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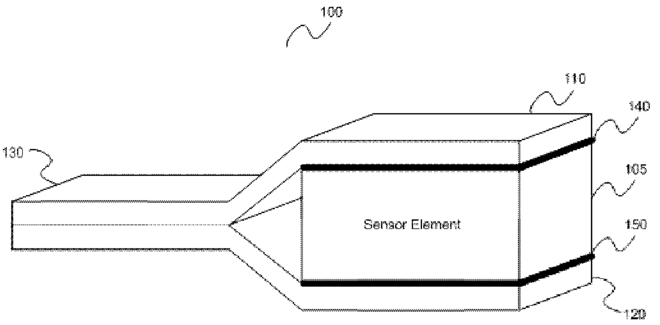

FIG.1

(57) Abstract: A non-destructive testing technique and sensor are described for measuring surface magnetic permeability and surface stress distribution in ferromagnetic materials. The sensor uses a thin film magnetoresistive sensing element that is either sandwiched between two thin film current conductors and insulators or placed above or below one conductor. Changes in the magnetic permeability of the ferromagnetic material upon which the sensor is placed create an output voltage which is monotonically depending on the magnetic permeability and also on the stress tensor of the ferromagnetic material. Appropriate calibration of the sensor may provide accurate stress distribution measurements, which may be wirelessly transmitted. Surface scanning is also supported by an integrated position sensor.

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MULTI-LAYER THIN FILM STRESS SENSOR FOR NON-DESTRUCTIVE TESTING OF FERROMAGNETIC MATERIALS

TECHNICAL FIELD

[0001] The present disclosure relates to non-destructive testing of ferromagnetic materials and, in particular, using magnetic field sensors for measuring magnetic permeability and residual stress without using coils or permanent magnets.

BACKGROUND

[0002] Steel and other ferromagnetic materials are used extensively in critical electromechanical systems where the strength of the material and its behavior under stress must be accurately known. Examples include aviation, railway, shipping, construction and others. In these applications defects in the used materials must be detected and cured so as to avoid unexpected and catastrophic failures. These failures may be caused where stress is applied, fatigue altering their structural integrity, or magnetic fields and temperature changes creating stress that may eventually lead to cracks and failures. Modern industrial manufacturing and maintenance of such materials employ a variety of techniques for identifying residual stresses and imperfections on the surface or in bulk of ferromagnetic materials, most often steel. Among these techniques is the Strain gage stress measuring technique. Strain gages typically consist of an insulating flexible backing which supports a metallic foil pattern, which is attached to the object under test by a suitable adhesive. As the object is deformed, the foil is also deformed, causing the electrical resistance of the foil to change. These gages can be fixed at a given point and are able to measure the stress component along their length at the point they are fixed. However, strain gages are sensors that measure stress at individual points. They also require preparation of the under-monitoring surface and are not suitable for scanning surfaces.

[0003] Another stress measuring technique is the Drill-Hole technique. Drill-Hole is based on drilling a small hole into the material under test. When the material containing residual stress is removed, the remaining material reaches a new equilibrium state. The new equilibrium state has associated deformations around the drilled hole. The deformations are related to the residual stress in the volume of material that was removed through drilling. The Drill-Hole technique measures deformations around the hole using strain gages or optical sensors. The original residual stress in the material is calculated from the measured deformations. However, the Drill-hole technique is a point measurement technique, which causes a destruction on the under test surface and is not suitable for scanning surfaces.

[0004] Another commonly used technique for stress measurement is the Magnetic Barkhausen Noise technique. The Magnetic Barkhausen Noise technique is based on the noise in the magnetic output of a ferromagnet when the magnetizing force applied to the ferromagnet is changed. The technique is based on the Barkhausen effect, which is a series of sudden changes in the size and orientation of ferromagnetic domains, or microscopic clusters of aligned atomic magnets (spins), that occur during a continuous process of magnetization or demagnetization. A slow, smooth increase of a magnetic field applied to a piece of ferromagnetic material, such as steel, causes the steel to become magnetized, not continuously but in minute steps. The technique is very sensitive to sensor orientation with respect to the surface under measurement. This sensitivity may cause large uncertainties in industrial surface monitoring, although the technique is excellent in laboratory use.

[0005] Another technique used in stress monitoring is stress measurement in the bulk and the surface of ferromagnetic steels. This technique has low uncertainty and high speed of measurement for the case of surface permeability and surface stress monitoring. Although the technique is able to monitor residual stresses and plastic deformation, the technique can monitor stress on an area of several cm^2, which is not a sufficient resolution level for many applications.

[0006] Another common stress measurement technique is the magnetostrictive delay line technique, which uses surface permeability sensors. The technique offers a claimed speed of measurement in the order of 1 point every 1 ms. However, despite claiming sensitive measurements and low uncertainty with a high speed of measurement, the technique requires air between the sensing element and its packaging to operate properly.

[0007] All these techniques refer to surface stress measurement, with the first two of them being point stress tensor techniques and not stress tensor distribution techniques. The third technique is a surface stress tensor distribution monitoring technique and is very sensitive to the geometrical uncertainties of the sensor set-up. The fourth technique has a large footprint and low response. The fifth technique has the best performance with a measuring surface of some mm^2 and speed of stress distribution monitoring of 1 point per ms.

[0008] There is, therefore, a need for a new sensor and a non-destructive technique to determine the surface permeability tensor distribution and consequently the residual stress tensor distribution on a ferromagnetic material surface. This technique and sensor should provide high sensitivity, low uncertainty, high resolution, and suitability for surface scanning. Furthermore, the sensor should be easy and cheap to manufacture, and simple and fast to use in industrial environments.

SUMMARY

[0009] A non-destructive testing technique and sensor are described for measuring surface magnetic permeability and surface stress distribution in ferromagnetic materials. In one approach, the sensor uses a thin film magnetoresistive sensing element that is either sandwiched between two thin film current conductors and insulators or placed above or below one conductor. Changes in the magnetic permeability of the ferromagnetic material upon which the sensor is placed, create an output voltage which is monotonically depending on the magnetic permeability and also on the stress tensor of the ferromagnetic material. Appropriate calibration of the sensor can provide accurate stress distribution measurements.

[0010] In alternate approaches, the sensor is made of either giant magnetoresistive or spin valve sensing elements. Other examples include the integration of the sensor with control and processing electronics manufactured in ASIC or other IC technology and enclosed in a packaging suitable for protecting the sensor and for direct applicability on the ferromagnetic surface under test.

[0011] Last, other implementations of the sensor may comprise a position sensor element, preferably implemented with a photonic sensor, to help track the position of the sensor on the surface under test and facilitate the surface scanning. Alternative implementations of the sensor may also comprise a wireless communication electronic transceiver to enable sensor stress tensor data to be wireless transmitted to a computer for visualization and analysis.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] **FIG.1** shows a schematic diagram of the components of a multi-layer thin film sensor in accordance with an exemplary embodiment.

[0013] **FIG.2** shows a schematic diagram of the sensor components of FIG.1 integrated with electronics and positioning modules, and positioned on a material under measurement.

