g., before the equipment/structure 121 was installed in a subsea application. In other applications, the fatigue detection sensor module 100 may be attached to the equipment/structure 121 after the equipment/structure 121 is placed in service. Additionally, the novel fatigue detection sensor module 100 may be attached to existing equipment/structure 121 that has been in service for many years. In some applications, after the fatigue detection sensor module 100 attached to the equipment/structure 121, insulation and/or fireproofing were placed around the equipment/structure 121 and over the fatigue detection sensor module 100. Figure 2F depicts an illustrative example wherein the equipment/structure 121 is a marine riser or tubular that may extend from a platform downward toward the sea floor. In this example, the fatigue detection sensor module 100 is secured to the marine riser by a plurality of bands 125 that extend around the marine riser or tubular. In all applications, it is important that the fatigue detection sensor module 100 remain in its originally installed position on the equipment/structure 121 and does not slip or move from its installed position. In the case where the fatigue detection sensor module 100 is attached to the equipment/structure 121 by “non-permanent” means, like the bands 125 mentioned above, at least some portion of the fatigue detection sensor module 100, e.g., the bottom plate 102 may be configured to as to engage, nest or register with the equipment/structure 121 or adjacent structure such that the fatigue detection sensor module 100 remains in its installed location throughout its useful life.

In general, the fatigue detection sensor module 100 may be placed at one or more locations where high or repeated cyclic stresses or high fatigue stress were expected to occur, e.g., at a structural discontinuity (e.g., the area between the nozzle 123 and the vessel wall 121, a location where an attachment lug or plate is attached to the outer surface of the equipment/structure by a fillet weld, etc.) or at a location where relatively higher temperatures might be expected during operations (adjacent the primary inlet of an item of equipment that is adapted to receive a hot process fluid). The location and placement of such fatigue detection sensor modules 100 is based upon sound engineering judgment based upon the particular equipment/structure 121 at issue and its anticipated operating conditions. Any desired number of such fatigue detection sensors module 100 may be placed on an item of equipment/structure 121.

In one illustrative embodiment, the fatigue detection sensor module 100 houses several components or systems that enable it to perform its intended functions. Figure 2G depicts, at a systems level, one illustrative embodiment of a fatigue detection sensor module 100 disclosed herein as well as the components and systems of the module 100. As shown in Figure 2G, the fatigue detection sensor module 100 disclosed herein may comprise a crack-type sensor 110, a separate crack

image sensor 112, an on-board power supply 120, a computer-data storage system 122 and a communications system 124. The fatigue detection sensor module 100 may also comprise several interfaces 150 that permit the fatigue detection sensor module 100 to interface with external systems or devices. In one illustrative embodiment, the fatigue detection sensor module 100 may comprise a power interface 151, a communications interface 152 and a fluid supply interface 153.

In one illustrative embodiment the crack-type sensor 110 may have a configuration like that depicted in Figures 2B-2C. In the depicted example, the bottom plate 102 of the fatigue detection sensor module 100 is operatively coupled to the outer surface 121A of the equipment/structure 121 by welding or gluing, etc. In some applications, the sidewalls 105 of the housing 104 are a separate structure from that of the bottom plate 102 and they may be affixed to the bottom plate 102 by any desired means, e.g., welding or gluing. In other applications, the sidewalls 105 and the bottom plate 102 may be formed integrally with one another. In one example, the lid 106 may be coupled to the sidewalls 105 by a plurality of threaded fasteners (not shown) that extend around the perimeter of the lid 106. A seal (not shown) may be provided between the lid 106 and the sidewalls 105 so as to provide a fluid-tight cavity 115. The housing 104 may be comprised of a variety of different materials, e.g., a plastic, a metal, a metal alloy, etc., or a combination thereof, and not all components of the housing 104 need to be comprised of the same materials, although such a configuration is possible. For example, in one embodiment, the bottom plate 102 may be comprised of a metal, while the sidewalls 105 and the lid 106 may be comprised of plastic. In another example, the sidewalls 105 and the bottom plate 102 may be an integrally formed plastic structure, and the lid 106 may be made of plastic. The window 107 may be a transparent glass structure that is adapted to allow light to pass there through. The physical area occupied by the window 107 relative to the area of the lid 106 may vary depending upon the particular application. The thickness of the components of the housing 104 may also vary depending upon the particular application.

In another illustrative embodiment the foil substrate 111 may be directly attached to the outer surface 121A of the equipment/structure 121 and the sidewalls 105 form a seal directly with the equipment/structure 121, i.e., the bottom plate 102 may effectively be omitted. In this embodiment, the equipment/structure 121 effectively forms the bottom plate of the housing 104 and provides for a more optimal transfer of stress/strain directly to the crack-type sensor 110.

As shown in Figures 2B-2C, the crack-type sensor 110 comprises a foil substrate 111 and a foil fracture piece 113. A fabricated notch or slit 117 of a known size and length was initially formed in the foil fracture piece 113. The shape, thickness and configuration of the crack-type sensor 110 as well as that of the fabricated notch or slit 117 may vary depending upon the particular application. In some cases, the thickness of the foil fracture piece 113 as well as the geometry of the fabricated notch

117 may be governed by certain industry standards such as ASTM E1457 and 1820. In one example, the foil fracture piece 113 was attached to the foil substrate 117 by tack welding or by use of adhesives. Thereafter, the foil substrate 117 portion of the crack-type sensor 110 was attached to the upper surface of the bottom plate 102 by tack welding or by use of an adhesive. Also depicted in Figure 2C is a simplistically depicted crack 119 in the foil fracture piece 113 emanating from notch 117 as a result of stresses on the foil fracture piece 113 during operation or use of the equipment/structure 121. The foil fracture piece 113 and the foil substrate 117 may be made of any desired material and they both need not be made of the same material, but they may be in some applications.

The crack image sensor 112 of the fatigue detection sensor module 100 will be used to detect the presence or absence of a crack 119 in the foil fracture piece 113 of the crack-type sensor 110. In particular, the crack image sensor 112 is non-contact type of sensor that is adapted to capture an image of the crack 119 without physically contacting the foil fracture piece 113. The crack image sensor 112 may be mechanically secured within the cavity 115 of the housing 104 using desired technique. In one illustrative embodiment, the crack image sensor 112 is positioned above the foil fracture piece 113 such that it can take an image of the entire foil fracture piece 113. The crack image sensor 112 may be any type of sensor that can be positioned in the cavity 115 and be used to obtain a non-contact image of the foil fracture piece 113 (and the crack 119). In one illustrative embodiment, the crack image sensor 112 may be a tomographic algorithm that creates a virtual picture based on reading a plurality of electrical properties between combinations of pairs of sensors located around the perimeter of the foil fracture piece 113. In other embodiments, the crack images sensor 112 may comprise a MEMS camera, a laser scanning device, micro-strain rosettes, two piezoelectric materials positioned adjacent the crack-type sensor 110, an ultrasonic based method wherein electrodes are placed on opposite sides of the crack-type sensor 110 and crack growth is detected by a signal echo between a transponder and a receiver etc. In the case of the piezoelectric based sensor, two piezo materials may be placed along the side of the crack sensor 110. The frequency response of the crack sensor 110 changes if and when a crack 119 forms and will further change as the crack 119 continues to grow. One of the piezo materials can be used to provide excitation of the crack sensor 110 while the second piezo material can be used to measure the response, i.e., measure the frequency of the crack sensor 110. Changes in the measured frequency of the crack sensor 110 will indicate the presence and/or growth of the crack 119.

