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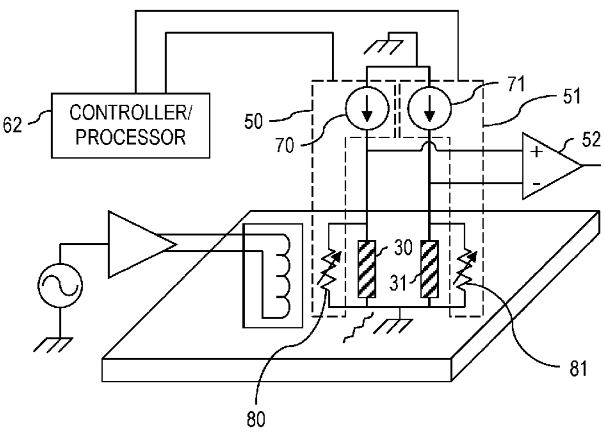

FIG. 7

(57) Abstract: An eddy current probe using magnetic field sensors in the resulting magnetic field readout is provided. At least two sensors are configured to measure the same magnetic field component but at different locations separated by an arbitrary distance. These sensors are 5 simultaneously electrically biased at to the same current level leading to similar voltage across each sensor. A differential amplifier is configured to amplify the difference between the voltages across the two sensors.

EDDY CURRENT PROBE WITH DIFFERENTIAL MAGNETIC FIELD SENSORS

TECHNICAL FIELD

The present disclosure relates in general to non-destructive testing, and in particular to eddy current probes applied in the detection and characterization of irregularities including defects associated with conductive parts.

BACKGROUND ART

There are a number of applications where it is necessary to inspect a conductive part for the presence of irregularities such as surface cracks, sub-surface defects, etc. In this regard, an eddy current probe can be used to inspect the part. Eddy current probes are particularly useful in many inspection applications because such probes can be used to employ non-destructive inspection techniques.

There are numerous approaches to the implementation of eddy current probes. However, regardless of implementation, eddy current probes operate based upon the principle of electromagnetic induction. An example of a basic configuration for a conventional eddy current probe includes an excitation coil and a receiver coil. A current is passed through the excitation coil so as to create a primary magnetic field. As the excitation coil is brought into proximity with the conductive part, the primary magnetic field generates eddy currents in the part. The receiver coil senses the presence of irregularities in the part by detecting changes in the generated eddy currents.

DISCLOSURE OF INVENTION

According to aspects of the present disclosure, an eddy current probe for testing conductive parts is provided. The eddy current probe comprises a magnetic field generator to which a drive signal is applied to generate a primary magnetic field. The primary magnetic field, when approached near a part being tested, induces eddy currents in the part. The eddy current probe also comprises a first magnetic field sensor, which outputs a first sensor signal indicative of a magnetic field sensed thereby, as well as a second magnetic field sensor positioned spaced from the first magnetic field sensor, which outputs a second sensor signal indicative of a magnetic field sensed thereby. In this regard, a space between the first magnetic field sensor and the second magnetic field sensor defines a region under test of the part. The eddy current probe still further comprises a first controllable bias system coupled to the first magnetic field sensor, and a second controllable bias system coupled to the second magnetic field sensor. Here, the second controllable bias system is controlled independently of the first controllable bias system, the first controllable bias system biases (e.g., electrically) the first magnetic field sensor, and the second controllable bias system biases (e.g., electrically) the second magnetic field sensor so as to achieve a similar first sensor signal and second sensor signal outside the presence of a secondary magnetic field indicative of the presence of a defect in the region under test of the part. Still further, the eddy current probe comprises a sensor amplifier circuit that receives the first sensor signal and the second sensor signal, and generates a difference signal therefrom.

In illustrative implementations, the first magnetic field sensor and the second magnetic field sensor are each positioned proximate to the magnetic field generator and are separated by a known distance having a maximum distance limited by a range of adjustability in the control of the first controllable bias system and the second controllable bias system such that a requirement is satisfied that the first magnetic field sensor and the second magnetic field sensor produce a similar output when the magnetic field generator produces the primary magnetic field and the probe is positioned in a defect-free region of the part being tested.

Still further, in a selected configuration, the first magnetic field sensor comprises a first magneto-resistive sensor and the second magnetic field sensor comprises a second magneto-resistive sensor. Moreover, the at least one bias source comprises a first bias source implemented as a first current source that is associated with the first magnetic field sensor, and a second bias source implemented as a second current source that is associated with the second magnetic field sensor.

The eddy current probe may further comprise a function generator and a drive amplifier having an input coupled to the function generator and an output coupled to the magnetic field generator such that a signal output by the function generator is amplified by the drive amplifier, and the drive amplifier outputs the drive signal to the magnetic field generator as an alternating current that flows through the magnetic field generator.

The eddy current probe may further comprise a controller connected to the function generator, where the controller controls the function generator to change at least one of the signal shape and signal amplitude of the drive signal to control the primary magnetic field. In alternative implementations, the first magnetic sensor and the second magnetic sensor are part of an array of magnetic field sensors having a plurality of magnetic field sensors. In this configuration, the controller controls a multiplexer to select a pair of magnetic field sensors of the array to represent the first magnetic field sensor and the second magnetic field sensor.

The controller may also control both the primary magnetic field and the distance between the first magnetic field sensor and the second magnetic field sensor according with a testing application requirement. Yet further, the controller can control the first controllable bias system and/or the second controllable bias system so as to achieve a similar first sensor signal and second sensor signal outside the presence of a secondary magnetic field indicative of the presence of a defect in the region under test of the part. In this regard, the controller can be used to control variable current sources, variable voltage sources, variable resistors, variable gain (or attenuation) amplifiers, etc.

According to still further aspects of the present invention, a method of implementing an eddy current probe for testing conductive parts is provided. The method comprises generating, in response to a drive signal, a primary magnetic field, where the primary magnetic field, when approached near a part being tested, induces eddy currents in the part. The method also comprises generating a first sensor signal using a first magnetic field sensor positioned within the primary magnetic field, which is indicative of a magnetic field sensed by the first magnetic field sensor. The method still further comprises generating a second sensor signal using a second magnetic field sensor positioned within the primary magnetic field, which is indicative of a magnetic field sensed by the second magnetic field sensor.

The method yet further comprises biasing the first magnetic field sensor with a first controllable bias system, and biasing the second magnetic field sensor with a second controllable bias system, which is independent from the first controllable bias system, so as to achieve a similar first sensor signal and second sensor signal outside the presence of a secondary magnetic field indicative of the presence of a defect in the region under test of the part. Also, the method comprises producing a difference signal using a differential circuit that receives the first sensor signal and the second sensor signal. Here, the method judges that there is no defect or other characteristic such as an irregularity in a part if the difference signal is indicative of a null and there is a defect or other characteristic such as an irregularity if the difference signal is indicative of a sensed magnetic field that is different in the first magnetic field sensor compared to the magnetic field sensed by the second magnetic field sensor, which is due to the presence of a defect or other material imperfection in the part being tested.

BRIEF DESCRIPTION OF DRAWINGS

FIG.1 shows a schematic representation of an eddy current probe according to aspects of the present disclosure;

FIG. 2 shows a schematic representation of an eddy current probe according to further aspects of the present disclosure, which includes several magnetic field generators;

FIG. 3 shows a schematic representation of an eddy current probe according to still further aspects of the present disclosure, wherein several frequencies are used to produce a drive signal applied to a magnetic field generator;

FIG. 4 shows a schematic representation of an eddy current probe according to yet further aspects of the present disclosure, wherein a pulsed waveform is used to drive a magnetic field generator;

FIG. 5 shows a schematic representation of an eddy current probe according to still further aspects of the present disclosure, wherein a one-dimensional array of magnetic field sensors is used by the eddy current probe to produce a resulting magnetic field readout;

FIG. 6 shows a schematic representation of an eddy current probe according to still further aspects of the present disclosure, wherein a two-dimensional array of magnetic field sensors is used by the eddy current probe to produce a resulting magnetic field readout;

FIG. 7 shows a schematic representation of a first embodiment of a controllable bias system, e.g., that can be used in the eddy current probe of FIG. 1, according to aspects of the present disclosure;

FIG. 8 shows a schematic representation of a second embodiment of a controllable bias system, e.g., that can be used in the eddy current probe of FIG. 1, according to aspects of the present disclosure;

FIG. 9 shows a schematic representation of a third embodiment of a controllable bias system, e.g., that can be used in the eddy current probe of FIG. 1, according to aspects of the present disclosure;

FIG. 10 shows a schematic representation of the third embodiment of the controllable bias system, e.g. that can be used in the eddy current probe of FIG. 1 to detect magnetic fields of two different amplitudes, according to aspects of the present disclosure;

FIG. 11 is a schematic of an exemplary probe having a magnetic field sensor array, according to aspects of the present disclosure; and

FIG. 12 illustrates a defect in a part and a corresponding scan from a probe as described herein.

MODES FOR CARRYING OUT THE INVENTION

According to aspects of the present disclosure, probes are disclosed, which can be used in the detection and characterization of defects or other characteristics such as irregularities associated with conductive parts using eddy currents testing. For instance, the present disclosure finds application in the inspection of critical aging parts and in the quality control of metallic parts in a broad range of industries. In such applications, the disclosed probes provide important improvements on the effectiveness achieved when testing both surface breaking and buried defects, as described more fully herein.

Eddy current probes herein, include one or more magnetic field generators to which a drive signal is applied to generate a primary magnetic field (also referred to herein as a primary contribution). For instance, the drive signal may comprise an alternating current that is made to flow through the magnetic field generator. In this configuration, the magnetic field generator may be implemented as a coil, a single wire filament, a moving magnet, etc. Different shaped coil(s) or single wire filament(s) can be employed, depending upon the particular application.

The primary magnetic field, when approached near a conductive part being tested, induces localized eddy currents in the part. In this regard, the magnetic field generator(s) is/are preferably designed to induce an eddy current pattern that exhibits a substantial modification when a defect is present within the primary magnetic field. As such, a part is inspected by scanning the eddy current probe over the part, while checking for such modifications in the eddy current pattern.