[0014] **FIG.3** shows electromagnetic lines causing a sensor element to produce an output.

[0015] **FIG.4** shows a flow diagram of a technique using the sensor of FIG.2 for point measurements on a ferromagnetic material.

[0016] **FIG.5** shows a flow diagram of a technique using the sensor of FIG.2 for scanning the surface of a ferromagnetic material.

[0017] **FIG.6** shows a schematic diagram of a multi-layer thin film sensor for measuring surface permeability tensors and surface stress tensors along several directions in a ferromagnetic material.

[0018] **FIG.7** shows a block diagram of the electronic modules of the sensor of FIG.2.

DETAILED DESCRIPTION

[0019] The word "exemplary" is used herein to mean "serving as an example, instance, or illustration". Any example described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments.

[0020] The acronym "ASIC" is intended to mean "Application Specific Integrated Circuit".

[0021] The acronym "CPU" is intended to mean "Central Processing Unit".

[0022] The acronym "A/D" is intended to mean "Analogue to Digital".

[0023] The acronym "IC" is intended to mean "Integrated Circuit".

[0024] The acronym "AMR" is intended to mean "Anisotropic MagnetoResistance".

[0025] The acronym "GMR" is intended to mean "Giant MagnetoResistive".

[0026] As used herein and in the appended claims, the singular forms "a," "and," and "the" include plural referents unless the context clearly dictates otherwise.

[0027] The term "WiFi" is intended to refer to wireless local area networking with devices based on the IEEE 802.11 standard.

[0028] The term "ZigBee" is intended to refer to the IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios.

[0029] The term "computing device" may be used interchangeably with "computer", "computing system" and "mobile device" unless otherwise specified.

[0030] The term "test" may be used interchangeably with "measurement" unless otherwise specified. Similarly, for all words having the same root with the previous two terms.

[0031] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood to one of ordinary skill in the art to which this invention belongs (magnetism, electronics, measurement systems, and physics). Although any techniques similar or equivalent to those described herein can be used in the practice or testing of the invention, the preferred techniques are described.

[0032] The present invention treats the problem of accurate, fast, cheap, and with high resolution non-destructive measurements of surface stress tensors in ferromagnetic steels, in industrial and other harsh, non-laboratory environments. The invention is based on measuring surface permeability tensors. The invention proposes a novel sensor and a technique suitable for any type of ferromagnetic material (and especially ferromagnetic steels). The sensor is based on a thin film magnetic field sensing element sandwiched between two thin film conductors, and separated from them with two insulating thin films. The conductors' surface is equal to each other's and to that of the insulators and sensing element and are parallel to each other, while merging at one side to form a single conductor which is supplied with pulsed current as input. This input current propagates to the two parallel conductors and creates two magnetic fields which are partially absorbed by the ferromagnetic material under test, creating an output voltage at the sensing element. Another implementation includes a thin film magnetic field sensing element placed above or below a thin film conductor, separated from it with an insulating thin film. The conductor's surface is equal that of the insulator's and sensing element's and are parallel to each other. The conductor is supplied with pulsed current as input, which creates a magnetic field which is partially absorbed by the ferromagnetic material under test, creating an output voltage at the sensing element. Accurate calibration of the device enables this voltage measurement to be transformed into magnetic permeability tensor measurements of the underlying ferromagnetic material under test and ultimately to the stress tensors of the material. The stress tensors can in turn be used to analyze residual stresses and imperfections created during the manufacturing process or use of the ferromagnetic material under test. As a result, the measured stress tensors may also be used to control conditioning or rejection of the material.

[0033] In another example, the invention presents a modification of the same sensor to include an electronic circuit to control the operation of the sensor and process the output of the sensing element. This electronic circuit is implemented in Application Specific Integrated Circuit (ASIC) or other Integrated Circuit (IC) technology.

[0034] In yet another example, the invention presents a sensor that is integrated with a wireless transceiver to wirelessly transmit sensory data to a computing device.

[0035] The invention may be implemented either as a technique, a software program implementing the technique, or as an integrated sensor, a microprocessor, or a computer, or a computational device. The description of the invention is presented, for simplicity, in terms of the sensor and technique implementing the invention but it is assumed to equally apply to the other forms of implementation previously mentioned.

[0036] **FIG.1** shows a schematic diagram of the components of a multi-layer thin film sensor in accordance with an exemplary embodiment. The sensor 100 comprises a thin film magnetic film sensing element 105, which may be of any type. By means of example and without limiting the scope of the invention, sensing element 105 may be an Anisotropic MagnetoResistance (AMR) sensor, a Giant MagnetoResistive (GMI) sensor, a spin valve sensor, etc.

[0037] The sensing element 105 is coated with two insulating thin films 140, 150, which are in turn coated with two thin film electrical conductors 110, 120, respectively. These conductors 110, 120 have, as much as possible, identical dimensions and are bent at one end to merge and form a single conductor 130, which single conductor 130 forms the input of the sensor 100. A pulsed current applied to the input, i.e. at conductor 130, will cause the sensor to produce an output voltage at the sensor output, i.e. at the sensing element 105.

[0038] **FIG.2** shows a schematic diagram of the sensor components of FIG.1 integrated with electronics and positioning modules, and positioned on a material under measurement. The sensor 200, comprises the thin film sensing element 205, the thin film insulators 240, 250, and the thin film conductors 210, 220 merging into the input thin film conductor 230. On top of conductor 210 is located an electronic circuit 260, which may be implemented in Application Specific Integrated Circuit (ASIC) or other Integrated Circuit (IC) technology. The electronic circuit 260 contains electronic modules for driving and controlling the operation of the sensor, processing output voltage to produce the magnetic permeability and stress measurements characterizing the ferromagnetic material under test 280.

[0039] On the outer surface of conductor 220, a packaging 270 is attached. This packaging 270 is selected to act as an interface for attaching the sensor to the material under test 280. The function of the packaging is to keep a fixed separation of the sensor from the material under test, so as not to bias the sensor measurements. The packaging also functions as a protective shield for the sensor and for this reason the packaging may be formed in such a way as to enclose the sensor from all sides as shown in the diagram of **FIG.2**. In an alternative exemplary embodiment, the packaging 270 may comprise a first material for the face that touches the material under test 280 and a second (or more) materials for the other sides.

[0040] Applying an input current pulse at the conductor 230 will produce a current and a voltage at the output, i.e. sensing element 205. The output of the thin film magnetic field sensing element 205 is monotonically dependent on the surface permeability μ and the residual stresses σ of the surface area of the ferromagnetic material under measurement 280, defined by the projection of the surface of the thin film magnetic field sensing element 205.

[0041] In an alternative embodiment, the sensor 200 also contains a position sensor element 290 for tracking the position of the sensor 200 when the sensor scans the surface of the ferromagnetic material under test 280 by moving the sensor 200 across the surface 280. Data from the position sensor element 290 characterize the dependence of the stress components on the different locations on the surface of the ferromagnetic steel under measurement 280 and therefore, permeability and stress tensors can be derived.