Yet another type crack image sensor 112 that may be employed is a CCD (Charge Coupled Device) or a CMOS array device with adjacent lighting wherein the lighting may be positioned to enhance detection of the crack 119 by, for example, dark field illumination. All of the above mentioned crack image sensors 112 allow for remote measurement of the crack 119 over time. These

remote measurement devices (the crack image sensors 112) are positioned in a protective environment within the cavity 115 inside the housing 104 so as to extend the life of the crack image sensor 112 and to otherwise protect it from a harsh external environment. Absent such protection, the crack image sensor 112 may not be able to accurately perform its function over an extended period of time when it is exposed to a harsh external environment

In one illustrative embodiment, the fatigue detection sensor module 100 comprises an on-board power supply 120 that is positioned within the cavity 115 of the housing 104. For example, the power supply 120 may comprise one or more batteries, an array of solar cells that are positioned so as to be irradiated through the window 107. Alternate power sources and power/data lines from control system equipment or mission-specific battery packs may be incorporated to power and obtain data from the sensor 112. In another embodiment, the power supply for the fatigue detection sensor module 100 may be supplied from an external source, such as an external battery, a generator, general electrical power from a power generation station, an ROV, a source of electrical power positioned subsea, a power source that is based upon power scavenging in remote areas through heat or vibration, etc. In general, the module should be configured so as to keep power and sensor processing electronics away from high temperatures that may radiate from the equipment/structure 121 to which the crack-type sensor 110 is attached. By moving the electronics away from the heat source, the overall life of the sensor package may be extended.

In one illustrative embodiment, the fatigue detection sensor module 100 also comprises a computer-data storage system 122 (CDS system) that, in one embodiment, is positioned within the cavity 115 in the housing 104. The CDS system 122 may be any type of device or system, or combinations of devices and systems, that collectively can store data received from the crack image sensor 112 and perform scheduling activities as it relates to the timing of activating the crack image sensor 112 to obtain an image of the foil fracture piece 113 as well as any crack 119 that might be present. In some applications, the CDS system 122 may not include on-board computing and scheduling capabilities, i.e., it may only provide a data storage function. In general, in one embodiment, the CDS system 122 may comprise any type of device capable of executing instructions, e.g., a controller, a microprocessor, a computer. The functions performed by the CDS system 122 may be performed by multiple computing resources within the housing 104. The data storage capabilities of the CDS system 122 may be performed using any type of storage medium, volatile or non-volatile memory devices, such as DRAM devices, SRAM devices, etc.

In one illustrative embodiment, the fatigue detection sensor module 100 also comprises an on-board communications system 124 positioned within the housing 104. The communications system 124 is the means by which the images of the foil fracture piece 113 (and the crack 119) taken by the

crack image sensor 112 and stored in the CDS system 122 to be sent from or retrieved from the fatigue detection sensor module 100. The communications system 124 may take a variety of forms using different technologies. In one embodiment, the communications system 124 may be a wireless system that transmits data wirelessly to a receiver that is positioned remotely from the fatigue detection sensor module 100, e.g., a land-based receiver, a receiver positioned on a platform or sea-going vessel, an ROV, etc. In other embodiments, the communications system 124 may be an RFID based system that can be accessed by an RFID reader to obtain the information. In some cases, the RFID reader may be hand-held or it may be attached to an ROV. In the case of an RFID based communication system, the communications system 122 may be powered by an internal battery or power harvested from the reader's electromagnetic field. In yet other embodiments, the communications system 124 may be hard wired to an external receiver via the communications interface 152. In some applications, the functions performed by the computer-data storage system 122 and the communications system 124 may be performed by a single device or system. In some cases, the communications system 124 may not be positioned on-board the fatigue detection sensor module 100, and communications with the fatigue detection sensor module 100 may be accomplished via the communications interface 152. For example, a communications system on-board an ROV may be operatively coupled to the crack image sensor 112 and/or the computer-data storage system 122 via a line extending from the ROV that is coupled to the communications interface 152.

The fatigue detection sensor module 100 also comprises a fluid supply interface 153 that permits fluids to be introduced into or withdrawn from the cavity 115. As shown in Figure 2B, in one illustrative embodiment the fluid supply interface 153 takes the form of a plurality of tubes 114 that penetrate the sidewall 105 of the housing 104. Various valves or caps that might be used in conjunction with the tubes 114 are not depicted. In one illustrative embodiment, the cavity 115 may be filled with an oil so as to protect the components and systems within the fatigue detection sensor module 100 from outside effects of hydrostatic pressure, salt water corrosion, insulation constriction effects, etc. The presence of such a fluid in the cavity 115 should protect the crack-type sensor 110, and particularly the foil fracture piece 113, from undue influences that could distort results.

In the embodiment previously described, the fatigue detection sensor module 100 has been described as being positioned in a single housing 104. However, as shown in Figures 2H-2I, in some applications, the systems and components described herein may be positioned in one or more additional housings, e.g., housing 130 (see Figure 2H) that are connected by one or more simplistically depicted lines 132 whereby data, power, etc. may be transmitted between and among the various systems positioned in the housings 104, 130. Figure 2H depicts an application wherein equipment/structure 121 a vessel that has a nozzle 14 that penetrates the wall of the vessel. However, in this application, insulation and or fire-proofing material 134 is positioned around the vessel and an

external protective metal layer 136 is positioned around the material 134. In this embodiment, the lower housing 104 is positioned on the outer surface 121A of the equipment/structure 121 while the other housing 130 is positioned on the outer layer of metal 136. One or more wires 132 extend between the housing 104, 130 to provide the necessary means of transmitting data and/or power. In this embodiment, the housing 104 will include at least the crack-type sensor 110 and the crack image sensor 112, while the computer-data storage system 122 and the communications system 124 may be positioned in a cavity 130D in the housing 130. The housing 130 may have a construction similar to that of the housing 104, e.g., it may have a bottom plate 130A, sidewalls 130B, a lid 130C and a window (not shown). It may also be provided with one or more of the external interfaces 150 and with the means for filling the cavity 130D with a fluid. Such an arrangement may be beneficial to protect the electronics within at least the computer-data storage system 122 and the communications system 124 from over-heating due to being placed under the insulation/fire-proofing materials 134.

Figure 2J depicts a unique system for using impedance tomography techniques to capture an image of any crack 119 that may form in the foil fracture piece 113. In general, in this embodiment, a plurality of conductive electrodes 160 (e.g., metal dots) are formed on the foil fracture piece 113 around the perimeter of the foil fracture piece 113. Each of the conductive electrodes 160 is individually coupled to a resistance (impedance) measurement device 162 by a plurality of individual wires 164. Only some of the individual electrodes 160 shown in Figure 2J are shown as being individually coupled to the resistance measurement device 162 so as not to overly obscure and needlessly complicate Figure 2J. In one illustrative embodiment, the resistance measurement device 162 may be an ohmmeter and connections may be established using Kelvin connections/4-wire measurement techniques in order for small resistances changes to be detected and recorded. The resistance measurement device 162 may be positioned within the housing 104 or the housing 130.

Figure 2K depicts another embodiment disclosed herein wherein the detection/growth of the crack 119 may be detected. In this example, a current (AC or DC) generation device 170 may be used to inject a current into a first set of the electrodes 160 and the voltage at a second set of electrodes 160 may be measured using traditional voltage measuring equipment 172. The presence of a crack and/or the growth of the crack 119 will cause changes in the measured voltage. i.e., voltage changes correspond to the presence/growth of the crack 119. Multiplexing techniques may be used to switch the electrodes 160 that are connected to the voltage measurement equipment.

In some applications, a coating may be applied to the foil fracture piece 113 of the crack-type sensor 110. The coating comprises a material that has a higher sheet resistivity than that of the foil fracture piece 113. The coating may be applied to the surface of the foil fracture piece 113 so as to enhance the impedance measurement. The coating may be applied, for example, by evaporation,

sputtering, spin or dip coating. The electrodes 160 are then attached to the surface of the coating. The coating may be patterned to form strip conductors that further enhance and simplify the measurement.