More particularly, the induced eddy currents generate their own local magnetic field, which is denoted herein as a secondary magnetic field (also referred to herein as a secondary contribution). The presence of a defect or other material imperfection in a scanned section of the conductive part causes a change in the secondary magnetic field relative to the secondary magnetic field in a previously scanned defect-free section of the part. According to aspects of the present disclosure, the resulting magnetic field (with both primary and secondary contributions) is read to detect and characterize defects in the part.

For instance, the resulting magnetic field can be read using inductive sensors such as coils or other structures. Alternatively, the resulting magnetic field can be read using magnetic field sensors.

Inductive sensors are driven by the derivative of the magnetic flux. Comparatively, magnetic field sensors allow direct measurement of the resulting magnetic field. Thus, the sensitivity of a magnetic field sensor is not dependent upon the magnetic field frequency.

However, the sensitivity of inductive coil sensors is dependent upon the magnetic field frequency. Another advantage of magnetic field sensors is the possibility of having small active area, which can be reduced to a few square microns, which improves spatial resolution compared to inductive sensors. The use of magnetic field sensors also enables the production of sensor arrays with a large number of devices.

According to aspects of the present disclosure, the resulting magnetic field readout is achieved using at least two magnetic field sensors. For instance, the eddy current probe may utilize a first magnetic field sensor, which outputs a first sensor signal indicative of a magnetic field sensed thereby. The eddy current probe may further utilize a second magnetic field sensor, which outputs a second sensor signal indicative of a magnetic field sensed thereby. The first magnetic field sensor is spaced from the second magnetic field sensor. A differential circuit receives the first sensor signal and the second sensor signal, and generates a difference signal therefrom.

According to specific aspects of the current disclosure, two magnetic field sensors are configured to measure the same magnetic field (e.g., in-plane and/or out-of-plane magnetic fields) under normal conditions, and are separated by a known distance. Because both magnetic field sensors measure the same magnetic field and because the first magnetic field sensor and the second magnetic field sensor are independently biased so as to output similar signals (under normal conditions), the differential circuit coupled to the first and second magnetic field sensors outputs a magnetic field sensor readout corresponding to a null signal.

Both the measured magnetic field and the distance between sensors are determined according with the testing application requirements. For instance, a first magnetic field may be measured when inspecting for surface defects, whereas a second magnetic field may be desirable when inspecting for sub-surface defects. As yet another example, a first distance between the two magnetic field sensors may be desirable for inspecting for surface defects, whereas a second distance between the two magnetic field sensors may be more desirable when inspecting for sub-surface defects.

As noted above, the magnetic field sensor readout is accomplished by measuring the difference between the two sensor outputs. In this regard, the sensors are simultaneously biased such that, in the presence of a defect-free area, each sensor outputs a similar result (since each sensor normally measures the same magnetic field). Accordingly, in a defect-free region, the sensor read-out will be zero (or substantially zero) because the two sensor signals are similar. However, if one of the two sensors approaches a crack, sub-surface defect or other irregularity in a conductive part under test, the magnetic field sensed by each sensor will no longer be similar, thus the read-out will no longer be null, e.g., zero or substantially zero.

In further aspects of the current disclosure, an eddy current array probe employing multiple magnetic field sensors is provided. The multiple sensors are configured (e.g., in a one-dimensional array, in a two-dimensional array, etc.) to measure the same magnetic field under normal conditions and are separated by a known distance from each other. In this exemplary configuration, the array readout is accomplished by multiplexing different sensor pairs, e.g., on a known sequence. In each of the sequence steps, the difference of the signal sensed by each sensor of a given pair is measured.

Eddy current testing instruments are employed to operate probes, control scanning devices and gather results. For instance, as will be described in greater detail herein, such instruments may feature circuitry to drive the probes magnetic field generator(s) and may feature circuitry to amplify the probes magnetic field sensors. For instance, in illustrative implementations, an amplifier circuit has a differential input allowing the measurement of the difference between two signals (e.g., a signal from a first magnetic field sensor and a signal from a second magnetic field sensor). In alternative implementations, the difference function may be implemented using a processor. Also, a demodulator may be utilized to recover features of the measured signals, which may be utilized after inspection for the assessment of the defects and imperfections.

Example Probe Configurations:

The above-described eddy current probe features can be utilized in any combination with the below-described exemplary embodiments. Moreover, components that are similar or otherwise analogous are illustrated with the same reference numbers throughout. Thus, features described with reference to one FIGURE can be integrated with, used in alternative to, or otherwise integrate with the features of another FIGURE in any desired configuration.

Referring now to the drawings and in particular to FIG. 1, an eddy current probe is schematically represented, according to certain aspects of the present disclosure. As illustrated, a part 10, which is under test, includes a defect 11. The eddy current probe is suitable for detecting the defect 11. In practice, the probe is also suitable for detecting other characteristics of the part, including irregularities, etc.

The eddy current probe includes a magnetic field generator 20 to which a drive signal is applied to generate a primary magnetic field, where the primary magnetic field, when approached near a part being tested, induces eddy currents in the part.

The eddy current probe also includes a first magnetic field sensor 30 that outputs a first sensor signal indicative of a magnetic field sensed thereby. The eddy current probe similarly includes a second magnetic field sensor 31 positioned spaced from the first magnetic field sensor 30, which outputs a second sensor signal indicative of a magnetic field sensed thereby. In use a space between the first magnetic field sensor and the second magnetic field sensor defines a region under test of the part.

The eddy current probe also includes a drive amplifier 40, and a function generator 41, that cooperate to produce the drive signal that is applied to the magnetic field generator,

The eddy current probe still further includes at least one bias system (e.g., a first controllable bias system coupled to the first magnetic field sensor 50 and a second controllable bias system coupled to the second magnetic field sensor 51 as schematically illustrated). The eddy current probe still further includes differential circuitry (e.g., as illustrated by a sensor amplifier 52) take an output from the first magnetic field sensor 30 and a signal from the second magnetic field sensor 31 to produce a signal that is read to detect and/or characterize defects in the part under test.

More particularly, the magnetic field generator 20 may be implemented, for instance, as a coil, a single wire filament, a moving magnet, etc. Moreover, the magnetic field generator 20 may include other features that allow control over the field direction, strength, etc., of the primary magnetic field. As noted above, a drive signal is applied to the magnetic field generator 20 to generate a primary magnetic field such that the primary magnetic field, when approached near the part 10 being tested, induces eddy currents in the part 10. In this regard, the drive signal may be implemented as an alternating current that flows through the magnetic field generator (e.g., coil, wire filament, etc.).

As used herein, the term “magnetic field” sensor includes a sensor that requires or otherwise utilizes a bias signal (typically a bias current) to operate the sensor. An example of magnetic field sensor is a magneto-resistive sensor. The magnetic field sensors 30, 31 and their corresponding bias systems are described more fully herein.

The drive amplifier 40 and the function generator 41 are used to create the drive signal that is utilized to drive the magnetic field generator 20. For instance, the function generator 41 may be implemented as an alternating voltage source. In this regard, the drive amplifier 40 converts the voltage from the function generator into a current. Moreover, although schematically illustrated as a single amplifier, in practice the drive amplifier 40 comprises any necessary circuitry to buffer, scale, transform or otherwise condition the output of the function generator.

In practice, the function generator 41 can be used to generate any desired type of signal, including periodic signals, pulse signals, complex signals and/or other signal type necessary to produce the desired primary magnetic field. Moreover, a controller may be used to control the function generator 41, e.g., to alter the amplitude, wave shape, period, frequency, etc., of the function generator output. Still further, a controller may be utilized to implement the function generator.

Thus, the drive amplifier 40 is coupled (i.e., electrically connected) to the function generator 41 and the magnetic field generator 20 such that a signal output by the function generator 41 is amplified by the drive amplifier 40, and the drive amplifier 40 outputs the drive signal to the magnetic field generator 20, e.g., as an alternating current that flows through the magnetic field generator 20.

The primary magnetic field generated by the magnetic field generator 20 is responsible for the induction of eddy currents associated with the part 10 under test, when the eddy current probe is positioned nearby the part 10. The interaction of the induced eddy currents with an imperfection or a defect 11 in the part 10 results in a modification of the resulting magnetic field.

In specific aspects of the present disclosure, two magnetic field sensors, i.e., the first magnetic field sensor 30 and the second magnetic field sensor 31 are used in the resulting magnetic field readout. More particularly, the first magnetic field sensor 30 outputs a first sensor signal indicative of a magnetic field sensed thereby. Likewise the second magnetic field sensor 31 outputs a second sensor signal indicative of a magnetic field sensed thereby.

The first magnetic field sensor 30 and the second magnetic field sensor 31 are configured to measure the same magnetic field but at different locations separated by a known distance. The space on the part under test between the first magnetic field sensor and the second magnetic field sensor defines a region under test of the part. Design parameters, such as the distance between the first magnetic field sensor 30 and the second magnetic field sensor 31, are chosen for instance, in agreement to the morphology of the defects or imperfections to be accessed in the part 10.

As noted above, the probe includes at least one bias system that biases the magnetic field sensors 30, 31. For instance, as illustrated, the first magnetic field sensor 30 is biased by a first bias system 50 (e.g., which includes a current source). The second magnetic field sensor 31 is simultaneously biased by a second bias system 51 (e.g., which also includes a current source). The first bias system 50 and the second bias system 51 may utilize the same bias source (e.g. a current source, voltage supply, etc.). In alternative configurations, the first bias system 50 and the second bias system 51 can be implemented as independent or otherwise individual bias system, each with their own bias source. The bias is set in the first magnetic field sensor 30 and the second magnetic field sensor 31 so as to lead to similar sensor outputs when the first magnetic field sensor 30 and the second magnetic field sensor 31 are sensing a defect-free area/region of the part 10. In this regard, the bias signal applied to each of the first magnetic field sensor 30 and the second magnetic field sensor 31 can be individually tuned and controlled to account for the conditions of the test environment.

Generally, the bias supplied to each of the first magnetic field sensor 30 and the second magnetic field sensor 31 should be the same. However, it may be possible to configure the first bias system 50 and the second bias system 51 to produce different bias signals, e.g., to trim, compensate or otherwise accommodate imperfections in the sensors themselves, in the test environment, etc., so that the first magnetic sensor 30 and the second magnetic sensor 31 generate similar output signals (sense signals, i.e., the first sensor signal and the second sensor signal) in a defect-free region of the part 10 under inspection. FIGS. 7-10 below illustrate and discuss several controllable bias or trimming systems that may be used to produce the different bias signals. Control may be implemented using for instance, a controller such that automatic adjustments are made, e.g., as part of a setup operation before the acquisition of a probe readout signal. As such, any of the embodiments of controllable bias systems (each including a bias source) discussed below may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 1.