[0042] **FIG.3** shows electromagnetic lines causing a sensor element to produce an output. The sensor 300, comprises two thin film wires 310, 320, merging at one side to thin film conductor 330, and sandwiching two insulating thin films 340, 350, respectively, which in turn sandwich a thin film magnetic field sensing element 305. Sensor 300 sits on a packaging material 370 which is placed in direct or small lift-off contact with a ferromagnetic material under test 380. The sensor may comprise additional elements as shown in **FIG.2**.

[0043] When current is supplied to the thin film conductor 330, the current propagates to thin film conductors 310, 320 and magnetic fields are formed around these two conductors. Conductor 310 has a magnetic field H_1 formed around it, which is illustrated with magnetic field lines 394, 396. These lines pass through the sensing element 305. Since thin film conductor 320 is of, as much as possible, identical shape and dimensions as thin film conductor 310, the same current flows to conductor 320 as in conductor 310, which current creates a magnetic field H_2 of equal strength to H_1. However, due to the proximity of conductor 320 to the ferromagnetic material 380, some of the magnetic lines of field H_2 get trapped in the material 380 and as a result a lower strength field H_2' reaches the sensing element 305. Field H_2' is represented by magnetic field line 392. The resulting magnetic field sensed by the sensing element 305 creates an output voltage which is proportional to the magnetic permeability (and residual stress) of the underlying volume of the ferromagnetic material under test 380.

[0044] **FIG.4** shows a flow diagram of a technique using the sensor of FIG.2 for point measurements on a ferromagnetic material. The technique starts with positioning 400 the sensor 200 on the surface of the ferromagnetic material under test 280. The sensor is thus positioned at direct contact with the material 280 ideally leaving no gap in between, at a point (x, y) and at a direction θ. This positioning may be done manually by its user, or using a mechanical arm operating manually or automatically.

[0045] The technique then applies a pulsed current 410 (I_1) at the input of the sensor, i.e. at the conductor 230. Since conductor 230 is electrically connected with conductors 210, 220, and since the two conductors 210, 220 have the same dimensions to each other (and therefore the same resistance since they are made of the same material), they receive the same amount of pulsed currents I_2, I_3 where $I_2+I_3=I_1$. Currents I_2, I_3 create two magnetic fields H_1 and H_2 that are parallel to the surface of conductors 210, 220 and consequently to the surface of the sensor element 205 which they penetrate.

[0046] The fields H_1 and H_2 from the conductors 210 and 220, respectively, are proportional to the transmitted pulsed currents I_1 & I_2 to each one of them, and inversely proportional to the distance d_1 & d_2 between the pulsed current conductors 210 and 220 and the thin film magnetic field sensing element 205:

$$H_1 = a\frac{I_1}{d_1} \text{ and } H_2 = -a\frac{I_2}{d_2} \qquad \text{(Equation 1)}$$

where “α” is a proportionality constant. Considering that the pulsed currents I_1 & I_2 are equal to each other and the distances d_1 & d_2 are equal to each other, then the total field H along the surface of the thin film magnetic field sensor 205 is:

$$H = H_1 + H_2 = a\frac{I}{d} + \left(-a\frac{I}{d}\right) = 0 \qquad \text{(Equation 2)}$$

[0047] Thus, the output of the thin film sensor element 205 equals to zero and corresponds to its zero reference field.

[0048] When the sensor, and in particular its packaging 270 approaches the ferromagnetic material under measurement 280, provided that the distance between the packaging 270 and the ferromagnetic material 280 is small (in the order of a few μm) or zero, the magnetic lines due to the field H_1 are partially trapped by the ferromagnetic material under measurement 280, allowing only a part of the magnetic field H_2 to remain in the volume of the thin film magnetic field sensor element 205:

$$\mathrm{H}_2 = \mathrm{H}_2 - \mathrm{H}_2^{\mu} \qquad \text{(Equation 3)}$$

where H_2^{μ} is the magnetic field corresponding to the magnetic lines trapped by the surface of the ferromagnetic material under measurement 280, which are dependent on the surface permeability of the material 280.

[0049] Instead, most of the magnetic lines due to the field H_1 remain in the area close to the thin film magnetic field sensor element 205 according to Maxwell's equations. Therefore, an unbalance in the magnetic field within the volume of the thin film magnetic field sensor element 205 is generated and H becomes:

$$H = -H_2^{\mu} \qquad \text{(Equation 4)}$$

[0050] Therefore, the output of the thin film magnetic field sensor element 205 is proportional to the surface permeability component of the ferromagnetic material under measurement 280, parallel to the magnetic fields H_1 & H_2.

[0051] It is also known that the permeability component μ of a ferromagnetic material is proportional to the residual stress component σ in the area of its surface and the corresponding direction or in a corresponding volume just below it:

$$\sigma = b\mu \quad \text{or} \quad \sigma_x = b\mu_x \quad \& \quad \sigma_y = b\mu_y \qquad \text{(Equation 5)}$$

[0052] Therefore, the output of the thin film magnetic field sensor is proportional to the stress component parallel to the magnetic fields H_1 & H_2.

[0053] Change of orientation of the sensor or manufacturing of several sensors on the same chip, in corresponding directions, offers the ability of monitoring the stress components on the surface of the ferromagnetic material under measurement 280.

[0054] The thin film magnetic field sensor element 205 may be any of the existing, industrially available thin film magnetic field sensors, namely Anisotropic MagnetoResistance (AMR) sensors, Giant MagnetoResistive (GMR) sensors, spin valve sensors, etc. The largest surface of these sensors, currently available in the market of ASIC is below 100μm X 100μm, while as narrow as 1μm X 1μm thin film magnetic field sensor surfaces exist with similar or even better sensitivity and uncertainty. The spatial resolution of the sensor equals the surface of the thin film magnetic field sensor element 205. Thus, spatial resolution may range from 100μm X 100μm down to 1μm X 1μm.

[0055] The speed of each measurement of the sensor element 205 is less than 1μs, thus the speed of measurement per point on the material's 280 surface is less than 1μs.

[0056] The sensitivity and uncertainty of the stress sensor 200 are dependent on the sensitivity and uncertainty of the thin film magnetic field sensor element 205. Bearing in mind that the worst sensitivity of the above mentioned thin film magnetic field sensor elements 205 (AMR, GMR etc.) is 1 nT@$\text{Hz}^{-1/2}$ improving as a function of the inverse square route of the frequency, the sensitivity of the sensor 200 in pulsed current operation is far better than 1nT. This sensitivity corresponds to much less than 1MPa of local stress.

[0057] The technique continues with measuring the output voltage 420 at the sensor element 205 and processing 430 this voltage. The processing step 430 is optional and may comprise filtering, conditioning, A/D conversion, storage in memory, etc.

[0058] Using calibration data stored in the memory of the sensor 200, the technique derives surface permeability tensors and surface stress tensors 440. These tensors may be derived, for example, by associating a voltage measurement with μ and σ values by looking at a lookup table stored in memory. This exemplary embodiment uses A/D conversion of the output voltage prior to associating this voltage with the μ and σ values.