In operation, the resistance measurement device 162 may be used to measure the resistance between one of the electrodes 160 and each of the other electrodes 160, and this process may be repeated for every electrode 160 on the foil fracture piece 113. Such resistance measurements may be taken of the foil fracture piece 113 just prior to putting it into service so as to obtain a reference or baseline image for the foil fracture piece 113 against which future images of the foil fracture piece 113 (obtained by measuring the resistance between and among all of the electrodes 160) will be compared. At some point after this embodiment of the crack-type sensor 110 is placed in service, the resistance measurement device 163 again measures the resistance between all combinations of the electrodes 160 and generates a new image of the foil fracture piece 113 based upon the measured resistance values at that time. This new image may then be compared to the reference image of the foil fracture piece 113 to determine the existence and extent of any crack 119 that is present in the foil fracture piece 113. At this point, the most recent image will serve as the reference image for comparison to an image of the foil fracture piece 113 taken at a later point in time to determine the extent or absence of any further growth of the crack 119.

In general, the systems and components of the fatigue detection sensor module 100 may be configured and operate as follows. The power supply 120 may be operatively coupled to the crack image sensor 112, the computer-data storage system 122 and the communications system 124. The crack image sensor 112 may be operatively coupled to the computer-data storage system 122 and the communications system 124. In one embodiment, the communications system 124 has sufficient capability to set a schedule for activating the crack image sensor 112 to take an image of the foil fracture piece 113 (including any crack 119 therein), i.e., an image of the foil fracture piece 113 may be taken bi-weekly, monthly, quarterly, yearly, etc. The communications system 124 also has sufficient capability such that it may be accessed so as to cause the crack image sensor 112 to take an image of the foil fracture piece 113 immediately, an "on-demand" image as opposed to an image taken as part of a regularly scheduled protocol. As noted above, in some cases the communications system 124 may not be contained within the fatigue detection sensor module 100. In such a situation, a schedule for taking the images of the foil fracture piece 113 may be downloaded to the computer-data storage system 122 from, for example, an ROV, wherein the computer-data storage system 122 may have sufficient capability to schedule the taking of the images of the foil fracture piece 113. The crack image sensor 112 is operatively coupled to the computer-data storage system 122 such that data corresponding to the images of the foil fracture piece 113 may be stored in the computer-data storage system 122. In turn, where the fatigue detection sensor module 100 includes an on-board communications system 124, the communications system 124 may access the computer-data storage

system 122 and transmit the data corresponding to the image(s) of the foil fracture piece 113 to a remote receiver, e.g., to a receiver on an ROV, a vessel or a platform. In cases where the communications system 124 is not present on the fatigue detection sensor module 100, another device, such as an ROV may establish communication with the computer-data storage system 122 via the communications interface 152. If desired, two or more crack-type sensors 110 may be positioned within a single housing 104 for a variety of reasons, e.g., to provide a redundant back up, to confirm with two different crack-type sensors 110 the growth of the crack 119, to measure the fatigue stress in a different orientation relative to that measured by one of the other crack-type sensors 110 (i.e., two crack-type sensors 110 may be positioned in the housing 104 in such a manner that the long-axis of the pre-fabricated notches 117 are oriented transverse to one another).

In general, after the crack-type sensor 110 is installed in the housing 104 and the housing 104 is secured to the equipment/structure 121, the crack image sensor 112 may be activated to take an initial image of the foil fracture piece 113 (with the pre-fabricated crack 117). This initial image of the foil fracture piece 113 will serve as a reference or baseline image for the foil fracture piece 113 against which future images of the foil fracture piece 113 (obtained by actuating the crack image sensor 112) will be compared. At some point after this fatigue detection sensor module 100 is placed in service, the crack image sensor 112 will be actuated to obtain a second image of the foil fracture piece 113 at that point in time. The second image may then be compared to the initial reference image of the foil fracture piece 113 to determine the existence and extent of any crack 119 that is present in the foil fracture piece 113. If a crack 119 is present in the foil fracture piece 113, calculations may be made as to the size of the crack 119 and to determine the remaining useful life of the equipment/structure 121. At this point, the most recent image (i.e., the second image) of the foil fracture piece 113 will serve as the reference image for comparison to an image of the foil fracture piece 113 taken at a later point in time to determine the extent or absence of any further growth of the crack 119.

As will be appreciated by those skilled in the art after a complete reading of the present application, the novel sensor systems and methods disclosed herein can be employed to monitor accumulated fatigue on equipment/structures even when the equipment/structures are located or positioned in environments that make access to equipment/structures difficult if not impossible for a human inspector. That is, the methods, devices and systems disclosed herein may be employed to periodically inspect items, such as pressure vessels (and the like), to make sure that stressed areas (the areas of interest) of the vessel is not exhibiting any fatigue cracks that could compromise the future integrity of the pressure vessel. As noted in the background section of this application, in the case where a pressure vessel was in an environment where it could not be inspected for fatigue cracks, the assumed safety factor used in designing the pressure vessel was raised with the net result being that

the pressure vessel was taken out of service much sooner than its predicted service life. By using at least some aspects of at least portions of the presently disclosed subject matter, such vessels may be inspected periodically and the owners of such equipment do not have to assume an increased safety factor for such equipment with the net result being that the pressure vessel does not have to be taken out of service prematurely, i.e., the vessel may be used for its entire predicted service life. Thus, the difference in safety factor on allowable design life can be of huge commercial advantage without changing the equipment design, just by adding a monitoring feature to the equipment, such as using the embodied sensors, systems and methods disclosed herein.

The particular embodiments disclosed above are illustrative only, as the disclosed subject matter may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. For example, the process steps set forth above may be performed in a different order. Furthermore, no limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope and spirit of the claimed subject matter. Note that the use of terms, such as “first,” “second,” “third” or “fourth” to describe various processes or structures in this specification and in the attached claims is only used as a shorthand reference to such steps/structures and does not necessarily imply that such steps/structures are performed/formed in that ordered sequence. Of course, depending upon the exact claim language, an ordered sequence of such processes may or may not be required. Accordingly, the protection sought herein is as set forth in the claims below.

CLAIMS

1. A system for measuring fatigue stress on an item of equipment/structure (121), comprising:
 - a fluid tight cavity (115) defined at least partially by sidewalls (105), a lid (106) and at least one of a lower plate (102) or an outer surface (121A) of the equipment/structure (121);
 - a crack-type sensor (110) positioned in the fluid-tight cavity (115), the crack-type sensor (110) comprising a foil fracture piece (113); and
 - a crack image sensor (112) that is positioned in the fluid-tight cavity (115) and oriented such that, when actuated, the crack image sensor (112) is adapted to obtain a non-contact image of the foil fracture piece (113).
2. The system of claim 1, further comprising at least one of a power supply (120), a computer-data storage system (122) and a communications system (124) positioned within the fluid-tight cavity (115).
3. The system of claim 2, wherein:
 - the power supply (120) comprises one of a battery or an array of solar cells;
 - the computer-data storage system (122) comprises one of DRAM or SRAM memory cells;
 - and
 - the communication system (124) comprises one of a controller or a computer that is adapted to execute instructions.
4. The system of claim 2, wherein the computer-data storage system (122) is adapted to store an image of the foil fracture piece (113) taken by the crack image sensor (112).
5. The system of claim 4, wherein the communication system (124) is adapted to access and retrieve the stored image of the foil fracture piece (113) in the computer-data storage system (122).
6. The system of claim 5, wherein the communication system (124) is adapted to actuate the crack image sensor (112) to take an image of the foil fracture piece (113) in accordance with a schedule maintained on one of the computer-data storage system (122) or the communication system (124).

7. The system of claim 1, further comprising a fluid positioned with the fluid-tight cavity (115) so as to substantially fill unoccupied areas of the fluid-tight cavity (115) with the fluid.

8. The system of claim 1, further comprising a window (107) positioned in the lid (106).

9. The system of claim 1, wherein the system comprises the lower plate (102) and wherein the crack-type sensor (110) comprises a foil substrate (111) that is coupled to a first surface of the bottom plate (102) within the fluid-tight cavity (115) and wherein the foil fracture piece (113) is coupled to the foil substrate (111).

