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United States Patent [19]

Wincheski et al.

[54] **ROTATING FLUX-FOCUSING EDDY CURRENT PROBE FOR FLAW DETECTION**

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[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,617,024.

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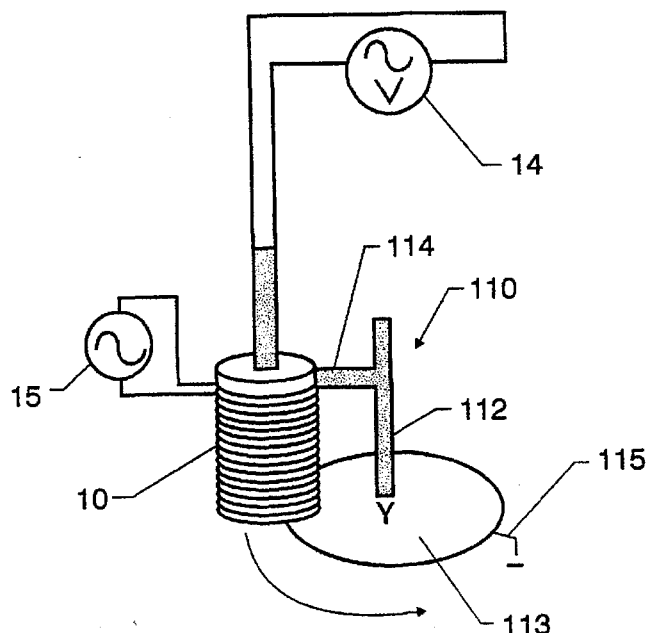|			
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Primary Examiner—Gerard R. Strecker
Attorney, Agent, or Firm—Robin W. Edwards

[57] **ABSTRACT**

A flux-focusing electromagnetic sensor which uses a ferromagnetic flux-focusing lens simplifies inspections and increases detectability of fatigue cracks about circular fasteners and other circular inhomogeneities in high conductivity material. The unique feature of the device is the ferrous shield isolating a high-turn pick-up coil from an excitation coil, The use of the magnetic shield is shown to produce a null voltage output across the receiving coil in the presence of an unflawed sample. A redistribution of the current flow in the sample caused by the presence of flaws, however, eliminates the shielding condition and a large output voltage is produced, yielding a clear unambiguous flaw signal.

By rotating the probe in a path around a circular fastener such as a rivet while maintaining a constant distance between the probe and the center of a rivet, the signal due to current flow about the rivet can be held constant. Any further changes in the current distribution, such as due to a fatigue crack at the rivet joint, can be detected as an increase in the output voltage above that due to the flow about the rivet head.
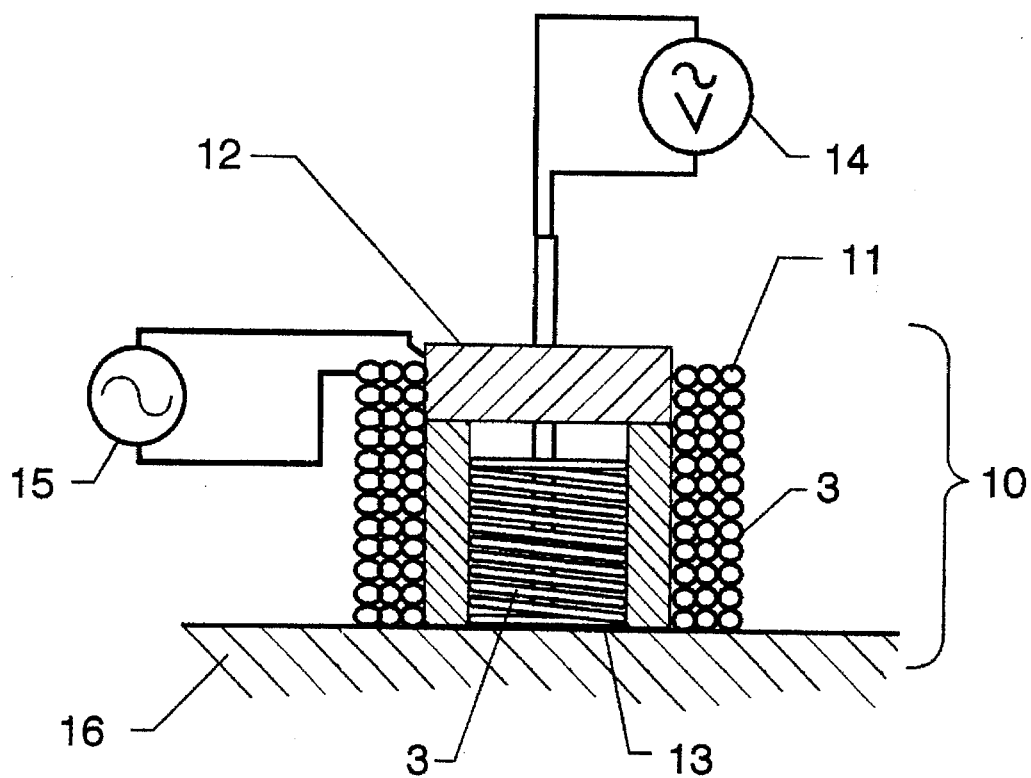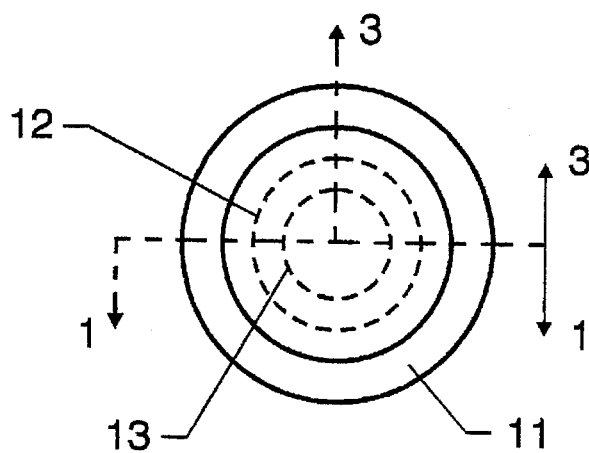
5 Claims, 15 Drawing Sheets