Where the magnetic field sensors 30, 31 are implemented as magneto-resistive sensors, it may be desirable to use a current as the bias signal. However, the bias signal could alternatively be a voltage, resistance, impedance or other reference. Moreover, the bias signal may be generated in any suitable configuration, e.g., a current derived by a voltage source and corresponding load element, e.g., resistor, diode, transistor etc.; a variable resistor; a transistor-based current source, etc.

The first magnetic field sensor 30 and the second magnetic field sensor 31 are measured using a differential circuit that receives an output of the first magnetic field sensor 30 (a first sensor signal indicative of a magnetic field sensed thereby) and an output of the second magnetic field sensor 31, (a second sensor signal indicative of a magnetic field sensed thereby) and generates a difference signal therefrom. For instance, as illustrated, the differential circuit includes a sensor amplifier 52 that is configured to output the difference between the output of the first magnetic field sensor 30 and the output of the second magnetic field sensor 31. The sensor amplifier 52 may receive inputs as current, voltage, resistance, etc., depending upon the implementation of the first and second magnetic field sensors 30, 31 and bias system 50 and 51. In this regard, the output of the sensor amplifier 52 may be based upon a current differential, voltage differential, resistance differential, phase differential, other measureable difference, combinations thereof, etc.

In practice, the differential circuit may include other circuitry, such as to buffer, scale, transform or otherwise condition the sensor outputs. Moreover, in other illustrative examples, the differential circuit can be implemented digitally, e.g., using a processor in a suitable controller. This approach allows potentially sophisticated processing such as noise filtering, etc. Such an approach may also more readily facilitate processes that use dynamically varying signal output by the function generator 41. Still further, the use of a processor may facilitate convenient analysis of the inspection, such as by collecting and saving the sensor outputs to facilitate different computational analysis, such as may be desirable to evaluate inspection results based upon different types of detected irregularities.

If the eddy current probe is positioned about a defect-free section of the part 10 (i.e., a defect-free region under test), a null measurement is expected since the voltages across the first magnetic field sensor 30 and the second magnetic field sensor 31 are expected to be similar. In this case, the result may not be exactly zero, e.g., due to noise and other conditions that are not indicative of a detected irregularity in the part 10. As such, "null" refers to a conclusion of a defect-free region. In practice, there may be a slight difference. As such, a threshold may be used as a gate. In other examples, there is no filtering or thresholds. Rather, the difference between the sensor outputs is evaluated, such as by a domain expert (automated or human), to determine the confidence that a non-zero reading is, or is not, a surface irregularity.

Thus, when the probe is in a defect-free region of the part 10, the output of the differential circuit is indicative of a null. In an exemplary implementation, the measurement amplitude of the sensor amplifier 52 increases if a defect 11 moves into the magnetic field sensed by the first magnetic field sensor 30, since the sensor output of each of the first magnetic field sensor 30 and the second magnetic field sensor 31 is no longer the same.

An inversion on the measurement happens when the defect 11 moves from the second magnetic field sensor 31 into the magnetic field sensed by the first magnetic field sensor 30.

The disclosed eddy current probe exhibits numerous advantages when compared to the measurement of a conventional magneto-resistive based eddy current probe. For instance, one advantage relates with the possibility of achieving a null measurement even when the first magnetic field sensor 30 and the second magnetic field sensor 31 are configured to measure a magnetic field that is different than zero when measuring a defect-free section of a part under test. This is an interesting advantage since in many testing cases, the presence of the defect 11 leads to higher modification of these resulting magnetic fields. The null measurement enables the use of high amplification gain in the sensor amplifier 52 and to maximize the utilization of the eddy current testing instrument input dynamic range. This leads to improvements on the signal-to-noise ratio at which a defect 11 can be detected.

Further advantages result from the differential measurement. For instance, the differential measurement enables a reduction in the influence of the inductive coupling between the primary magnetic field and the interconnections of the first magnetic field sensor 30 and the second magnetic field sensor 31. Inductive coupling can be verified both in the probe interconnections and on any cabling establishing connection with the eddy current testing instrument. Since such inductive coupling appears as a common contribution summed across the first magnetic field sensor 30 and the second magnetic field sensor 31, the effect is at least partially cancelled when the differential measurement is applied (as long as the first magnetic field sensor 30 and the second magnetic field sensor 31 connection loops are similar). The same is verified for external electromagnetic interference sources whose presence on the measurement is at least partially canceled.

Other advantages relate with specific testing applications. For instance, conventional magneto-resistive devices use off-the-shelf magneto-resistive sensors, which are configured in a Whetstone bridge configuration. This results in a large package and configuration that is non-optimal. Correspondingly, as used herein, the magnetic field sensors 30, 31 are custom-fabricated, e.g., as individual magneto-resistive sensor devices. This allows for extremely small and compact sensor configurations. For very small superficial defects, the distance between the first magnetic field sensor 30 and the second magnetic field sensor 31 is made small (for example, less than 1 mm). This condition minimizes the effect of modifications in the resulting magnetic field resulting from surface profile and gradual conductivity changes detected in the part 10 under test, which otherwise could mask the response to defects.

Moreover, the disclosed configuration also reduces the influence of the separation between the eddy current probe and the part 10 under test or any misalignment with the part 10 under test. For buried defects, the eddy current probe is designed with the first magnetic field sensor 30 and the second magnetic field sensor 31 separated by a substantially increased distance. The main advantage in this situation relates with the possibility of employing high amplification to read very weak differences in the resulting magnetic field.

Still further, the first magnetic field sensor 30 and the second magnetic field sensor 31 may be adjustable or preconfigured, e.g., to sense in-plane and/or out-of-plane magnetic fields.

It will be appreciated that the output of the probe as described herein is substantially more accurate, and provides a more clear reading of any detected irregularities. For instance, when performing a scan of the part 10 using the probe, the first magnetic field sensor 30 and the second magnetic field sensor 31 are swept relative to the surface of the part 10. Assume that the probe starts to the far right of FIG. 1 and sweeps to the left (relative to the part - in practice, the probe may move, or the part may move).

As will be appreciated, as schematically illustrated, to the far right, the probe will measure a null so long as the probe is sufficiently spaced from the defect 11. However, as the probe approaches the defect 11, the first magnetic field sensor 30 will encounter the defect 11 before the second magnetic field sensor 31. As such, the probe output (e.g., the output of the differential circuit) is rendered in a first value (positive or negative depending upon how the first and second magnetic field sensors 30, 31 are biased, depending upon how the differential circuitry is configured, etc.). As the probe moves across the defect 11, the difference signal changes. At some point in the sweep, the field sensed by the second magnetic field sensor 31 will be stronger than the field sensed by the first magnetic field sensor 30. Thus, for instance, the differential signal will increase towards a maximum value in a first polarity, then reverse and start transitioning towards a maximum in the opposite polarity, then return to a null reading. Thus, the differential signal now has two amplitude elevations caused by the modification of the secondary magnetic field on the two different measurement locations (i.e., the location of the first magnetic sensor 30 and the location of the second magnetic sensor 31). Another relevant feature in the differential signal is the 180º phase shift which happens when the characteristic (e.g., imperfection, defect, crack, etc.) is centered with the two measured locations.

Comparatively, if the probe were to sweep from left to right across the page of FIG. 1, the opposite of that above would be realized.

By knowing the spatial relationship between the first magnetic sensor 30 and the second magnetic sensor 31, and by knowing the scan direction (and field orientations), detailed information can be extracted about the nature of the defect 11. In illustrative implementations, the output of the probe can be rendered as color in a chart, where the displayed color is representative of the difference determined from the sensor outputs. In this regard, accurate defect identifications are possible. Note that the color-coding of the present invention is different compared to that realizable with a conventional sensor, allowing more ready defect identification by a domain expert. Moreover, a different set of measurements is realized compared to static sensing (i.e., keeping the probe and the part fixedly positioned relative to one another, and by selecting different sensor elements in an array of sensor elements of the probe to search for possible defects).

Referring to FIG. 2, an alternative configuration shows the use of multiple magnetic field generators 21 to allow different primary magnetic field patterns to be created. Otherwise, this configuration is similar to that described with reference to FIG. 1. In this regard, the multiple magnetic field generators 21 can be implemented by multiple instances of the magnetic field generator 20 described with reference to FIG. 1. Moreover, a single instance of the drive amplifier 40 and function generator 41 may be utilized, or each instance of the magnetic field generator 20 can have its own instance of a corresponding drive amplifier 40 and function generator 41. In this regard, the multiple magnetic field generators 21 may be utilized such that one magnetic field generator 20 is used a time, or multiple instances of the magnetic field generator 20 can be utilized at the same time, e.g., to create the different magnetic field patterns.

Similar to the embodiment of FIG. 1, any of the embodiments of controllable bias systems discussed below in reference to FIGS. 7-10 may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 2.

As an illustrative example, a first magnetic field generator 20 can be configured for a magnetic field pattern, field direction, etc., to facilitate inspection for surface cracks, whereas a different magnetic field generator 20 can be configured with a different magnetic field pattern, field direction, etc., to facilitate inspection for sub-surface irregularities.

Referring to FIG. 3, a schematic illustration of a probe clarifies that the magnetic field generator 20 can be driven by any type of drive signal. For instance, in yet another alternative configuration, the input to the amplifier 40 used to drive the magnetic field generator is connected to an adder 43. The adder 43 has a plurality of inputs, each input connected to the output of a corresponding function generator 41. In this configuration, each function generator

41 may be an alternating voltage source or other source for generating a signal. The adder 43 combines the signals from one or more function generators 41 to synthesize complex signals. This configuration is particularly useful where complex drive signals are required and only simple alternating sources are available. In practice, not all function generators 41 need to be used. Moreover, the output of certain function generators 41 may be scaled, inverted, filtered or otherwise processed to achieve the desired drive signal. Moreover, the combination of function generators 41 and the adder 43 can alternatively be implemented by utilizing one function generator 41 capable of producing the desired drive signal.