10. The system of claim 1, wherein the crack-type sensor (110) comprises a foil substrate (111) that is coupled to the outer surface (121A) of the equipment/structure 121 within the fluid-tight cavity (115) and wherein the foil fracture piece (113) is coupled to the foil substrate (111).

11. The system of claim 9 wherein the foil fracture piece (113) is coupled to the foil substrate (111) by one or more welds or by an adhesive.

12. The system of claim 1, further comprising the item of equipment/structure (121), wherein the equipment/structure (121) comprises one of a wellhead, a connector, a tubing head, a pressure vessel, a marine riser, a tension leg, a pipeline, a compressor, a pump, an on-shore platform or an off-shore platform.

13. The system of claim 11, wherein a second surface of the bottom plate (102) is coupled to the outer surface (121A) of the equipment/structure (121).

14. The system of claim 10, wherein the foil substrate (111) is coupled to the outer surface (121A) by one or more welds or an adhesive material.

15. The system of claim 1, wherein the crack image sensor (112) comprises one of a MEMS camera, a laser scanning device, a micro-strain rosette, a piezoelectric material, a charge coupled device, a CMOS array device or a device that employs a tomographic algorithm that creates a virtual picture of the foil fracture piece 113 based on reading a plurality of electrical properties between combinations of pairs of sensors located around the perimeter of the foil fracture piece (113).

16. The system of claim 1, wherein the system comprises the lower plate (102) and the lower plate (102), the sidewalls (105) and the lid (106) define a housing (104) that defines the fluid-tight cavity (115).

17. A system for measuring fatigue stress on an item of equipment/structure (121), comprising:

a fluid tight cavity (115) defined at least partially by sidewalls (105), a lid (106) and at least one of a lower plate (102) or an outer surface (121) of the equipment/structure (121);

a crack-type sensor (110) positioned in the fluid-tight cavity (115), the crack-type sensor (110) comprising a foil fracture piece (113); and

a plurality of conductive electrodes (160) positioned in electrical contact with the foil fracture piece (113);

a resistance measurement device (162) that is electrically coupled each of the plurality of electrodes (160) wherein the resistance measurement device (162) is adapted to, for each of the electrodes (160) in the plurality of electrodes (160) measure a resistance between each of the plurality of electrodes (160) and all other electrodes (160) in the plurality of electrodes (162) so as to obtain an image of any crack (119) in the foil fracture piece (113).

18. The system of claim 17, wherein the plurality of conductive electrodes (160) are positioned around substantially an entire outer perimeter of the foil fracture piece (113).

19. The system of claim 17, wherein the resistance measurement device (162) is positioned within the fluid-tight cavity (115).

20. The system of claim 17, wherein the system comprises the lower plate (102) and wherein the crack-type sensor (110) comprises a foil substrate (111) that is coupled to a first surface of the bottom plate (102) within the fluid-tight cavity (115) and wherein the foil fracture piece (113) is coupled to the foil substrate (111).

21. The system of claim 17, wherein the crack-type sensor (110) comprises a foil substrate (111) that is coupled to the outer surface (121A) of the equipment/structure (121) within the fluid-tight cavity (115) and wherein the foil fracture piece (113) is coupled to the foil substrate (111).

22. The system of claim 20, wherein a second surface of the bottom plate (102) is coupled to the outer surface (121A) of the equipment/structure (121).

23. The system of claim 17, wherein the system comprises the lower plate (102) and the lower plate (102), the sidewalls (105) and the lid (106) define a housing (104) that defines the fluid-tight cavity (115).

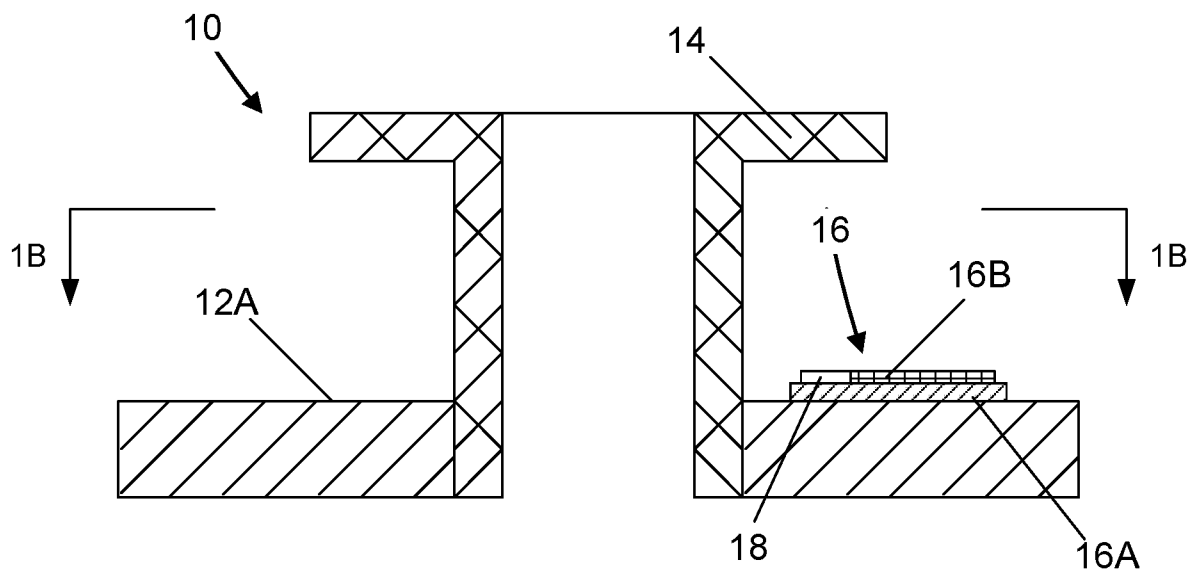


Figure 1A (Prior Art)

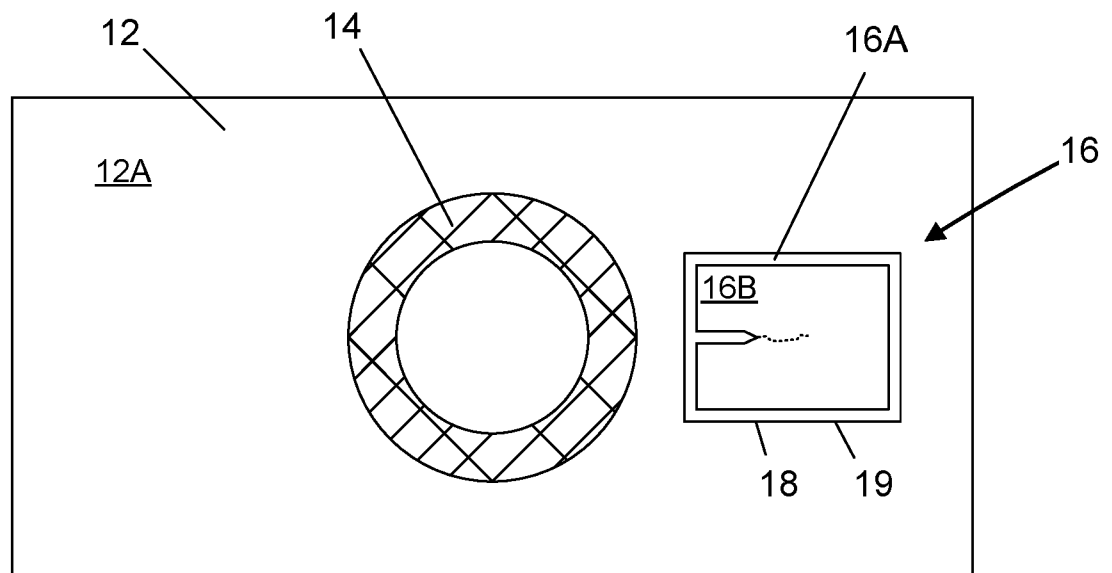


Figure 1B (Prior Art)