[0059] In a variation of the above exemplary embodiment, the association of the three values may also use interpolation to calculate intermediate values to those contained in the lookup table.

[0060] In an alternative exemplary embodiment, the technique may perform the above steps in the analogue domain, i.e. no A/D conversion of the output voltage is used.

[0061] The technique ends by wirelessly transmitting the μ and σ values to a receiving computer 450. According to the chosen implementation of the current technique, as presented by the various exemplary embodiments, step 450 may transmit either digital or analogue data. In a variation of this exemplary embodiment, the sensor has no memory and simply transmits output voltage measurements to a computer which has the lookup table and performs the necessary calculations to produce the μ and σ values.

[0062] In a variation of this exemplary embodiment, the technique may store μ and σ data in the memory of the sensor 200, either volatile memory for facilitating data processing and/or transmission (e.g. to cater for unsuccessful wireless transmission), or non-volatile memory for long-term availability.

[0063] **FIG.5** shows a flow diagram of a technique using the sensor of FIG.2 for scanning the surface of a ferromagnetic material. The technique starts with positioning 500 the sensor 200 on the surface of the ferromagnetic material under test 280. The sensor is thus positioned at direct contact with the material 280, ideally leaving no gap in between, at a point (x, y) and at a direction θ.

[0064] The technique then applies a pulsed current 510 (I_1) at the input of the sensor, i.e. at the conductor 230. Since conductor 230 is electrically connected with conductors 210, 220, and since the two conductors 210, 220 have the same dimensions (and, therefore, the same resistance since they are made of the same material), they receive the same amount of pulsed currents I_2, I_3 where $I_2+I_3=I_1$. Currents I_2, I_3 create two magnetic fields H_1 and H_2 that are parallel to their surface and consequently to the surface of the sensor element 205 which they penetrate.

[0065] The technique continues with measuring the output voltage 520 at the sensor element 205 and processing 530 this voltage. The processing step 530 is optional and may comprise filtering, conditioning, A/D conversion, storage in memory, etc.

[0066] Using calibration data stored in the memory of the sensor 200, the technique derives surface permeability tensors and surface stress tensors 540. These tensors may be derived, for example, by associating a voltage measurement with a μ and σ values by looking at a lookup table stored in memory. This exemplary embodiment uses A/D conversion of the output voltage prior to associating this voltage with the μ and σ values.

[0067] In a variation of the above exemplary embodiment, the association of the three values may also use interpolation to calculate intermediate values to those contained in the lookup table.

[0068] In an alternative exemplary embodiment, the technique may perform the above steps in the analogue domain, i.e. no A/D conversion of the output voltage is used.

[0069] The technique continues by wirelessly transmitting the μ and σ values to a receiving computer. According to the chosen implementation of the current technique, as presented by the various exemplary embodiments, the technique may transmit either digital or analogue data.

[0070] In a variation of this exemplary embodiment, the technique may store μ and σ data in the memory of the sensor 200, either volatile memory for facilitating data processing and/or transmission (e.g. to cater for unsuccessful wireless transmission), or non-volatile memory for long-term availability.

[0071] The technique checks if the scanning of the ferromagnetic material surface under test 280 continues with measurements at other points 560. If not, then the technique ends, otherwise the sensor 200 is moved to a new position 570. The technique repeats until no new points are left to measure and then ends. Data from the position sensor 290 are stored alongside each μ and σ values. The mechanism for moving the sensor over the scanned surface is not part of the present invention. By means of example it may be implemented by a human operator manually moving the sensor by hand, or by means of a mechanical arm that it either manually or automatically operated.

[0072] In a modification of this exemplary embodiment of the invention, the wireless transmission of the scan data (i.e. the μ, σ, and position values of the set of points where measurements were performed to cover the selected area of the material 280; e.g. a lattice of points) is performed in step 580 once for the entire set of data.

[0073] In a variation of this exemplary embodiment, the sensor has no memory and simply transmits output voltage and position measurements to a computer which has the lookup table and performs the necessary calculations to produce the μ and σ values.

[0074] **FIG.6** shows a schematic diagram of a multi-layer thin film sensor for measuring surface permeability tensors and surface stress tensors along several directions in a ferromagnetic material. This sensor 600 contains at least two sensors at an angle to each other for measuring μ and σ values at various orientations at each measurement position on the surface of the ferromagnetic material under test 280. In this particular example, three sensors 610, 620, 630 are used, each one being of the type of sensor 200. Sensor 600 is enclosed in a packaging of the same type as the packaging used in sensor 200.

[0075] In an alternative embodiment, the ASIC or IC 260, and positioning sensor 290 contained in each sensor 610, 620, 630 are replaced by a single ASIC or IC, and positioning sensor for the entire sensor 600 which control the operation of all three sensors 610, 620, 630. This exemplary implementation results in simpler design and manufacturing of sensor 600, as well as, reduced cost. Alternative implementations of sensor 600 may be manufactured, employing alternative arrangement of the three sensors 610, 620, 630 on the surface and volume of sensor 600.

[0076] In an alternative exemplary embodiment, the sensor may be manufactured to contain an array of tightly packed sensors of the type of sensor 200 or sensor 600 so as to perform several (equal to the number of packed sensors in the array) simultaneous measurements and speed up surface scanning of the ferromagnetic materials under test.

[0077] **FIG.7** shows a block diagram of the electronic modules of the sensor of FIG.2. The sensor 700 is shown positioned on a ferromagnetic material under test 730. The sensor 700 comprises a sensor element module 705 of the same type as sensor 200, and an ASIC or IC 702.

[0078] The ASIC or IC 702 comprises a pulsed current generator 740 for supplying current to the current conductor 230 which forms the input 710 of the sensor module 705. The pulsed current generator 740 is controlled by the processor 750 (e.g. a microcontroller), which is in turn connected to a memory module 760. Memory 760 may comprise a volatile memory, a non-volatile memory, or a combination of the two memory types and this memory 760 may store computer instructions, data, measurements of μ, σ and position from the sensor 705 and data from previous measurements, etc.

[0079] The output 720 of the sensor module 705 outputs a voltage which is fed to an analogue filter 770 which outputs its signal to an A/D converter 780. The A/D converter 780 converts the (analogue) voltage signal to a digital representation and feeds the digitized voltage to the processor 750.

[0080] In alternative exemplary embodiments, the analogue filter 770 may be omitted, or replaced by a digital filter (not shown) placed between A/D converter 780 and processor 750, or implemented in software in the processor 750.

[0081] Having received the digitized representation of the voltage from the output of the sensor module 720, the processor 750 may derive or calculate the μ and σ values for the point under measurement of the ferromagnetic material 730.

[0082] Using calibration data stored in memory 760, the processor 750 may derive surface permeability tensors μ and surface stress tensors σ by associating a voltage measurement with a μ and σ values by looking at a lookup table stored in memory 760.