FIG.1

FIG. 2

32

31

FIG. 3A

31

33
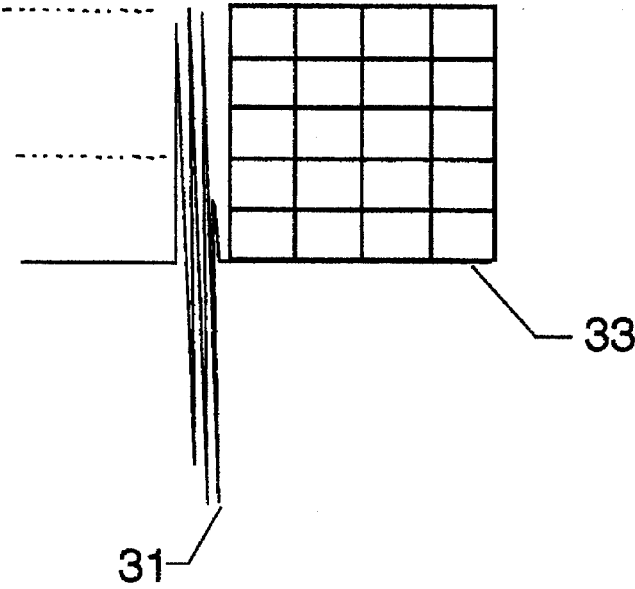
FIG. 3B
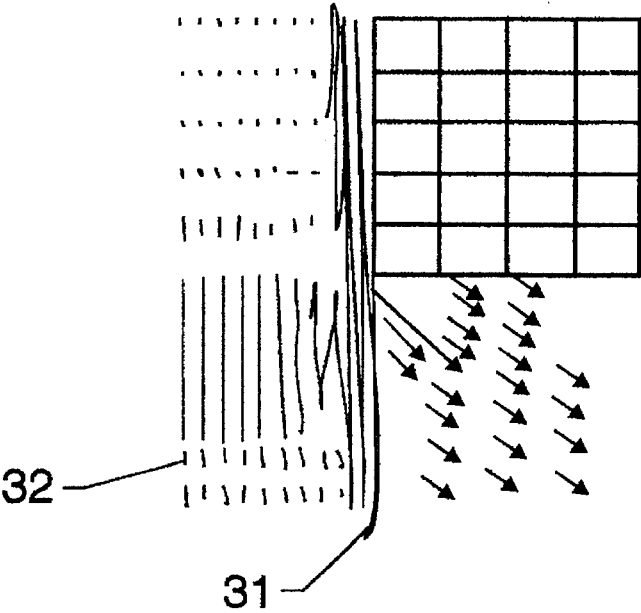
FIG. 4A