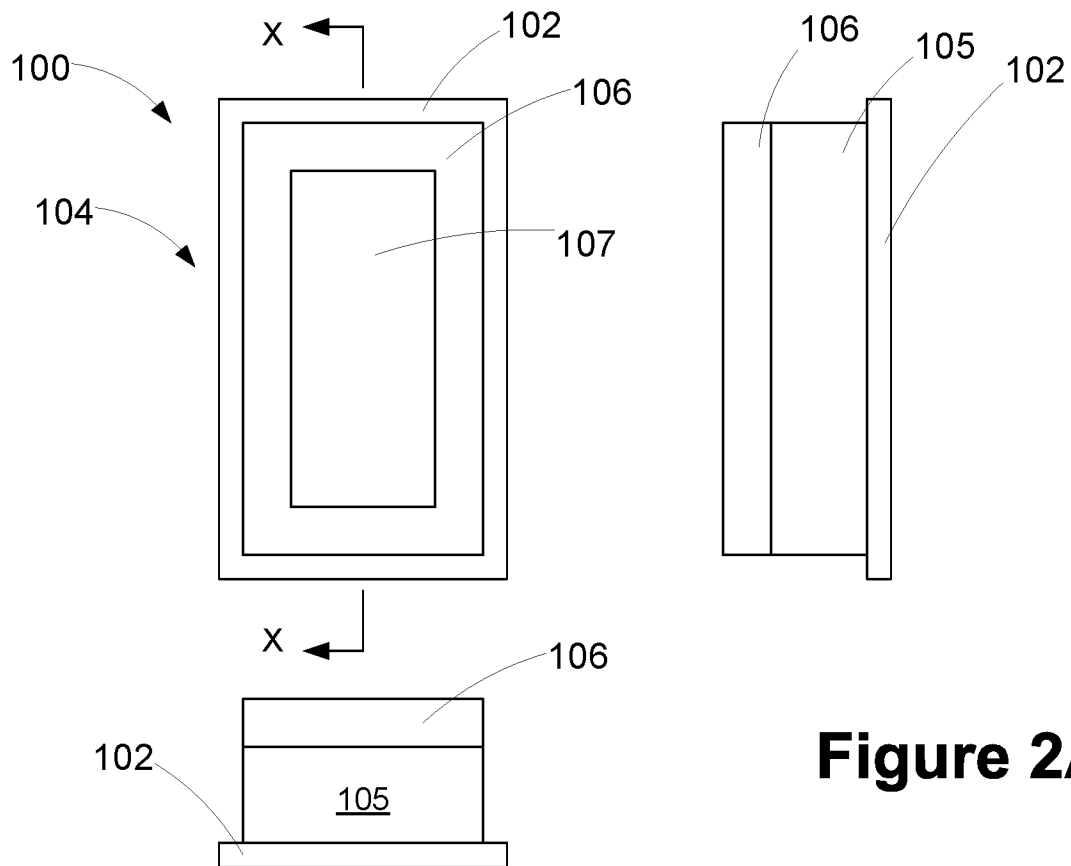


Figure 2A

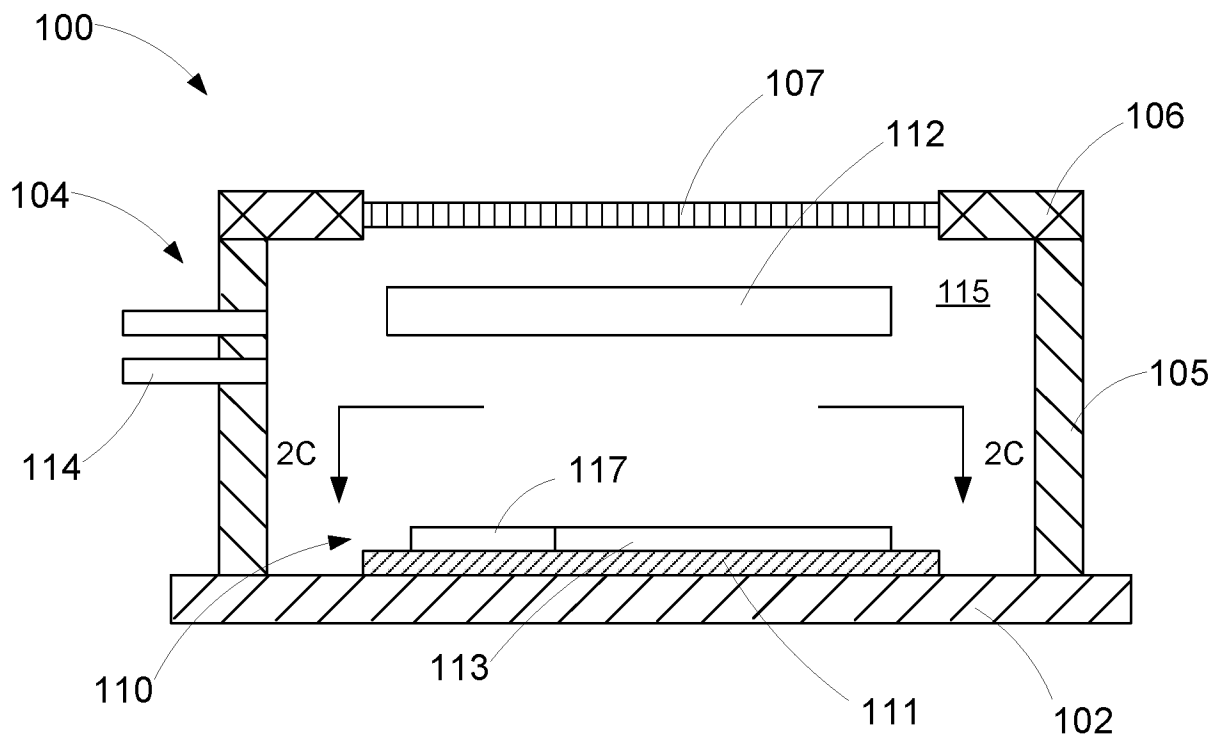


Figure 2B

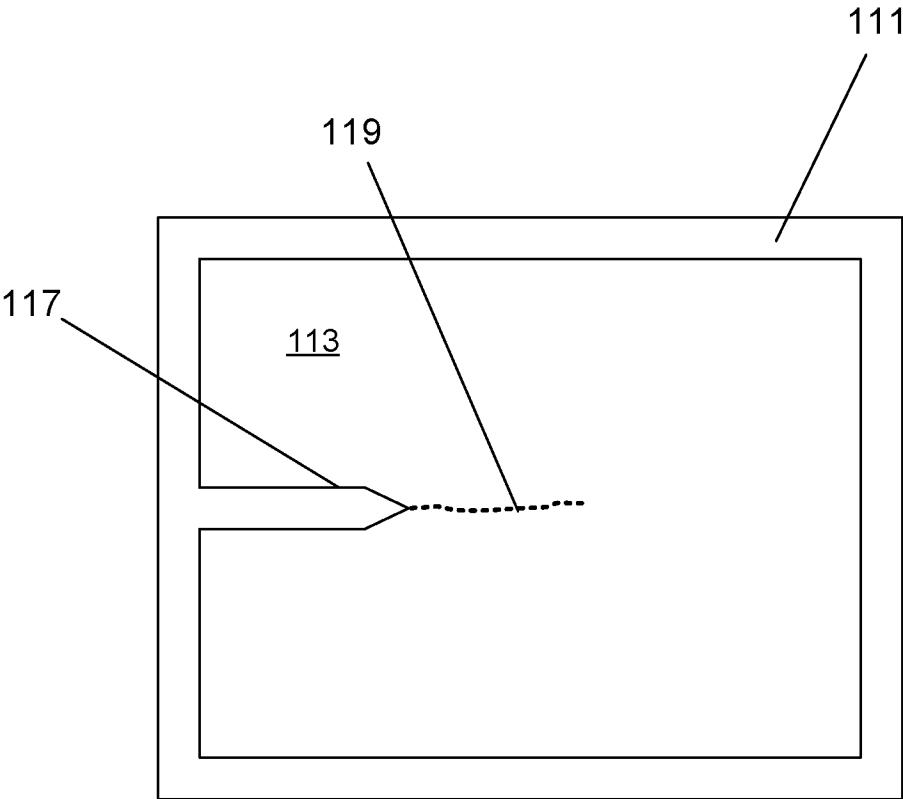