The configuration of FIG. 3 is otherwise similar to that described with reference to FIG. 1. Moreover, the multiple magnetic generators 20 of FIG. 2 can be incorporated into the configuration of FIG. 3. Similar to the embodiments of FIGS. 1-2, any of the embodiments of controllable bias systems discussed below in reference to FIGS. 7-10 may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 3.

Referring to FIG. 4, in a specific exemplary configuration, the function generator 41 (FIG. 1) is implemented by a pulsed waveform source. For instance, a pulse signal can be used to test multiple frequencies using a single signal due to the harmonic content of a pulse. In practice, other signal shapes could be used, such as chirp signals, etc. The configuration of FIG. 4 is otherwise similar to that described with reference to FIG. 1. Moreover, the multiple magnetic generators 20 of FIG. 2 and/or the multiple function generators 41 of FIG. 3, can be incorporated into the configuration of FIG. 4.

Similar to the embodiments of FIGS. 1-3, any of the embodiments of controllable bias systems discussed below in reference to FIGS. 7-10 may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 4.

Referring to FIG. 5, in still another alternative configuration, more than two magnetic field sensors are provided. More particularly, in further aspects of the disclosure, a linear magnetic field sensor array 33 of magnetic field sensors is used in the resulting magnetic field readout as schematically represented. This results in an increased testing area, which is limited by the size of the magnetic field sensor array 33. In this configuration, the testing duration is reduced since a shortened trajectory of the probe is required to cover a given part 10 under test. The magnetic field sensors (e.g., which are identical to the magnetic field sensors 30, 31 described more fully herein) of the magnetic field sensor array 33 are configured to measure the same magnetic field when in a defect-free region of the part 10. Moreover, each sensor in the magnetic field sensor array 33 is separated from the remaining sensors by a known distance. As such, the relative position of each magnetic field sensor is spatially resolved. In use, any pair of magnetic field sensors of the magnetic field sensor array 33 can be selected, either in a predetermined pattern, ad-hoc, etc., to implement the first magnetic field sensor 30 and the second magnetic field sensor 31 (see FIG. 1). As such, a given distance may or may not remain constant as an arbitrary pair of sensors is selected from the sensor array 33.

In an exemplary implementation, measurement is accomplished by time multiplexing the different sensors of the sensor array 33 on an arbitrary sequence using the multiplexer 53. In each of the sequence steps, a different pair of magnetic field sensors (which may or may not be adjacent) is measured in a differential configuration as described before. That is, the multiplexer 53 selects different pairs of sensors of the sensor array 33 to implement the first magnetic field sensor 30 and the second magnetic field sensor 31 for differential sensing as described more fully herein.

A controller 62 having a processor can be utilized to control the multiplexer 53, the function generator 41, the first bias system 50 the second bias system 51, other components of the probe, or combinations thereof. The controller 62 receives the output of the differential circuitry (but may alternatively receive the output of each individual magnetic field sensor of the magnetic field sensor array 33). The controller 62 may include a processor that processes the probe output and presents the results of the processing to an output device 64. In this regard, the processing may occur in real-time, or the results may be provided to the output device 64 after the inspection has completed, e.g., by saving the probe output and by performing a signal analysis after the inspection has completed.

The configuration of FIG. 5 is otherwise similar to that described with reference to FIG. 1. Moreover, the multiple magnetic generators 20 of FIG. 2, the multiple function generators 41 of FIG. 3, the pulse generator 41 of FIG. 4, or combinations thereof, can be incorporated into the configuration of FIG. 5. Similar to the embodiments of FIGS. 1-4, any of the embodiments of controllable bias systems discussed below in reference to FIGS. 7-10 may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 5.

Referring to FIG. 6, in yet another alternative configuration, an implementation is the same as that of FIG. 5 except that the array 33 is modified to be a two-dimensional sensor array 34. In an analogous manner to that set out with reference to FIG. 5, in an exemplary implementation, measurement may be accomplished by time multiplexing the different sensors of the two-dimensional sensor array 34 on an arbitrary sequence using the multiplexer 53. In each of the sequence steps, a different pair of magnetic field sensors (which may or may not be adjacent) is measured in a differential configuration as described before. That is, the multiplexer 53 selects different pairs of sensors of the two-dimensional sensor array 34 to implement the first magnetic field sensor 30 and the second magnetic field sensor 31 for differential sensing as described more fully herein.

In an illustrative example, an eddy current probe includes a sensor array of sixteen or more magnetic field sensors, e.g., which detect the out of plane component of the field. More particularly, the probe is configured into two groups of 8 or more magnetic field sensors, which are separated by a known spatial distance, e.g., 2.5 mm or less (although greater distances are also realizable). As noted in greater detail herein, using one magnetic field sensor of each group in differential mode effectively cancels most of the local topography variations of the sample.

In a particular configuration, each magnetic field sensor is implemented as a magnetic tunnel junction sensor, such as [Ta 5/CuN 25]x6 /Ta 5/Ru 5/IrMn 20/$Co_{70}Fe_{30}$ 2/Ru 0.85/$CoFe_{40}B_{20}$ 2.6/MgO 1/$CoFe_{40}B_{20}$ 2/Ta 0.21/NiFe 4/Ru 0.20/IrMn 6/Ru 2/Ta 5/Ru 10 (thicknesses in nm). The resistance-area product of the stack may be 40 k$\Omega\mu m^2$ and each sensor has an area of 3.5x10 μm^2. Upon a biasing current of 90 μA, each sensor showed a sensitivity 84 ± 4 mV/mT, respectively.

To detect an irregularity, in one example, the magnetic field sensors of the sensor array were biased with an AC current of 180 μA at 999 kHz (f1) and the magnetic field generator was driven by a 2 A current at 1MHz (f2). The two-frequencies strategy modulates the magnetic information from the part under test in the frequencies f2-f1 and f2+f1 while other phenomena such as electric biasing and inductive coupling appear at the other frequencies (f1 and f2). The differential signal output from the differential circuitry is demodulated using a lock-in amplifier locked to 1kHz (f2-f1).

Using the above-configuration, a C-Scan reveals symmetric stripes corresponding to the passage of each magnetic field sensor of the differential pair over a defect in a part under inspection. The defect indication may be non-constant over the Y direction due to the much better spatial resolution of the magnetic tunnel junction (MTJ) sensors compared to that realizable using inductive sensors.

As another example, the sensor array may be constructed as a uniform sensor stack on a wide Si/SiO2 100 nm substrate, with a composition Ta 2 / $Ni_{80}Fe_{20}$ 3.2 / $Co_{81}Fe_{19}$ 2.3 / Cu 2.4 / $Co_{81}Fe_{19}$ 3.3 / $Mn_{76}Ir_{24}$ 11 / Ta 10 / $Ti_{10}W_{90}$(N) 15 – thicknesses in nm) with a magnetically active area of 4x100 μm^2. In a working example, the magnetic field sensors of the sensor array were biased by applying a 1 mA constant current, sweeping the magnetic field between -12.5 mT to 12.5 mT and measuring the voltage. A resulting transfer curve defines two saturations zones (low and high resistance) and a linear response in between. Unlike many conventional sensors, the above magnetic field sensors are linear at zero magnetic field, thus there is no need to apply an additional constant magnetic field bias.

Similar to the embodiments of FIGS. 1-5, any of the embodiments of controllable bias systems discussed below in reference to FIGS. 7-10 may be used in place of either or both of the bias system 50, 51 of the embodiment of the eddy current probe of FIG. 6.

Although described with regard to FIG. 6 for clarity, the implementation of the magnetic tunnel junction sensor described above, can be used with any other eddy current probe configuration set out herein, e.g., with regard to FIGS. 1-5, and 7-10.

With reference to FIG. 5 and FIG. 6, the magnetic field sensor array (regardless of dimension) provides numerous advantageous over conventional systems. For instance, conventional systems that utilize sensor arrays have leveraged the array for static sensing. However, the utilization of the controller 62 facilitates the use of the magnetic field sensor array as a way to utilize a single probe for numerous applications. As an example, when scanning for thin surface cracks, a relatively high resolution is achieved by placing the pair of magnetic field sensors as close together as possible.

By custom fabricating discrete magneto-resistive elements, extremely small cracks and surface imperfections can be detected with high resolution. In this regard, it should be appreciated that there is a minimum proximity that is practically achievable, e.g., due to the strength of the primary magnetic field, the nature of the irregularity to be detected, the resolution of the discrimination circuitry (i.e., the differential circuitry) etc. For instance, if the magnetic field sensors are too close together, there may not be sufficient resolution of the probe electronics to discern small magnetic field variations between the pair of magnetic field sensors.

As another example, if an inspection is required to perform a deep sub-surface scan, the magnetic field generator 20 may be required to generate a relatively strong primary magnetic field. As such, it may be desirable to allow for a relatively larger distance between the pair of magnetic field sensors to properly access the modification of the secondary magnetic field to such defects.

In this regard, the controller 62 can be utilized to perform different inspections suitable for different applications with a single device, by controlling the drive signal and by controlling the selection of magnetic field sensor pairs from the corresponding sensor array.

Controllable Bias Systems

Controllable bias systems may be used to bias one or more of the magnetic field sensors independently of other magnetic field sensors of the probe. In this regard, the bias for each individual magnetic field sensor is adjustable, programmable, or otherwise controllable. Moreover, the bias can be controlled (e.g., automatically by a controller, manually by a user interacting with the controller, a combination of both, etc.) before or during use to change the bias, e.g., for calibration, nulling, compensation, or for other uses. For example, in the embodiments of FIGS. 1-4, there may be two controllable bias systems, one for each magnetic field sensor, and in the embodiments of FIGS. 5-6, there may be two or more controllable bias systems each used to bias one or more sensors independently of other sensors. Thus, the bias signal sent to the first magnetic field sensor may be different than the bias signal sent to the second magnetic field sensor. Moreover, there may be different biases for each sensor in a sensor array. As such, the bias signal may trim, compensate or otherwise accommodate imperfections in the sensors themselves.