FIG. 4B

FIG. 4C
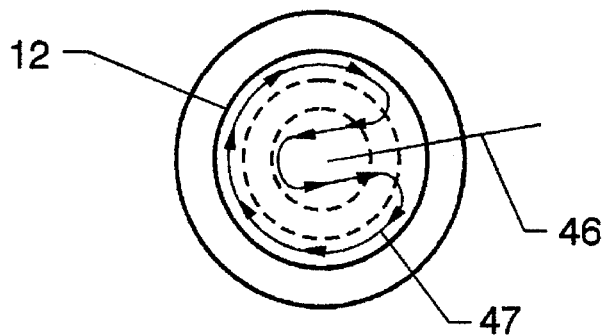
FIG. 4D
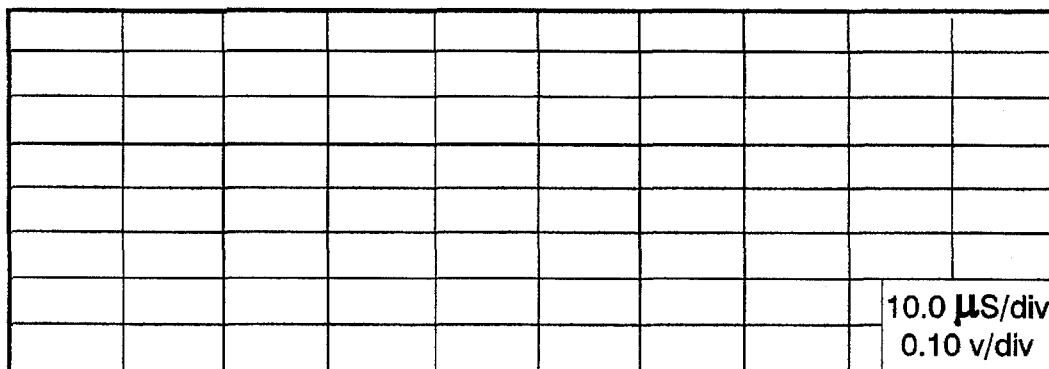