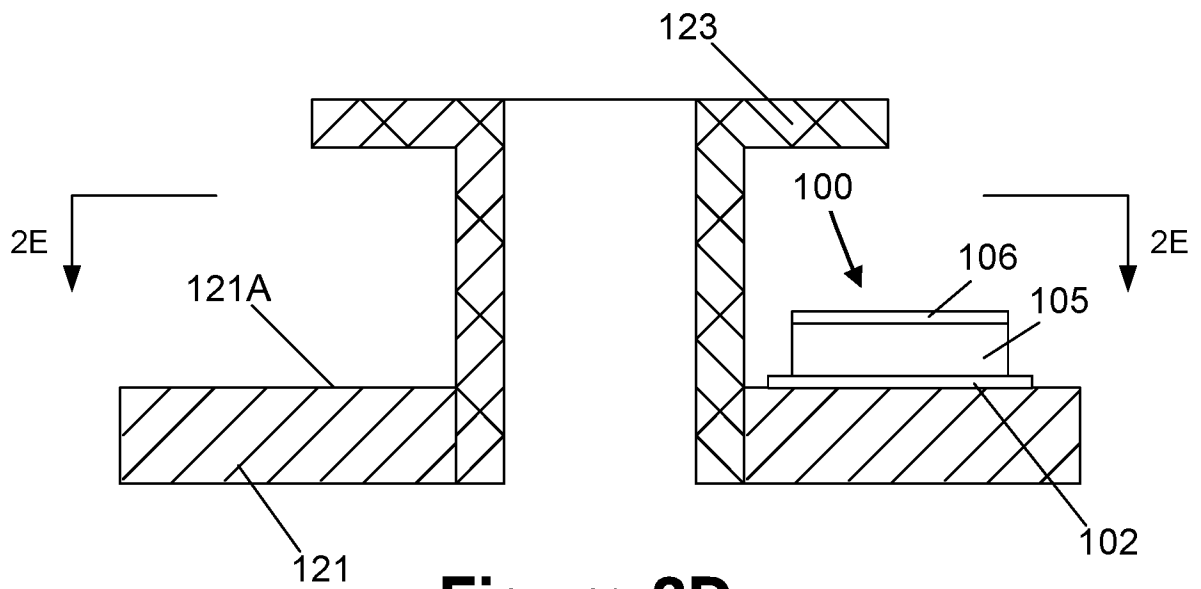
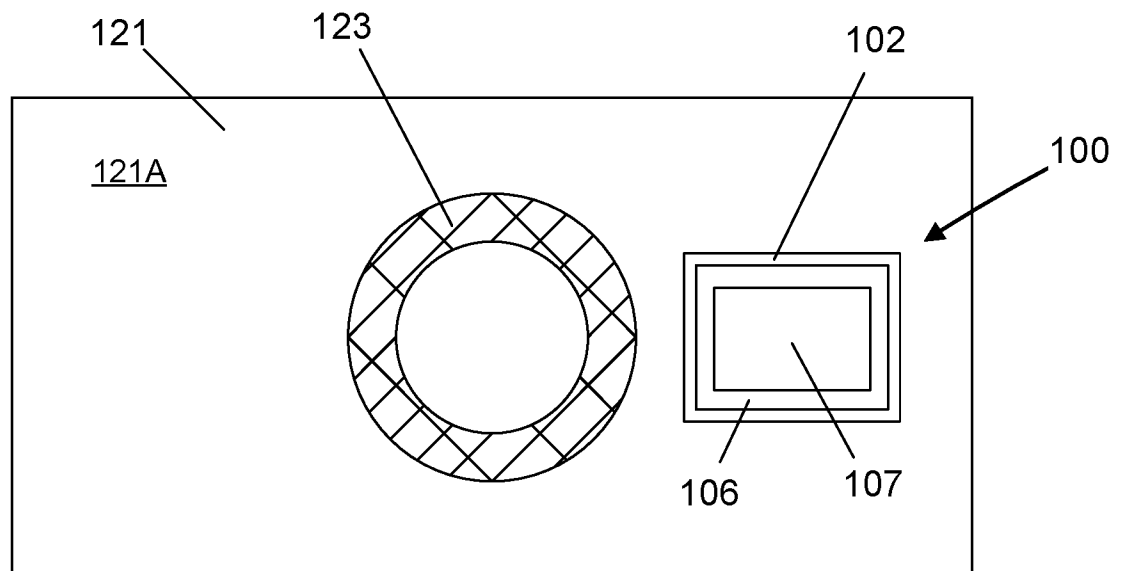
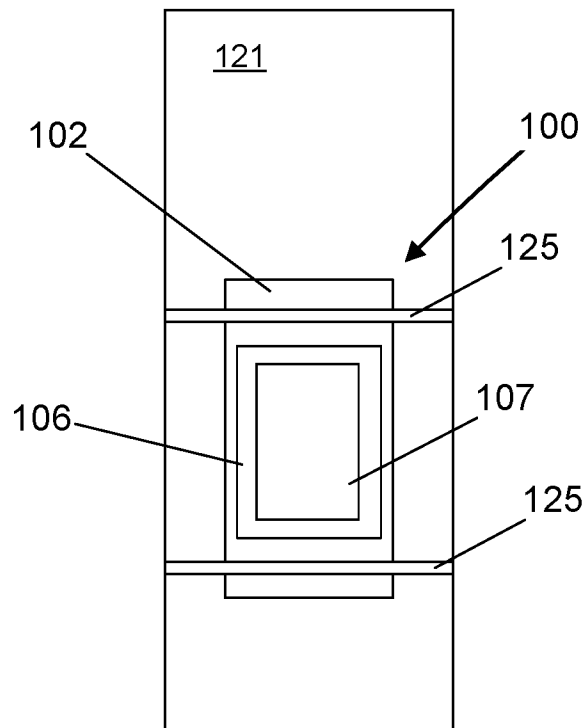
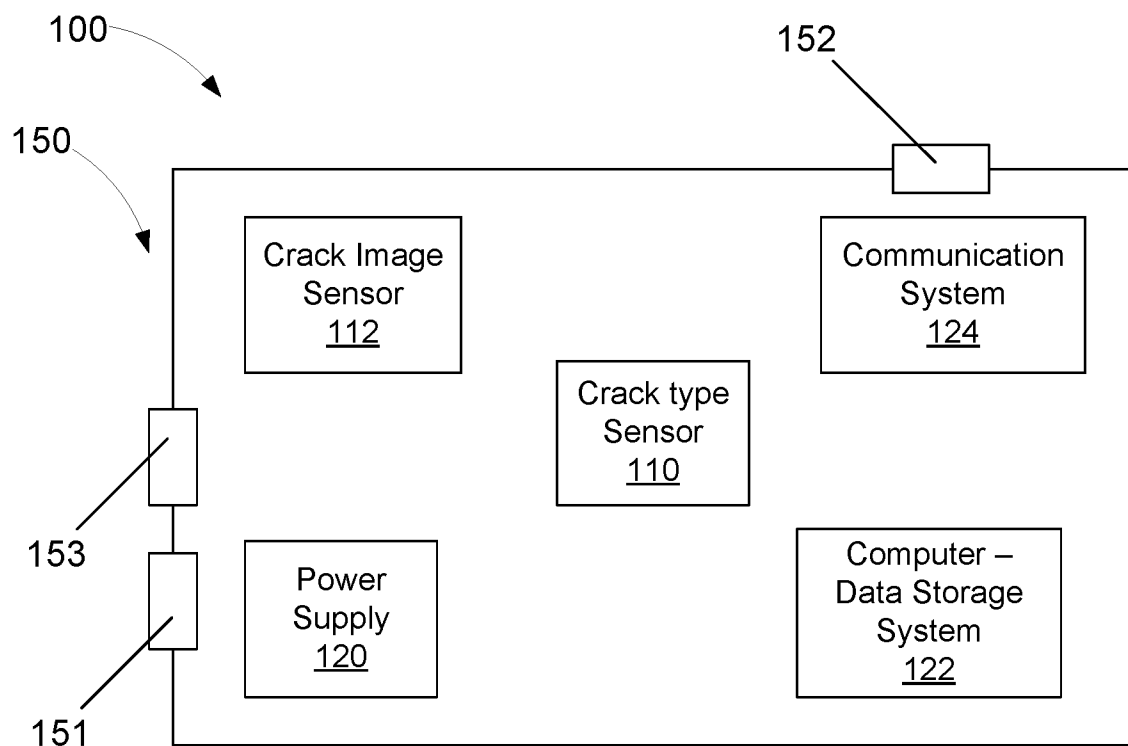