FIG. 7 illustrates an embodiment of a controllable bias system 50, 51 for use in the eddy current probe of FIG. 1. The first magnetic field sensor 30 is biased by a first controllable bias system 50, and the second magnetic field sensor 31 is biased by a separate second controllable bias system 51. Each controllable bias system 50, 51 of FIG. 7 includes a bias source 70, 71 that sends a bias signal to the magnetic field sensor 30, 31. Each bias signal may be adjusted with a corresponding variable resistor 80, 81. The variable resistor may be a potentiometer, or a digitally controlled potentiometer, thus allowing the controller 62 to control the bias during operation thereof. For example, as shown in FIG. 7, the bias sources can be constant current sources and the variable resistors 80, 81 are coupled in parallel to their respective magnetic field sensors 30, 31 and to the controller 62. Thus, when the resistance of the first variable resistor 80 is increased, less current will pass through the first variable resistor 80, but more current will pass through the first magnetic field sensor 30. Since the first variable resistor 80 is able to be adjusted independently of the second variable resistor 81, the resulting bias signals for the first magnetic field sensor 30 and the second magnetic field sensor 31 may be different. Moreover, since the variable resistors 80, 81 are controlled by the controller 62, the bias to each magnetic field sensor 30, 31 can be adjusted at any time during operation.

In an alternative arrangement, the current sources 70, 71 can be replaced by voltage sources. In this configuration, the variable resistor is placed in series with the magnetic field sensor. Accordingly, when the resistance of the variable resistor is increased, the bias current to the magnetic field sensor decreases.

The controllable bias systems described in reference to FIG. 7 may be used in conjunction with any of the eddy current probes of FIGS. 1-6, as described above. In the cases of the eddy current probes of FIGS. 5-6, additional multiplexers may be required if more than two controllable bias systems are used.

FIG. 8 illustrates another embodiment of the controllable bias system 50, 51 for use in the eddy current probes described herein. In the embodiment of FIG. 8, first and second variable gain amplifiers 90, 91 are coupled to differential inputs of the sensor amplifier 52 and to the controller 62. Thus, bias sources 70, 71 may be constant current sources, and the variable gain amplifiers 90, 91 may be tuned during operation by the controller 62, such that the signals going to the sensor amplifier 52 result in an essentially null signal (or other desired signal) out of the sensor amplifier 52 when used on region under test that is defect free. Each of the variable gain amplifiers (e.g., the first variable gain amplifier and the second variable gain amplifier) 90, 91 is independently controllable by the controller 62, so the signals to the sensor amplifier 52 are controllable independently.

Another embodiment of the controllable bias systems 50, 51 of FIG. 8 include variable attenuators in place of the variable gain amplifiers. Further, the controllable bias systems described in reference to FIG. 8 may be used in conjunction with any of the eddy current probes of FIGS. 1-6, as described above. In the cases of the eddy current probes of FIGS. 5-6, additional multiplexers may be required if more than two controllable bias systems are used.

FIG. 9 illustrates a further embodiment of the controllable bias system 50, 51 for use in the eddy current probes described herein. In the embodiment of FIG. 9, the bias sources 70, 71 are adjustable current sources (or adjustable voltage sources) that are controlled by the controller 62. Thus, the controller 62 adjusts the output of the adjustable bias sources as desired, e.g., to create a null signal from the sensor amplifier 52 when used on region under test that is defect free. The individual adjustable bias system 50, 51 may be adjusted independently by the controller 62. As such, the same controller 62 may be used to adjust the bias sources. Alternatively, each controllable bias system may be controlled with its own separate controller. Further, the controller 62 of FIGS. 5-6 may be used as the controller of the controllable bias systems 70, 71, or other controllers may be used. As with the controllable bias systems described in reference to FIGS. 7-8, the controllable bias systems described in reference to FIG. 9 may be used in conjunction with any of the eddy current probes of FIGS. 1-6, as described above.

Further, all of the controllable bias systems of an eddy probe are not required to be the same embodiment. For example, an eddy probe may use the embodiment of FIG. 7 as a first controllable bias system and the embodiment of FIG. 8 as a second controllable bias system.

Moreover, the controllable bias systems described herein may be used to tune the magnetic field sensors to sense magnetic fields of two separate amplitudes.

According to further aspects of the present disclosure, an eddy current probe is provided where the two sensors are subject to completely different amplitude magnetic fields. An example of this could be one probe for buried defects where the first sensor is close to the excitation coil (sensing a strong magnetic field) while the other is substantially apart to sense magnetic field lines that travel deeper in the material (which are substantially much weaker than the magnetic field in the location of the first sensor). In this situation, the bias current of sensor 1 would be reduced to the point where the two sensors output similar signal.

For example, in FIG. 10, the first magnetic field sensor 30 (closer to the magnetic field generator 20) may be used to sense a stronger magnetic field than the second magnetic field sensor 31, which is substantially farther from the magnetic field generator 20, and thus senses weaker magnetic fields. These weaker magnetic fields travel deeper into the part under test into the region under test to detect buried defects. In this situation, the bias current of the first magnetic field sensor 30 would be less than the bias current of the second magnetic field sensor 31, so the outputs of the magnetic field sensors 30, 31 are essentially equal. This can be readily accomplished by the controller 62. While FIG. 10 illustrates the controllable bias system of FIG. 9, any of the embodiments described with reference to FIGS. 7-9 (or otherwise herein) may be used to supply the different bias signals to the magnetic field sensors 30, 31 by the controller 62.

Miscellaneous Considerations:

Magnetic field sensors exhibit advantages over conventional inductive coil sensors when applied as the sensing element of eddy current probes as described more fully herein. For instance, instead of being sensitive to the magnetic flux derivative as coils are, magnetic field sensors directly detect the magnetic field. Therefore, the sensitivity of a magnetic field sensor is guaranteed, even when operating at low frequencies.

Also, the use of coils may be unpractical, such as due to the required spatial resolution of a given application. Thus, another advantage of magnetic field sensors is their typical small active area, which can be reduced to a few square microns. The small active area of such magnetic field sensors improves the spatial resolution realizable compared to conventional inductive coil sensors. Accordingly, the magnetic field sensor technology herein is preferably applied in applications requiring the detection of deep buried irregularities, as well as surface breaking defects on conductive parts.

By way of example, defects generated by lack of penetration (LOP) while welding two aluminum parts by Friction Stir Welding (FSW) are typically undetectable by eye and are very difficult to detect using non-destructive techniques due to its very small width and depth, which can be as small as 50μm. However, the small active area of an eddy current probe as described herein is suitable for such applications due to the ability to precisely control sufficiently small spatial distances between magnetic field sensors of the probe.

Referring to FIGS. 11 and 12 generally, the illustrated probe can be operated at medium and high frequencies (from hundreds of kHz to few MHz).

Moreover, the illustrated probe implements the magnetic field generator 20 as a driver trace (the corresponding function generator is not shown in FIG. 11), which enables the generation of very confined and straight eddy currents. In illustrative implementations, the width of the driver trace is made as small as possible to concentrate the magnetic field as close as possible the part. Accordingly, when testing for defects with known orientation, the illustrated probe can be aligned to promote the interaction between eddy currents and the defects. Also, in an illustrative configuration, the out of plane magnetic field was registered in two magnetic field sensor locations that are equally spaced from the center of the driver trace (magnetic field generator).

Also, in the illustrative implementation, a Printed Circuit Board (PCB) serves as the probe support structure, to implement the driver trace (magnetic field generator) and interconnections with the other electronics, e.g., drive circuitry, differential circuitry, function generator, etc. However, other substrates may alternatively be used.

The magnetic field sensors may be processed on a thin silicon substrate that is glued to the PCB.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention.

Having thus described the invention of the present application in detail and by reference to embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims.

CLAIMS

What is claimed is:

1. An eddy current probe for testing conductive parts, comprises:

a magnetic field generator to which a drive signal is applied to generate a primary magnetic field, wherein the primary magnetic field, when approached near a part being tested, induces eddy currents in the part;

a first magnetic field sensor, which outputs a first sensor signal indicative of a magnetic field sensed thereby;

a second magnetic field sensor positioned spaced from the first magnetic field sensor, which outputs a second sensor signal indicative of a magnetic field sensed thereby, wherein a space between the first magnetic field sensor and the second magnetic field sensor defines a region under test of the part;

a first controllable bias system coupled to the first magnetic field sensor;

a second controllable bias system coupled to the second magnetic field sensor, wherein:

the second controllable bias system is controlled independently of the first controllable bias system;

the first controllable bias system biases the first magnetic field sensor; and

the second controllable bias system biases the second magnetic field sensor so as to achieve a similar first sensor signal and second sensor signal outside the presence of a secondary magnetic field indicative of the presence of a defect in the region under test of the part; and

a sensor amplifier circuit that receives the first sensor signal and the second sensor signal, and generates a difference signal therefrom.

2. The eddy current probe according to claim 1, wherein:

the first magnetic field sensor and the second magnetic field sensor are each positioned proximate to the magnetic field generator and are separated by a known distance having a maximum distance limited by a range of adjustability in the control of the first controllable bias system and the second controllable bias system such that a requirement is satisfied the first magnetic field sensor and the second magnetic field sensor produce a similar output when the magnetic field generator produces the primary magnetic field and the probe is positioned in a defect-free region of the part being tested.

3. The eddy current probe of claim 1 further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first adjustable bias source implemented as a first adjustable current source that is controlled by the controller;

the second controllable bias system includes a second adjustable bias source implemented as a second adjustable current source that is controlled by the controller; and

the controller adjusts the first adjustable current source and the second adjustable current source independently of each other.

4. The eddy current probe of claim 1 further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first adjustable bias source implemented as a first adjustable voltage source that is controlled by the controller;

the second controllable bias system includes a second adjustable bias source implemented as a second adjustable voltage source that is controlled by the controller; and

the controller adjusts the first adjustable voltage source and the second adjustable voltage source independently of each other.

5. The eddy current probe of claim 1, further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first bias source implemented as a first constant current source, and a first variable resistor, wherein the first variable resistor is coupled in parallel with the first magnetic field sensor and is controlled by the controller;

the second controllable bias system includes a second bias source implemented as a second constant current source, and a second variable resistor, wherein the second variable resistor is coupled in parallel with the second magnetic field sensor and is controlled by the controller; and

the controller adjusts the first variable resistor and the second variable resistor independently of each other.

6. The eddy current probe of claim 1, further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first bias source implemented as a first constant voltage source, and a first variable resistor, wherein the first variable resistor is coupled in series with the first magnetic field sensor and is controlled by the controller;

the second controllable bias system includes a second bias source implemented as a second constant voltage source, and a second variable resistor, wherein the second variable resistor is coupled in series with the second magnetic field sensor and is controlled by the controller and

the controller adjusts the first variable resistor and the second variable resistor independently of each other.