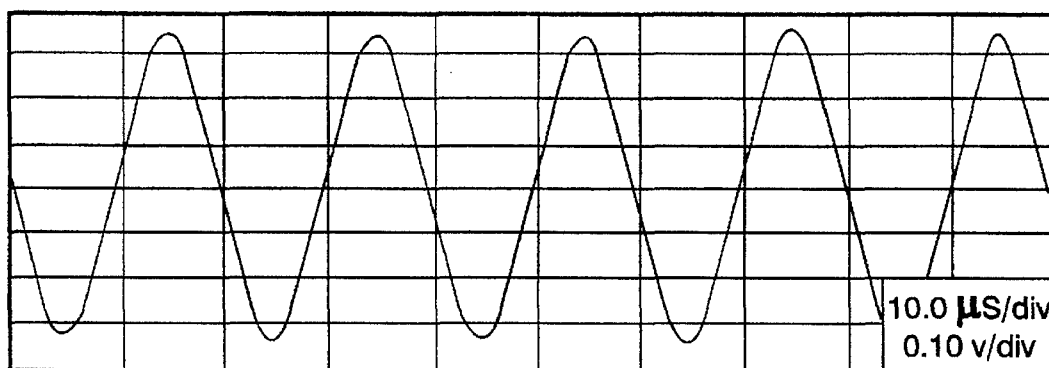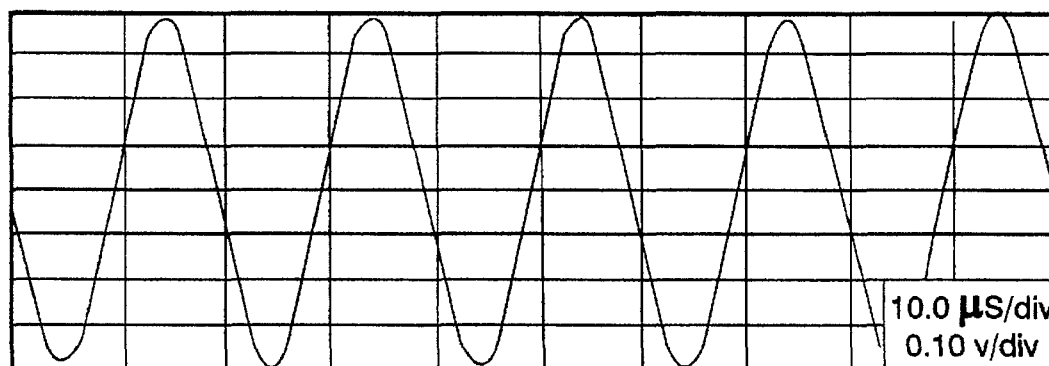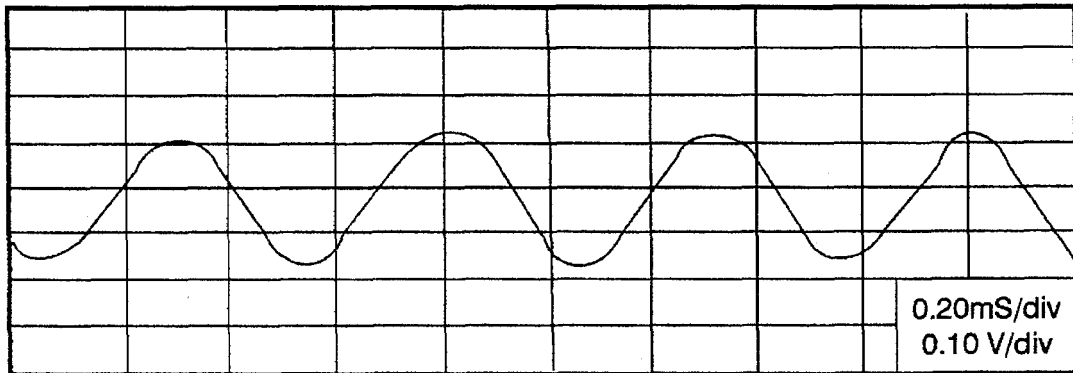