[0083] In a variation of the above exemplary embodiment, μ and σ values may be calculated by interpolating intermediate values to those contained in the lookup table.

[0084] Once the processor has derived or calculated the μ and σ values for a point or for the entire scan of the surface of the material 730, the processor may store them in memory 760 (volatile and/or non-volatile) and then send them to the wireless transceiver 790 for transmission to a computer 795. For a surface scan, position data are also stored. By means of example, the wireless data transmission may be done using one of the WiFi, ZigBee, Bluetooth, cellular network, or a proprietary wireless technology.

[0085] The computer 795 may store the received data and analyze and visualize them using a software program, allowing its user to visualize a mapping of the surface tensor distribution for the selected point or scanned area of the ferromagnetic material 795. The software program used in this visualization may be an in-house developed Application Specific Software, a general-purpose visualization software, a combination of software packages, a remote server or cloud-based software, and the like. The computer 795 may be a general-purpose or application-specific computer, computing device, portable device, server, computing system or the like.

[0086] By means of example, the sensor in the present invention may measure 100μm X 100μm or less, depending on the dimensions of the employed thin film sensing element. These dimensions are also the resolution achieved by the sensor. As new sensing elements become commercially available, significant improvements in size and resolution of the proposed sensor can be achieved. The proposed sensor is suitable for integration with ASIC and may operate both as an active device with integrated battery, as well as, a passive device where power is captured from electromagnetic energy transmitted to the sensor during measuring operation by an electronic reader or other device.

[0087] By means of example, the speed of measurement achieved by the proposed sensor is less than one point measurement per μs, rendering the sensor and the associated technique suitable for industrial applications and especially for scanning of ferromagnetic surfaces. This scanning is facilitated by the readings of the integrated position sensor, while the wireless data transmission speeds up the measurement processes and allows using the sensor and the associated technique in continuous measurement operation.

[0088] The sensitivity and uncertainty of the stress sensor are dependent on the sensitivity and uncertainty of the implemented thin film magnetic field sensor. Bearing in mind that the worst sensitivity of the above mentioned thin film magnetic field sensors (AMR, GMR etc.) is $1nT@Hz^{-1/2}$ improving as function of the inverse square route of the frequency, the sensitivity of the sensor in pulsed operation is far better than 1nT. This sensitivity corresponds to much less than 1MPa of local stress. These exemplary values are by no means limiting the scope of the present sensor and associated technique.

[0089] The above exemplary embodiment descriptions are simplified and do not include hardware and software elements that are used in the embodiments but are not part of the current invention, are not needed for the understanding of the embodiments, and are obvious to any user of ordinary skill in related art. Furthermore, variations of the described technique, system architecture, and software architecture are possible, where, for instance, technique steps, and hardware and software elements may be rearranged, omitted, or new added.

[0090] Various embodiments of the invention are described above in the Detailed Description. While these descriptions directly describe the above embodiments, it is understood that those skilled in the art may conceive modifications and/or variations to the specific embodiments shown and described herein. Any such modifications or variations that fall within the purview of this description are intended to be included therein as well. Unless specifically noted, it is the intention of the inventor that the words and phrases in the specification and claims be given the ordinary and accustomed meanings to those of ordinary skill in the applicable art(s).

[0091] The foregoing description of a preferred embodiment and best mode of the invention known to the applicant at this time of filing the application has been presented and is intended for the purposes of illustration and description. It is not intended to be exhaustive or limit the invention to the precise form disclosed and many modifications and variations are possible in the light of the above teachings. The embodiment was chosen and described in order to best explain the principles of the invention and its practical application and to enable others skilled in the art to best utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. Therefore, it is intended that the invention not be limited to the particular embodiments disclosed for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

[0092] Those of skill in the art would understand that signals may be represented using any of a variety of different techniques. For example, data, software, instructions, signals that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, light or any combination thereof.

[0093] Those of skill would further appreciate that the various illustrative radio frequency or analog circuit blocks described in connection with the disclosure herein may be implemented in a variety of different circuit topologies, on one or more integrated circuits, separate from or in combination with logic circuits and systems while performing the same functions described in the present disclosure.

[0094] Those of skill would also further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the disclosure herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present disclosure.

[0095] The various illustrative logical blocks, modules, and circuits described in connection with the disclosure herein may be implemented or performed with a general-purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g. a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0096] In one or more exemplary embodiments, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over as one or more instructions or code on a computer readable medium. Computer-readable media includes both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage media may be any available media that can be accessed by a computer. By way of example, and not limitation, such computer-readable media can comprise RAM, ROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code in the form of instructions or data structures and that can be accessed by a computer or any other device or apparatus operating as a computer. Also, any connection is properly termed a computer-readable medium. For example, if the software is transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and blu-ray disc where disks usually reproduce data magnetically, while discs reproduce data optically with lasers.

Combinations of the above should also be included within the scope of computer-readable media.

[0097] An exemplary storage medium is coupled to the processor such that the processor may read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an ASIC. The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[0098] The previous description of the disclosed exemplary embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these exemplary embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

CLAIMS

1. A sensor of the multi-layer thin film type for measuring surface permeability tensors and surface stress tensors in ferromagnetic steels, comprising:

a thin film magnetic field sensing element;

a first and a second insulating thin films deposited on each side of the thin film magnetic field sensing element, where the insulating thin films have substantially the same dimensions with each other and with the magnetic field sensing element and are substantially parallel to each other; and

a first and a second thin film current conductors each deposited on the distant to the magnetic field sensing element side of the first and second insulating thin films, respectively,

the thin film current conductors having substantially the same dimensions with each other and with the insulating thin films and being substantially parallel to each other, and being bent at one side so as to converge towards each other and form a third thin film current conductor, the three thin film conductors being electrically connected to each other.

2. The sensor of claim 1, further comprising:

an electronic circuit attached to the outer side of the first thin film current conductor, and

external packaging attached to the outer side of the second thin film current conductor, where the external packaging is configured to attach to the surface of a ferromagnetic steel under measurement without leaving a gap between the external packaging and the ferromagnetic steel.

3. The sensor of claim 2, where the electronic circuit comprises at least one of an analogue to digital converter, signal filtering, pulsed current generator, position tracker, wireless transceiver, processor, non-volatile memory, where the non-volatile memory stores sensor calibration data and instructions, volatile memory, where the volatile memory stores measurement data, and a battery.

4. The sensor of claim 3, where the electronic circuit is configured in the form of an Application-Specific-Integrated-Circuit (ASIC) or other integrated circuit.

5. The sensor of claim 3, where the position tracker module is of the form of a position sensor.

6. The sensor of claim 3, where the wireless communication module comprises one of: WiFi, ZigBee, Bluetooth, cellular network, or a proprietary wireless technology.

7. A method of measuring surface permeability tensors and surface stress tensors in ferromagnetic steels, comprising:

positioning a multi-layer thin film sensor at a location on the surface of a ferromagnetic steel;

applying a pulsed current to the input of the sensor;

measuring a voltage at the output of the sensor;

processing the measured voltage;

deriving and/or calculating surface permeability tensors and surface stress tensors for the surface of the ferromagnetic material in contact with the sensor; and

wirelessly transmitting the derived and/or calculated data.