7. The eddy current probe of claim 1, further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first bias source implemented as a first constant current source, and a first variable amplifier, wherein the first variable amplifier is coupled between the first magnetic field sensor and a first input of the sensor amplifier and is controlled by the controller;

the second controllable bias system includes a second bias source implemented as a second constant current source, and a second variable amplifier, wherein the second variable amplifier is coupled between the second magnetic field sensor and a second input of the sensor amplifier and is controlled by the controller; and

the controller adjusts the first variable amplifier and the second variable amplifier independently of each other.

8. The eddy current probe of claim 1, further comprising a controller coupled to the first controllable bias system and the second controllable bias system, wherein:

the first controllable bias system includes a first bias source implemented as a first constant current source, and a first variable attenuator, wherein the first variable attenuator is coupled between the first magnetic field sensor and a first input of the sensor amplifier and is controlled by the controller;

the second controllable bias system includes a second bias source implemented as a second constant current source, and a second variable attenuator, wherein the second variable attenuator is coupled between the second magnetic field sensor and a second input of the sensor amplifier and is controlled by the controller; and

the controller adjusts the first variable amplifier and the second variable amplifier independently of each other.

9. The eddy current probe according to any of the preceding claims, wherein:

the magnetic field generator comprises at least one of a coil, a single wire filament, and a moving magnet.

10. The eddy current probe according to any of the preceding claims further comprising:

a function generator;

a drive amplifier having an input coupled to the function generator and an output coupled to the magnetic field generator such that a signal output by the function generator is amplified by the drive amplifier, and the drive amplifier outputs the drive signal to the magnetic field generator as an alternating current that flows through the magnetic field generator; and

a controller connected to the function generator, wherein:

the controller controls the function generator to change at least one of the signal shape and signal amplitude of the drive signal to control the primary magnetic field.

11. The eddy current probe according to claim 10, wherein:

the function generator applies a pulse waveform to the magnetic field generator.

12. The eddy current probe according to any of the preceding claims further comprising:

a plurality of magnetic field generators configured to enable different magnetic field patterns to be created.

13. The eddy current probe according to claim 1 wherein:

the first magnetic field sensor and the second field magnetic sensor are part of an array of magnetic field sensors having a plurality of magnetic field sensors;

further comprising:

a controller; and

a multiplexer;

wherein the controller controls the multiplexer to select a pair of magnetic field sensors from the sensor array to represent the first magnetic field sensor and the second magnetic field sensor.

14. The eddy current probe according to claim 13, wherein:

the controller controls both the primary magnetic field generator and the distance between the first magnetic field sensor and the second magnetic field sensor according with a testing application requirement.

15. A method of implementing an eddy current probe for testing conductive parts, comprises:

generating, in response to a drive signal, a primary magnetic field, wherein the primary magnetic field, when approached near a part being tested, induces eddy currents in the part;

generating a first sensor signal, using a first magnetic field sensor positioned within the primary magnetic field, which is indicative of a magnetic field sensed by the first magnetic field sensor;

generating a second sensor signal, using a second magnetic field sensor positioned within the primary magnetic field, which is indicative of a magnetic field sensed by the second magnetic field sensor;

designating a region of the part under test between the first magnetic field sensor and the second magnetic field sensor as a region under test;

biasing the first magnetic field sensor with a first controllable bias system;

biasing the second magnetic field sensor with a second controllable bias system, which is independent from the first controllable bias system, so as to achieve a similar first sensor signal and second sensor signal outside the presence of a secondary magnetic field indicative of the presence of a defect in the region under test of the part; and

producing a difference signal using a differential circuit that receives the first sensor signal and the second sensor signal, wherein:

there is no defect in a part if the difference signal is indicative of a null; and

there is a defect if the difference signal is indicative of a sensed magnetic field that is different in the first magnetic field sensor compared to the magnetic field sensed by the second magnetic field sensor due to the presence of a defect or other material characteristic in the part being tested.