Figure 2C

**Figure 2D****Figure 2E**

**Figure 2F****Figure 2G**

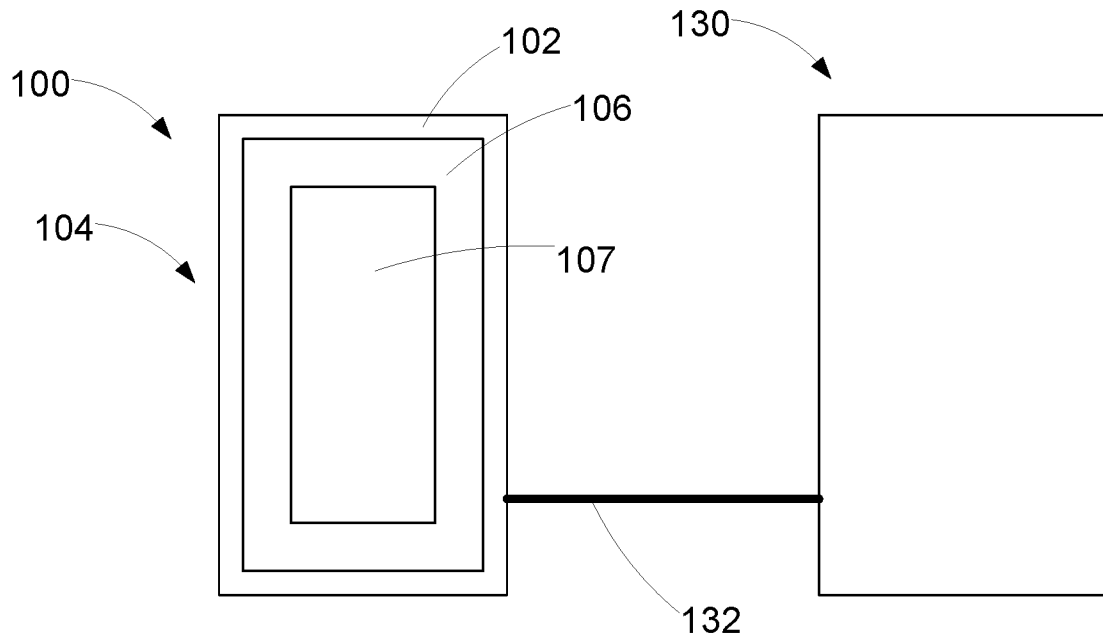


Figure 2H

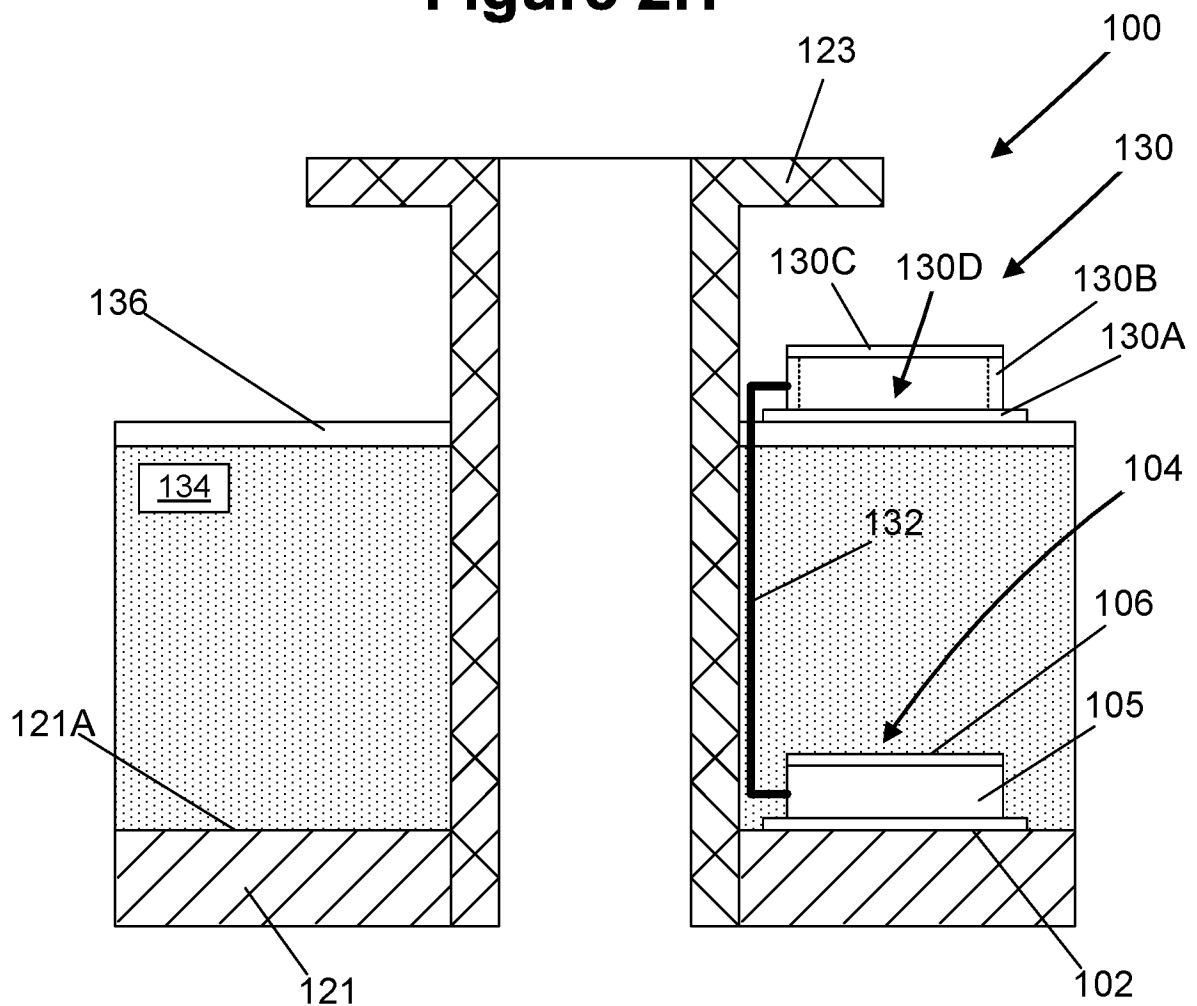


Figure 2I

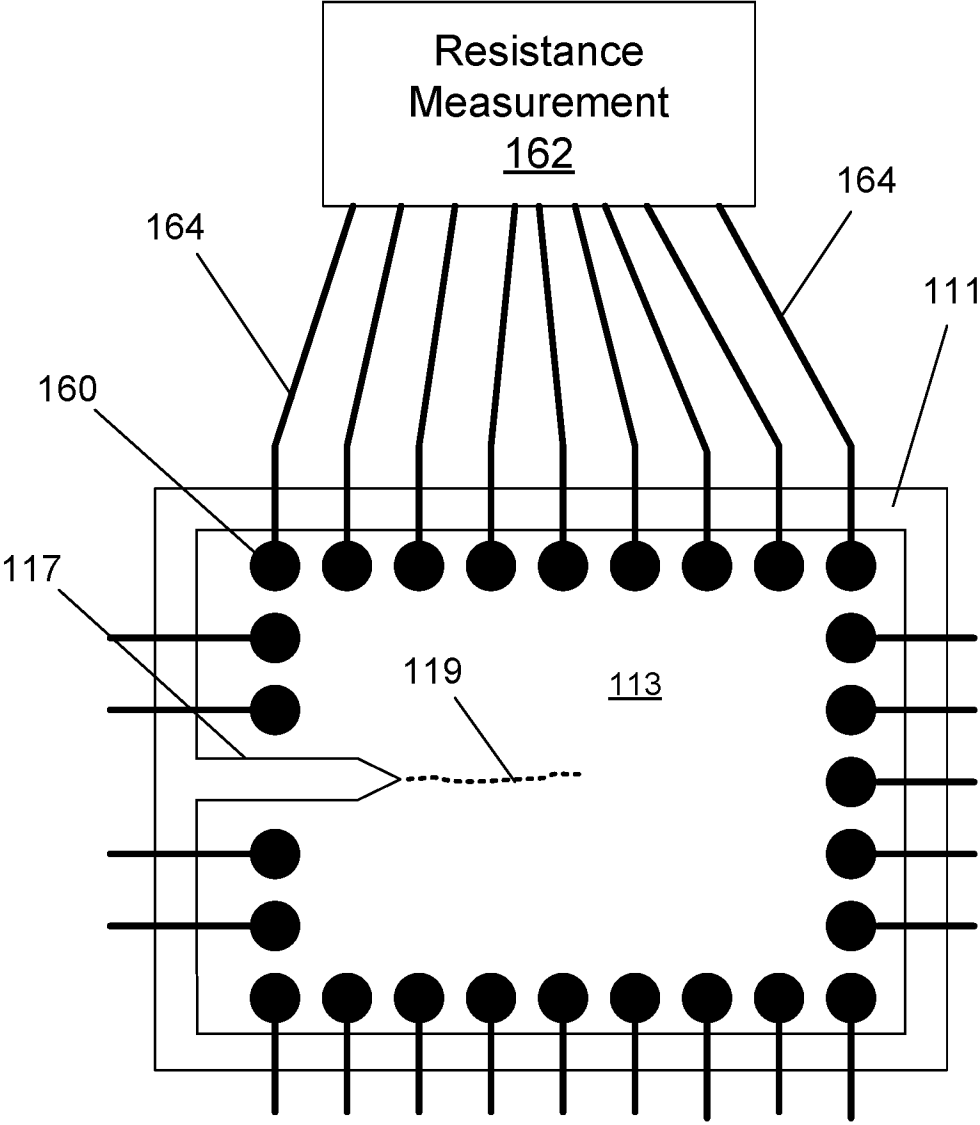


Figure 2J

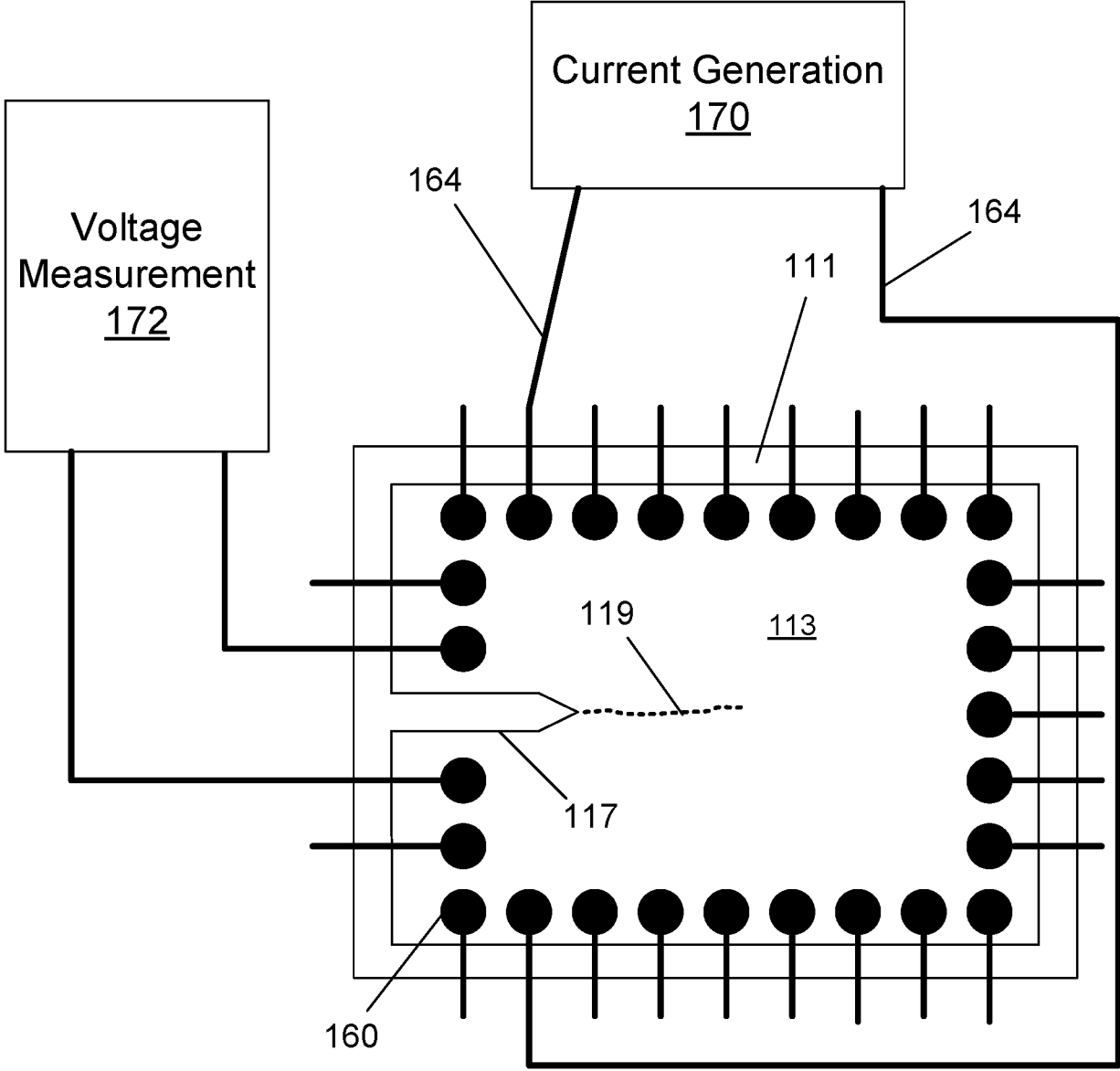


Figure 2K

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2016/046166

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01M5/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP S62 265558 A (KAWASAKI HEAVY IND LTD) 18 November 1987 (1987-11-18) abstract; figures 1-20	1-23
X	----- WO 02/01172 A1 (UNIV LONDON [GB]; BRENNAN FEARGAL PETER [GB]) 3 January 2002 (2002-01-03) page 11, line 5 - page 38, line 22; figures 1-10	1-23
X	----- EP 2 910 935 A2 (BOEING CO [US]) 26 August 2015 (2015-08-26)	1-16
A	paragraph [0019] - paragraph [0028]; figures 1-3	17-23
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Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

25 April 2017

Date of mailing of the international search report

04/05/2017

Name and mailing address of the ISA/

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Authorized officer

Gruss, Christian

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2016/046166

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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International application No

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