8. The method of claim 7, where the sensor is of the form of the sensor of claim 4.

9. The method of claim 8, further comprising moving the sensor to other locations on the surface of the ferromagnetic steel under test and repeating the method until all the surface has been scanned.

10. The method of claim 9, where the scanning is guided by the readings of the position sensor.

11. A sensor of the multi-layer thin film type for measuring surface permeability tensors and surface stress tensors in a multitude of directions in ferromagnetic steels, comprising at least two sensors of the type of sensor of claim 2, where the sensors are arranged coplanar and at an angle to each other.

12. The sensor of claim 11, further comprising at least one of the following modules:

an analogue to digital converter;
signal filtering;
pulsed current generator;
position tracker;
wireless transceiver;
processor;
non-volatile memory, where the non-volatile memory stores sensor calibration data and instructions;
volatile memory, where the volatile memory stores measurement data; and
a battery.

13. A non-transitory computer program product that causes a sensor of the multi-layer thin film type to measure surface permeability tensors and surface stress tensors in ferromagnetic steels, the non-transitory computer program product having instructions to:

apply pulsed current to the input of the sensor;
measure a voltage at the output of the sensor;
process the measured voltage;
derive and/or calculate surface permeability tensors and surface stress tensors for the surface of the ferromagnetic material in contact with the sensor; and
wirelessly transmit the derived and/or calculated data.

14. The non-transitory computer program product of claim 13, where the sensor is of the form of the sensor of claim 4.

15. The non-transitory computer program product of claim 14, further comprising scanning the surface of the ferromagnetic steel.

16. The non-transitory computer program product of claim 13, where the sensor is of the form of the sensor of claim 12.

17. A sensor of the multi-layer thin film type for measuring surface permeability tensors and surface stress tensors in a multitude of positions on ferromagnetic steels, comprising an array or sensors of the type of sensor of claim 2.

18. A sensor of the multi-layer thin film type for measuring surface permeability tensors and surface stress tensors in a multitude of directions and positions on ferromagnetic steels, comprising an array of sensors of the type of sensor of claim 11, where the sensors are arranged coplanar and at an angle to each other.

19. A thin-film sensor for non-destructive testing of ferromagnetic materials without using coils or magnets, the sensor comprising:

means for creating electromagnetic fields in the vicinity of a ferromagnetic material under test, where such fields are both positioned at the same side of the ferromagnetic material;

means for measuring the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material; and

means for calculating stress using the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material.

20. A method for non-destructive testing of ferromagnetic materials without using coils or magnets, the method comprising:

means for creating electromagnetic fields in the vicinity of a ferromagnetic material under test, where such fields are both positioned at the same side of the ferromagnetic material;

means for measuring the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material; and

means for calculating stress using the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material.

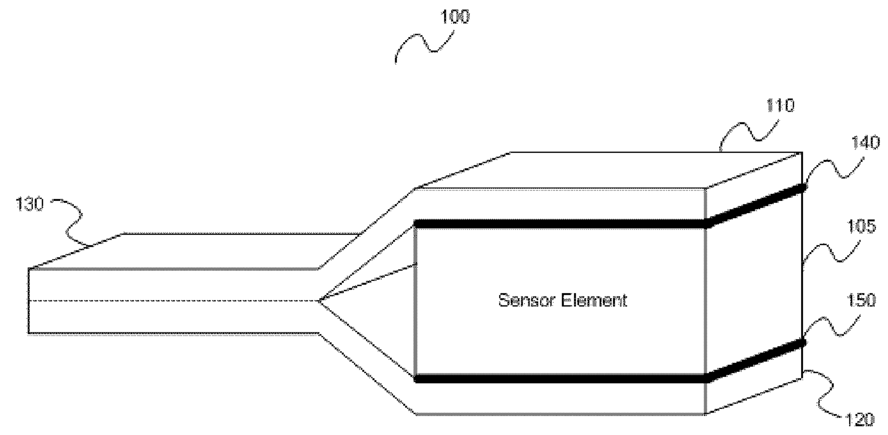
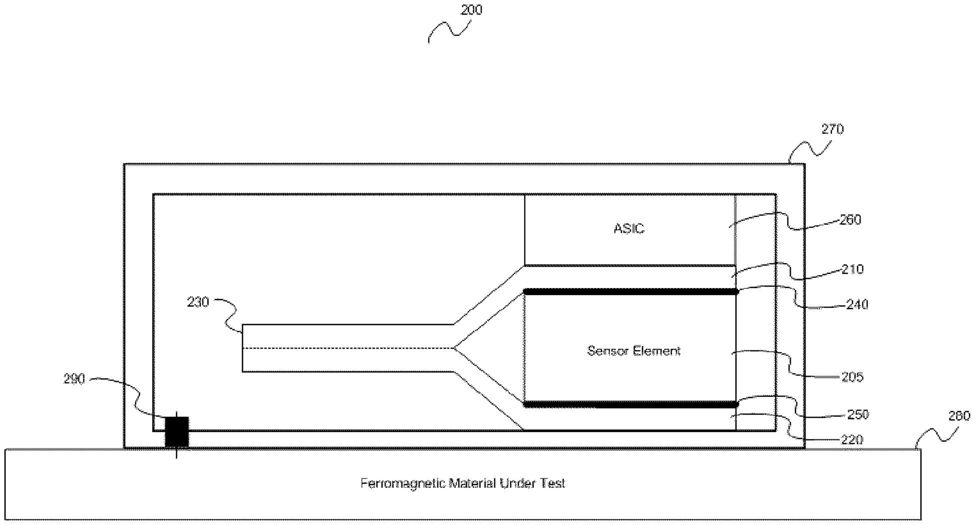

100
110
140
130
105
Sensor Element
150
120

FIG.1


200
270
ASIC
260
210
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240
Sensor Element
205
290
250
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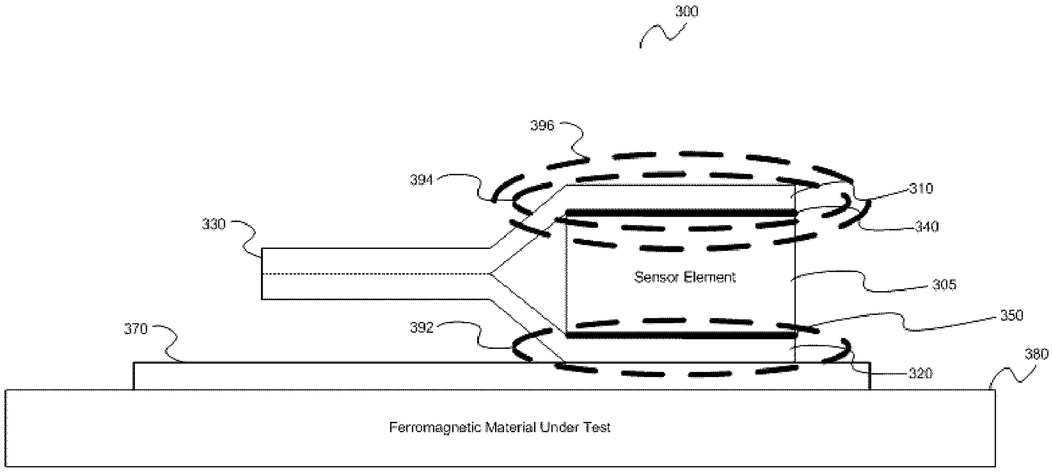
220
Ferromagnetic Material Under Test