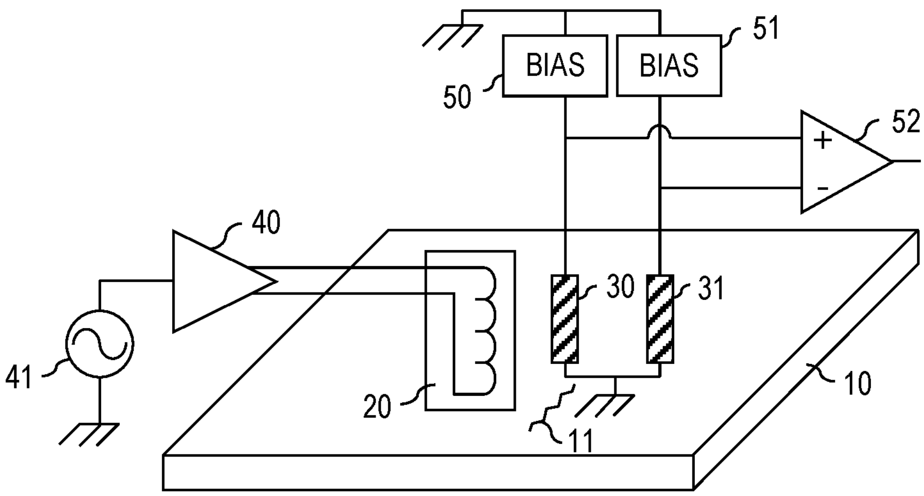

FIG. 1

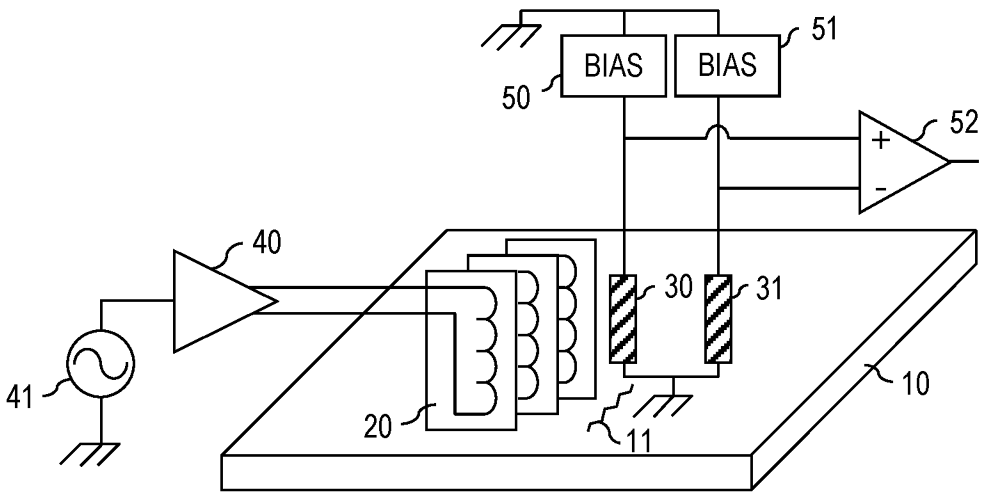

FIG. 2

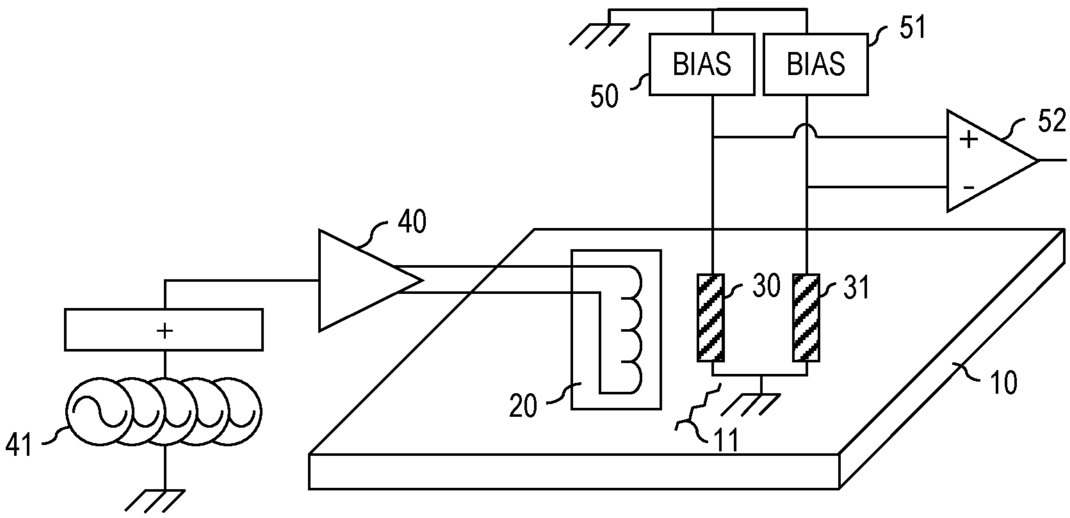

FIG. 3

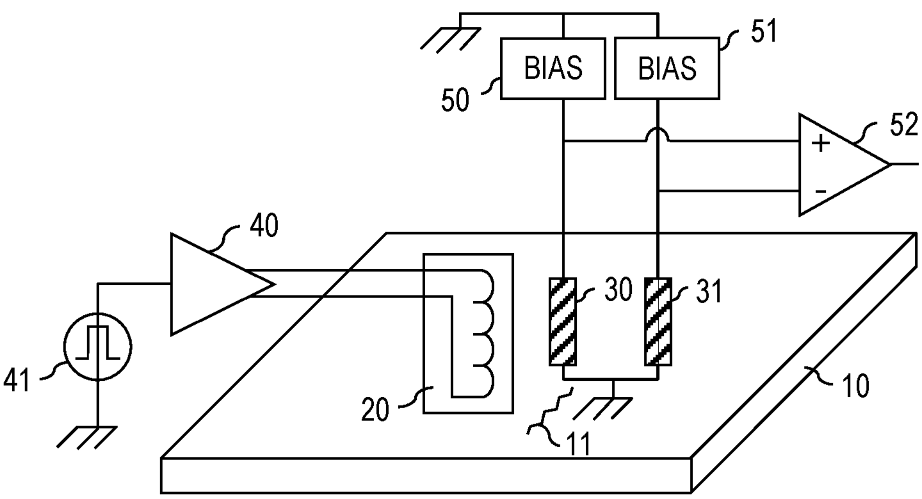

FIG. 4

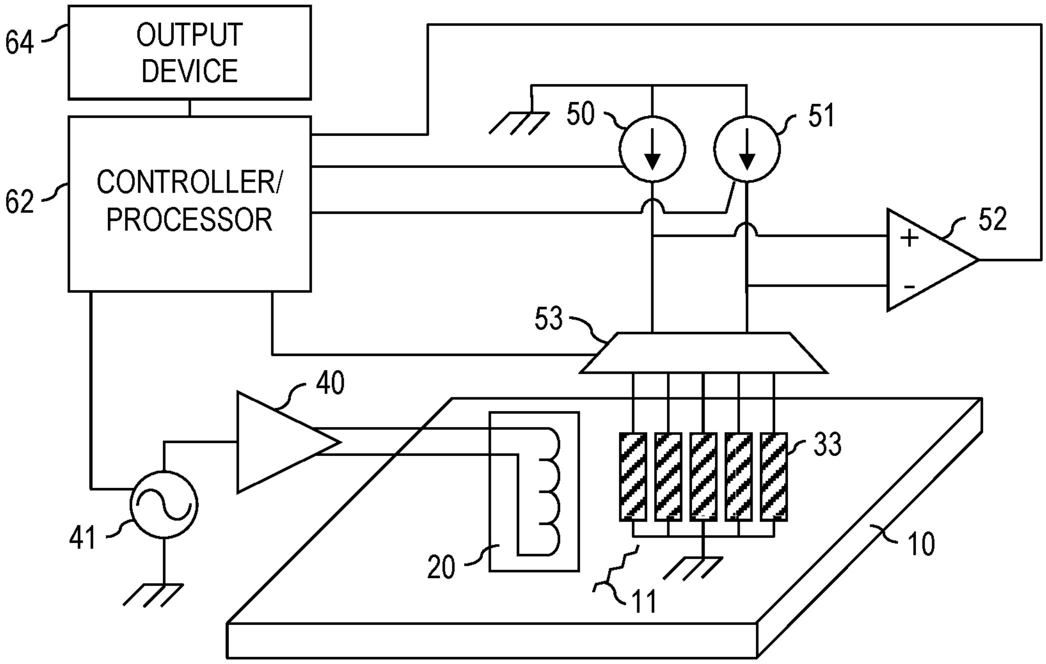
64
OUTPUT DEVICE
62
CONTROLLER/ PROCESSOR
50
51
52
+
-
53
40
33
41
20
10
11

FIG. 5

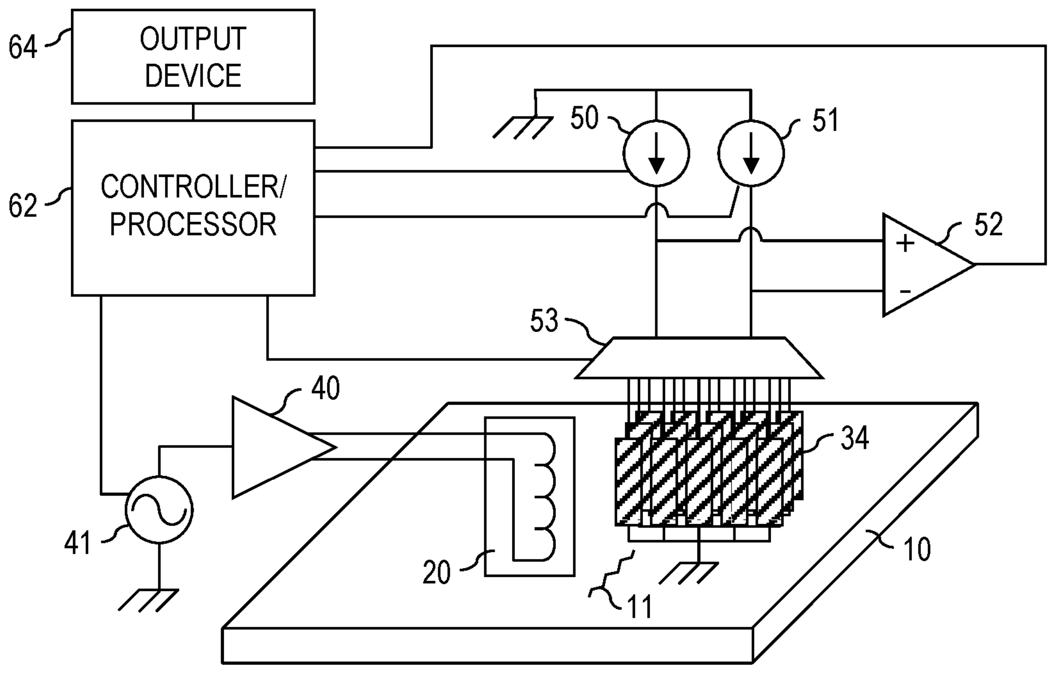
64
OUTPUT DEVICE
62
CONTROLLER/ PROCESSOR
50
51
52
+
-
53
40
34
41
20
11
10