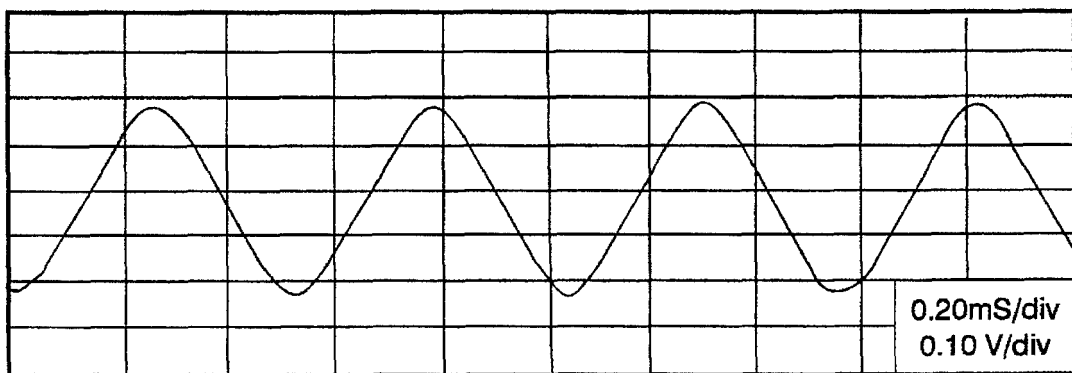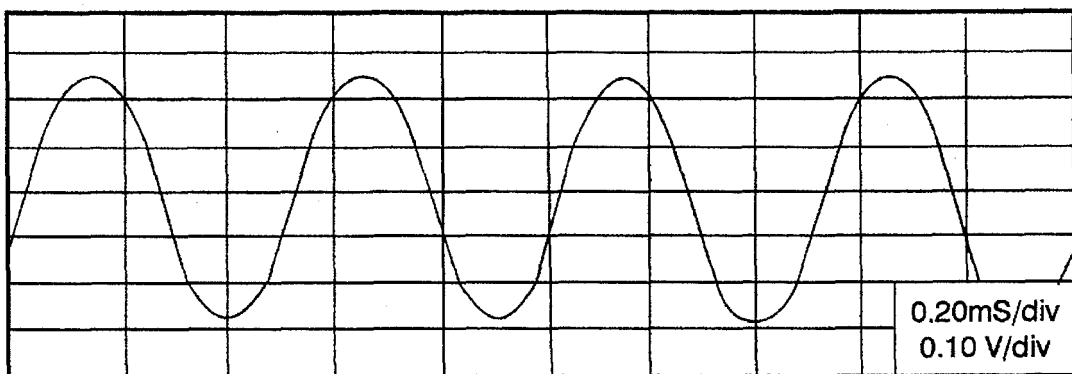