FIG.2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396
394
310
340
330
Sensor Element
305
350
370
392
380
320
Ferromagnetic Material Under Test

FIG.3

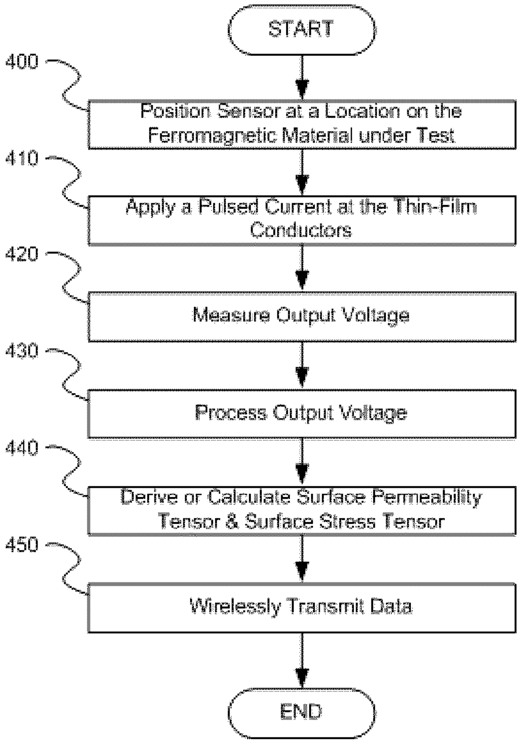
START
400
Position Sensor at a Location on the Ferromagnetic Material under Test
410
Apply a Pulsed Current at the Thin-Film Conductors
420
Measure Output Voltage
430
Process Output Voltage
440
Derive or Calculate Surface Permeability Tensor & Surface Stress Tensor
450
Wirelessly Transmit Data
END

FIG.4

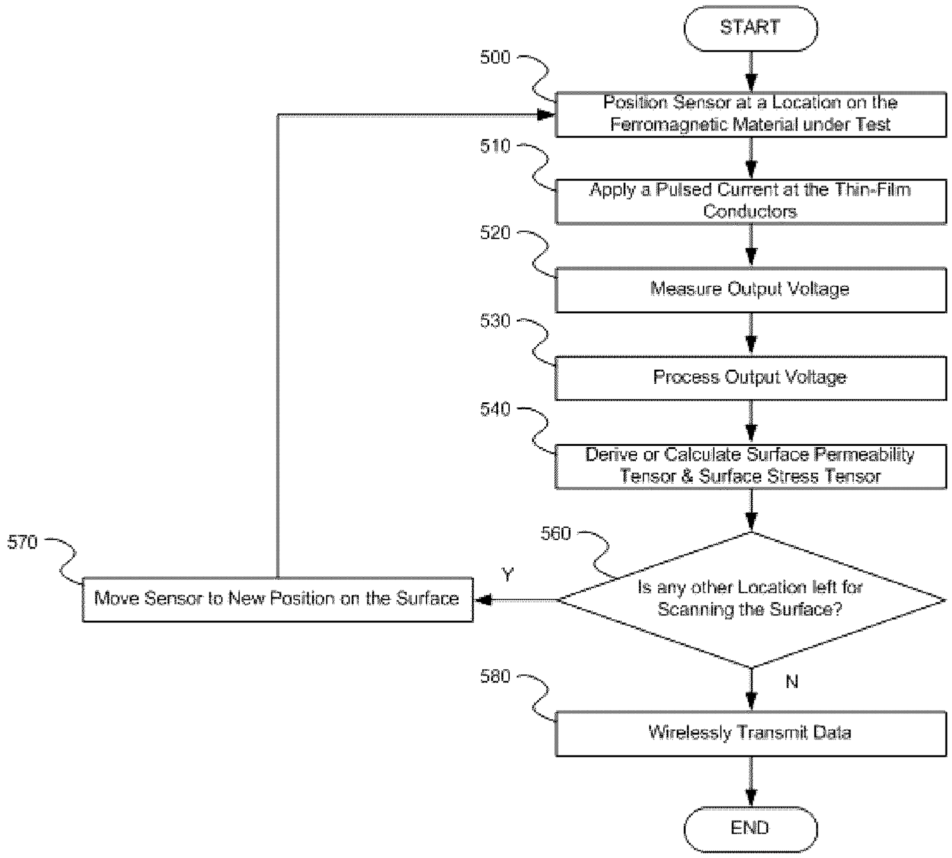
START
500
Position Sensor at a Location on the Ferromagnetic Material under Test
510
Apply a Pulsed Current at the Thin-Film Conductors
520
Measure Output Voltage
530
Process Output Voltage
540
Derive or Calculate Surface Permeability Tensor & Surface Stress Tensor
560
Is any other Location left for Scanning the Surface?
Y
570
Move Sensor to New Position on the Surface
N
580
Wirelessly Transmit Data
END