FIG. 6

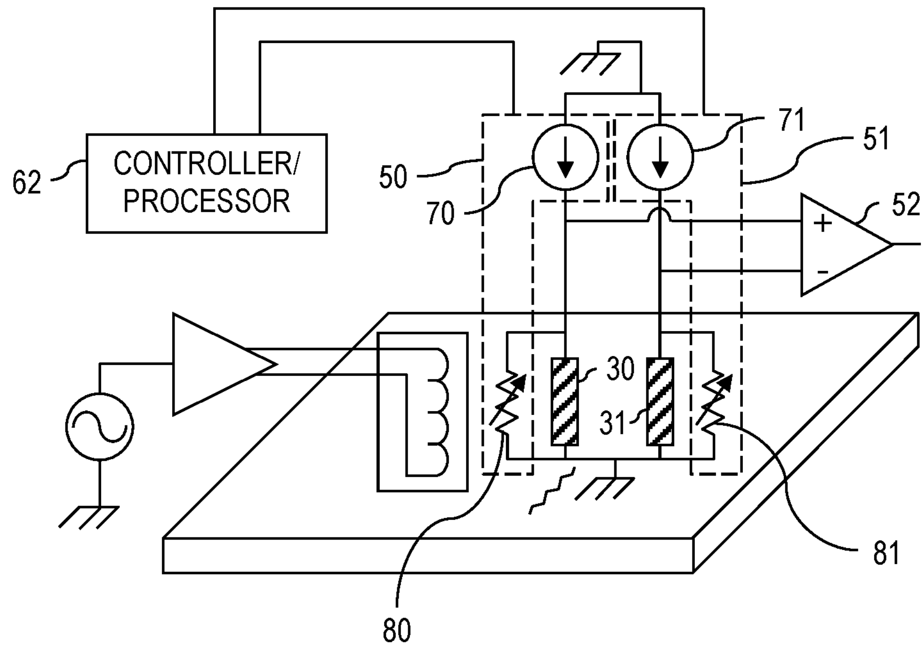

FIG. 7

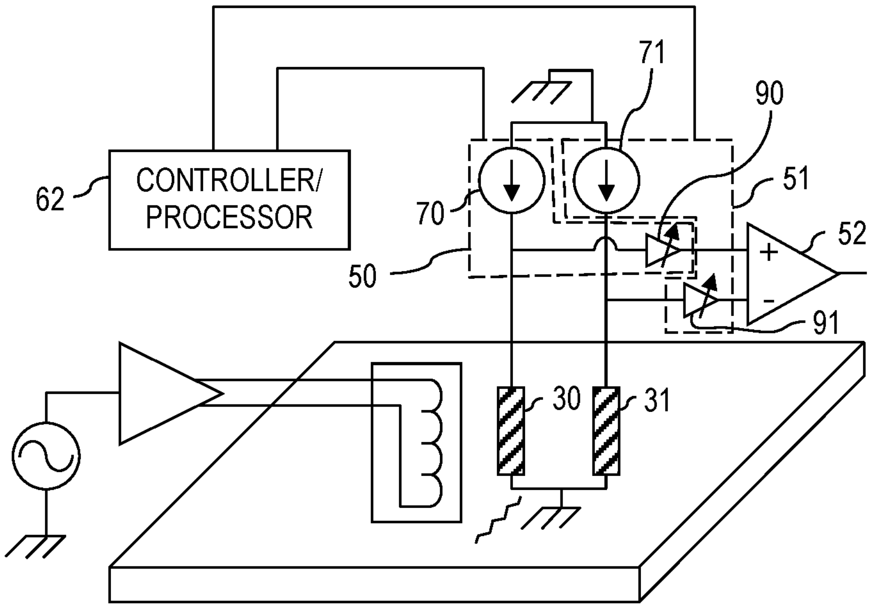

FIG. 8

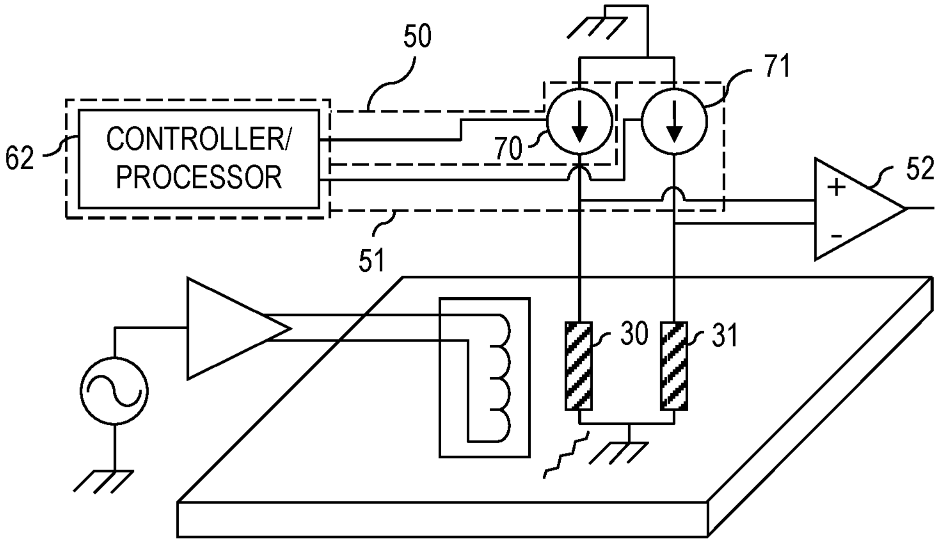

FIG. 9

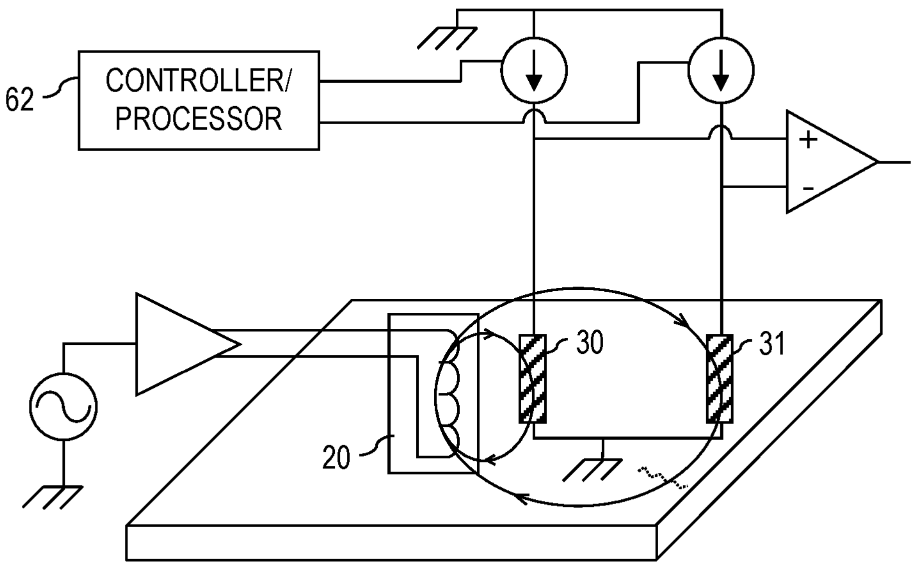

FIG. 10

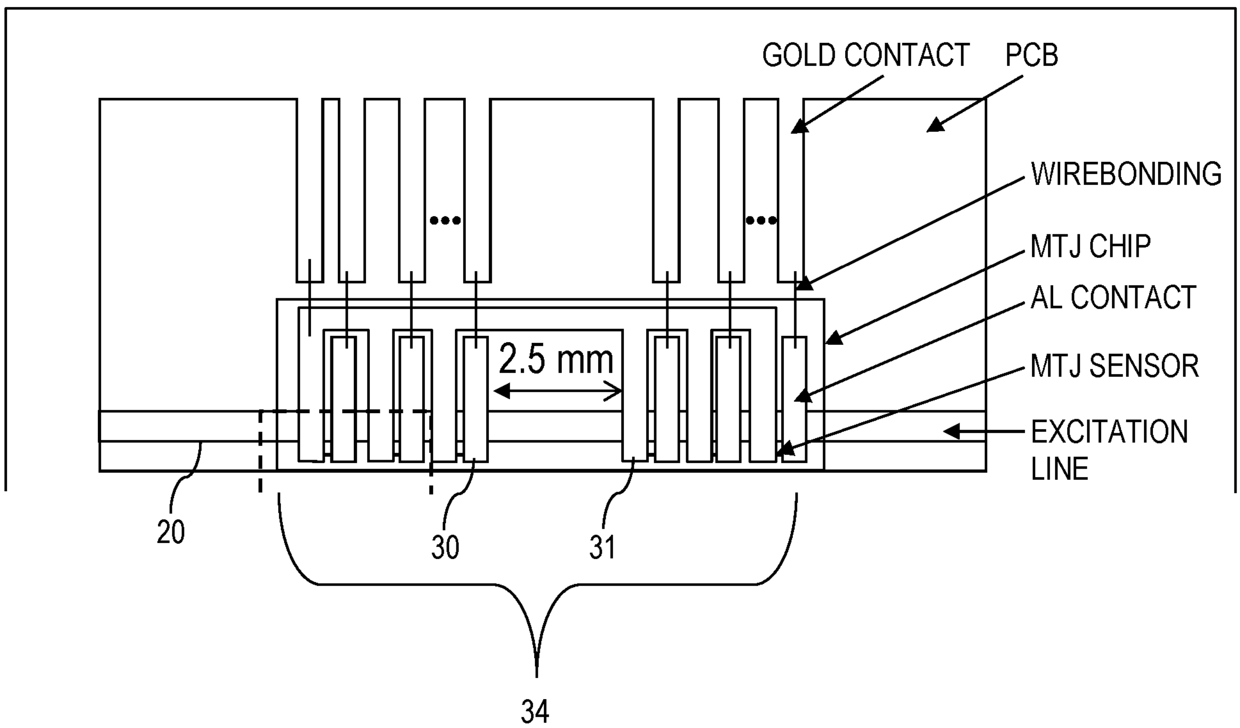
GOLD CONTACT
PCB
WIREBONDING
MTJ CHIP
AL CONTACT
MTJ SENSOR
EXCITATION LINE
2.5 mm
20
30
31
34

FIG. 11

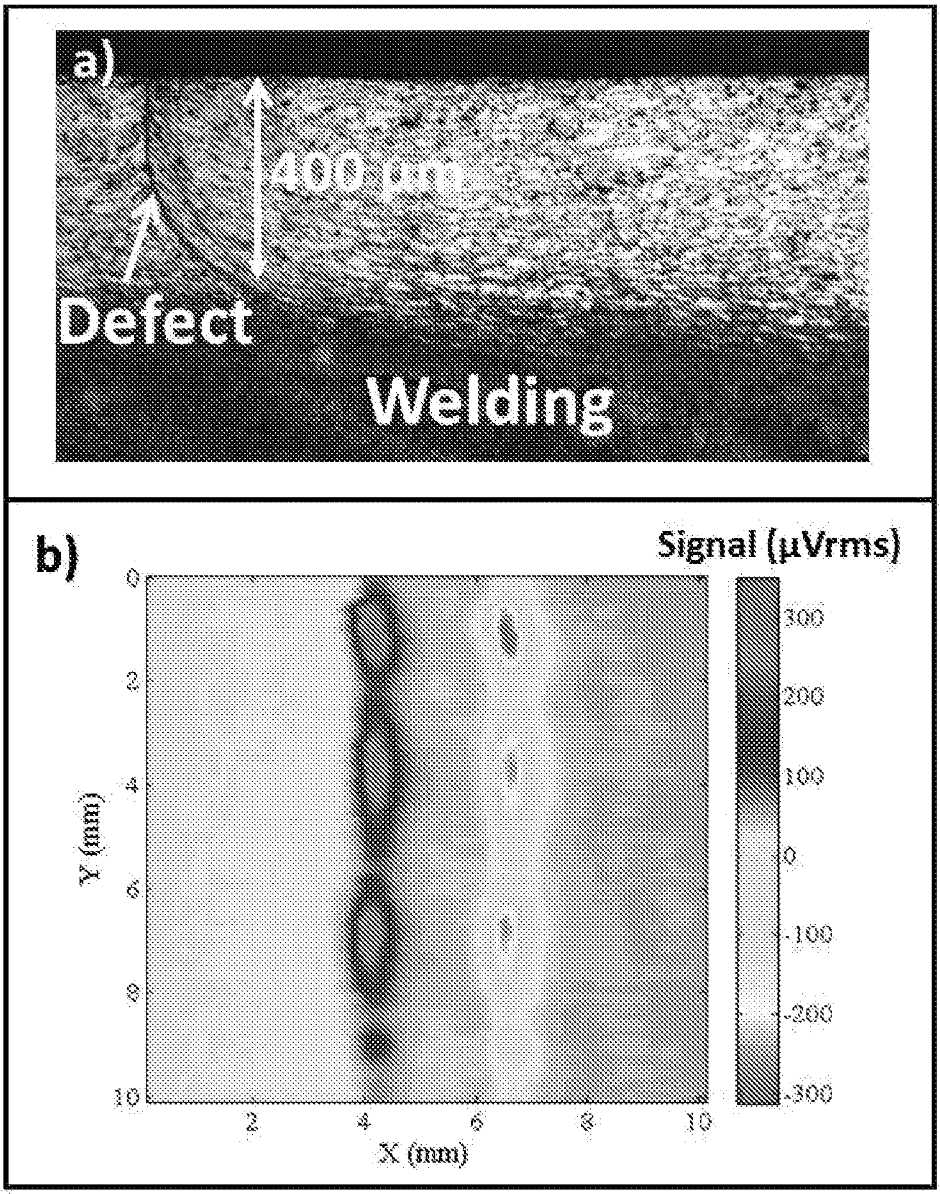
a)
400 µm
Defect
Welding
b)
Signal (µVrms)
Y (mm)
X (mm)
0
2
4
6
8
10
2
4
6
8
10
300
200
100
0
-100
-200
-300

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/050964

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N27/90 G01R33/09
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)
G01N G01R

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, WPI Data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 3 359 495 A (MCMASTER ROBERT C ET AL) 19 December 1967 (1967-12-19) column 12, lines 3-44; figures 20,21	1-15
Y	US 4 538 108 A (HUESCHELRATH GERHARD [DE] ET AL) 27 August 1985 (1985-08-27) column 6, line 33 - column 7, line 56; figure 7 column 8, lines 49-66	1-15
Y	GB 1 169 752 A (SUMITOMO METAL IND [JP]) 5 November 1969 (1969-11-05) page 4, lines 87-110; figure 5	1-15
A	FR 2 944 354 A1 (COMMISSARIAT ENERGIE ATOMIQUE [FR]) 15 October 2010 (2010-10-15) the whole document	1-15

-/--

[X] Further documents are listed in the continuation of Box C.

[X] 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	Date of mailing of the international search report
30 April 2015	18/05/2015

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Stussi, Elisa

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/050964

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	LUIS S. ROSADO ET AL: "Eddy currents testing probe with magneto-resistive sensors and differential measurement", SENSORS AND ACTUATORS A: PHYSICAL, vol. 212, 1 June 2014 (2014-06-01), pages 58-67, XP055186520, ISSN: 0924-4247, DOI: 10.1016/j.sna.2014.03.021 the whole document -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2015/050964

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		US 2012019239 A1	26-01-2012
		WO 2010115963 A1	14-10-2010