FIG.5

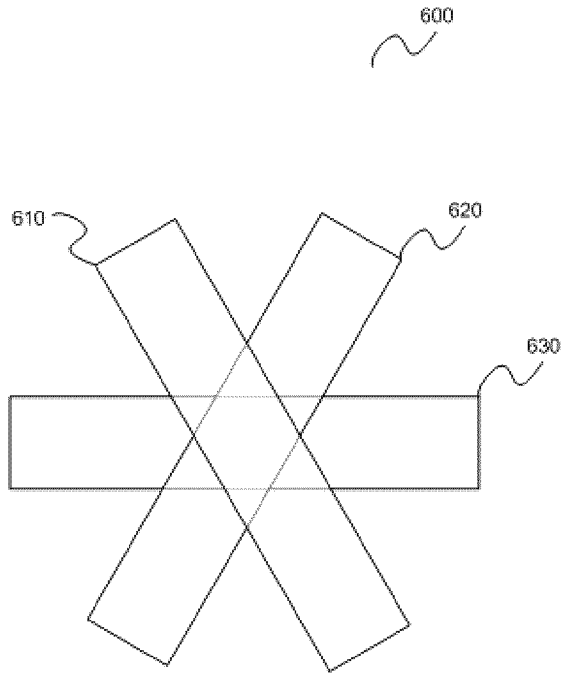

FIG.6

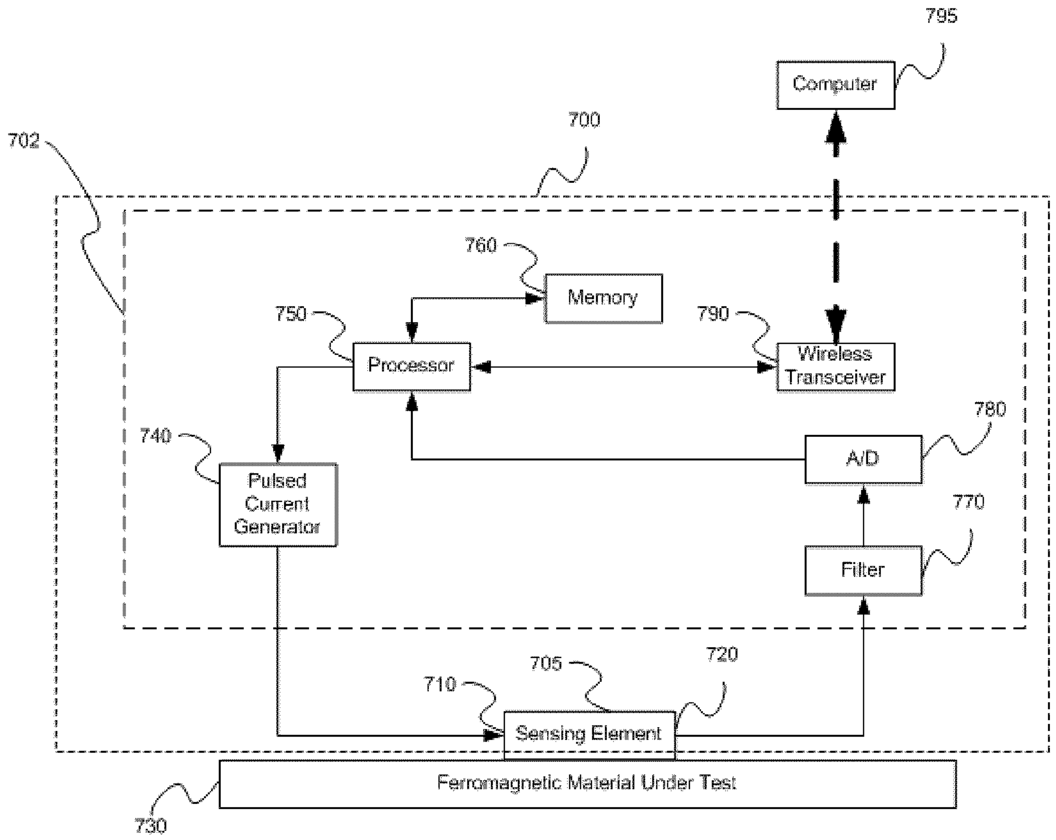
795
Computer
700
702
760
Memory
750
Processor
790
Wireless Transceiver
780
740
A/D
Pulsed Current Generator
770
Filter
705
720
710
Sensing Element
Ferromagnetic Material Under Test
730

FIG.7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2018/050891

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***G01R 33/16*** (2006.01) , ***G01L 1/12*** (2006.01) , ***G01N 27/83*** (2006.01)

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)
IPC(2006.01): G01R, G01L, G01N

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Canadian Patent Database, IEEE Xplore, Questel Orbit: (Keywords: sensor; multi-layer; thin film; magnetic field; insulating film/layer; deposited; conductors; ferromagnetic; surface permeability tensors; surface stress tensors)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2005/0006713 A1 (SHIM et al.) 13 January 2005 (13-01-2005) * Abstract; paragraphs [0007]-[0009]; figures 1A-1J and corresponding text *	1-6, 11, 12, 17 and 18

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

*	Special categories of cited documents:	"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
"A"	document defining the general state of the art which is not considered to be of particular relevance	"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
"E"	earlier application or patent but published on or after the international filing date	"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
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"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		

Date of the actual completion of the international search
11 October 2018 (11-10-2018)

Date of mailing of the international search report
14 November 2018 (14-11-2018)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C114 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 819-953-2476

Authorized officer

Patrick Abou-Antoun (819) 639-1681

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2018/050891

Box No. II **Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claim Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III **Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

See extra sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos.:

4. ☑ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos.:

1-6, 11, 12, 17 and 18

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

The claims are directed to a plurality of inventive concepts as follows:

Group I

Claims 1-6, 11, 12, 17 and 18 are directed to a sensor of the multi-layer thin film type for measuring surface permeability tensors and surface stress tensors in ferromagnetic steels, comprising: a thin film magnetic field sensing element; a first and a second insulating thin films deposited on each side of the thin film magnetic field sensing element, where the insulating thin films have substantially the same dimensions with each other and with the magnetic field sensing element and are substantially parallel to each other; and a first and a second thin film current conductors each deposited on the distant to the magnetic field sensing element side of the first and second insulating thin films, respectively, the thin film current conductors having substantially the same dimensions with each other and with the insulating thin films and being substantially parallel to each other, and being bent at one side so as to converge towards each other and form a third thin film current conductor, the three thin film conductors being electrically connected to each other.

Group II

Claims 7-10 and 13-16 are directed to a method of measuring surface permeability tensors and surface stress tensors in ferromagnetic steels, comprising: positioning a multi-layer thin film sensor at a location on the surface of a ferromagnetic steel; applying a pulsed current to the input of the sensor; measuring a voltage at the output of the sensor; processing the measured voltage; deriving and/or calculating surface permeability tensors and surface stress tensors for the surface of the ferromagnetic material in contact with the sensor; and wirelessly transmitting the derived and/or calculated data.

Group III

Claims 19 and 20 are directed to a thin-film sensor for non-destructive testing of ferromagnetic materials without using coils or magnets, the sensor comprising: means for creating electromagnetic fields in the vicinity of a ferromagnetic material under test, where such fields are both positioned at the same side of the ferromagnetic material; means for measuring the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material; and means for calculating stress using the different absorption of magnetic lines of each of the magnetic fields by the ferromagnetic material.

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2018/050891

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US2005006713A1	13 January 2005 (13-01-2005)	US2005006713A1	13 January 2005 (13-01-2005)
		US7041526B2	09 May 2006 (09-05-2006)
		AT364846T	15 July 2007 (15-07-2007)
		DE602004006905D1	26 July 2007 (26-07-2007)
		DE602004006905T2	07 February 2008 (07-02-2008)
		EP1467216A2	13 October 2004 (13-10-2004)
		EP1467216A3	26 January 2005 (26-01-2005)
		EP1467216B1	13 June 2007 (13-06-2007)
		EP1602936A1	07 December 2005 (07-12-2005)
		EP1602936B1	06 June 2012 (06-06-2012)
		JP2008003105A	10 January 2008 (10-01-2008)
		JP4633096B2	23 February 2011 (23-02-2011)
		JP2004258038A	16 September 2004 (16-09-2004)
		KR20040102661A	08 December 2004 (08-12-2004)
		KR100518796B1	06 October 2005 (06-10-2005)
		KR20040076460A	01 September 2004 (01-09-2004)
		KR100546880B1	26 January 2006 (26-01-2006)
		US2006115918A1	01 June 2006 (01-06-2006)