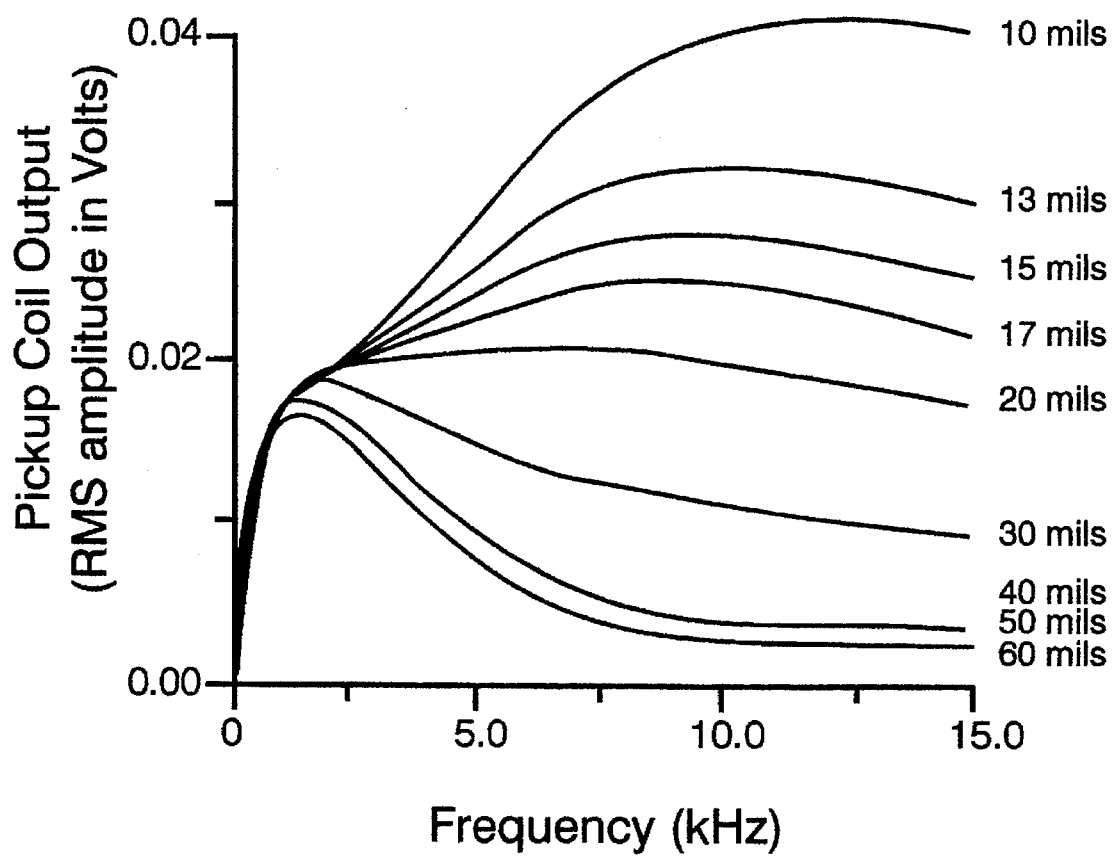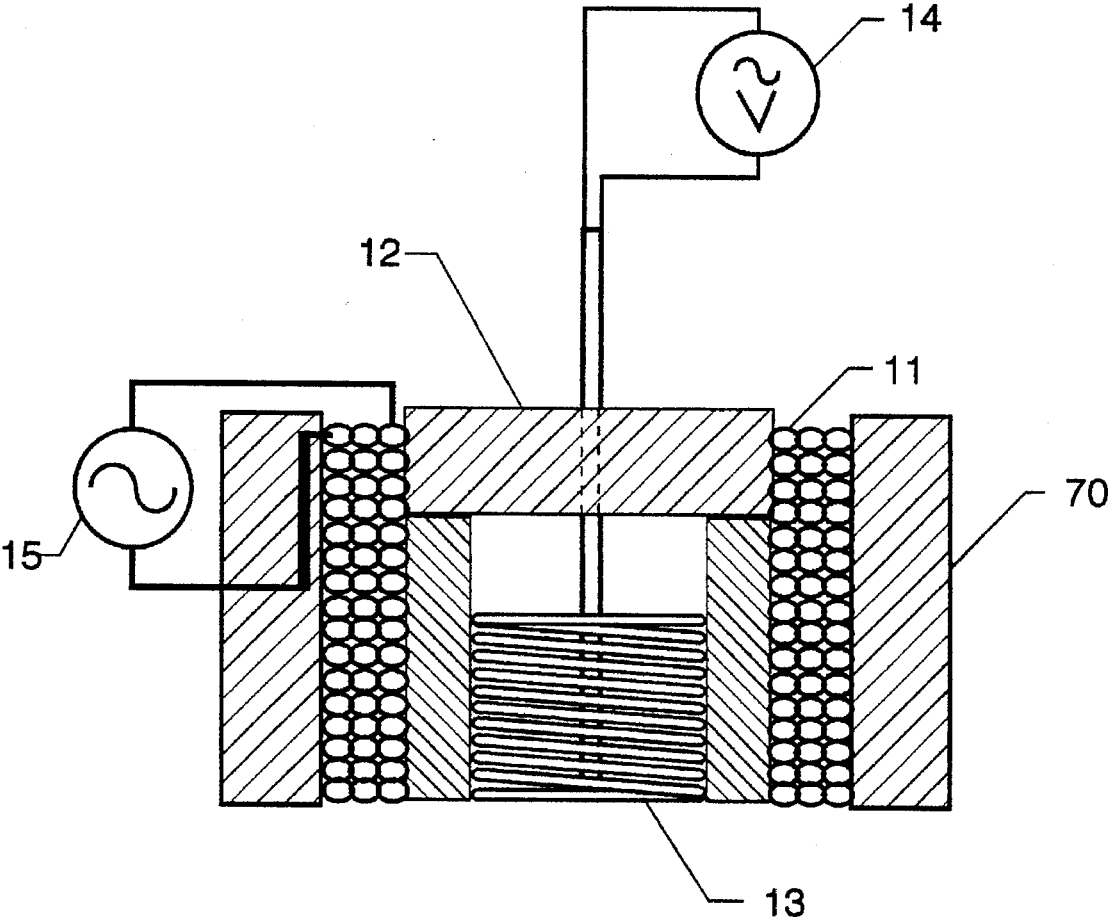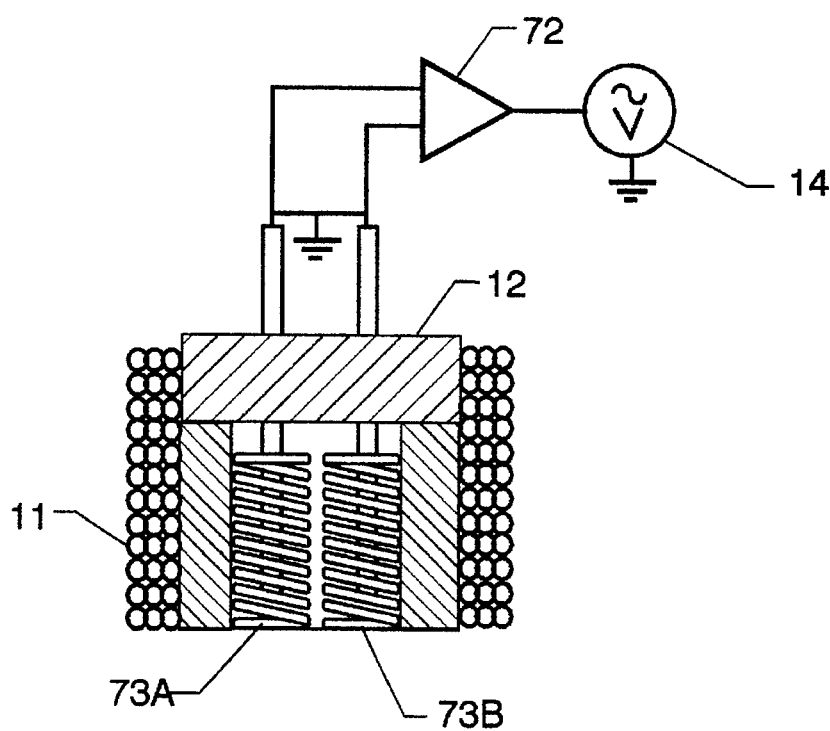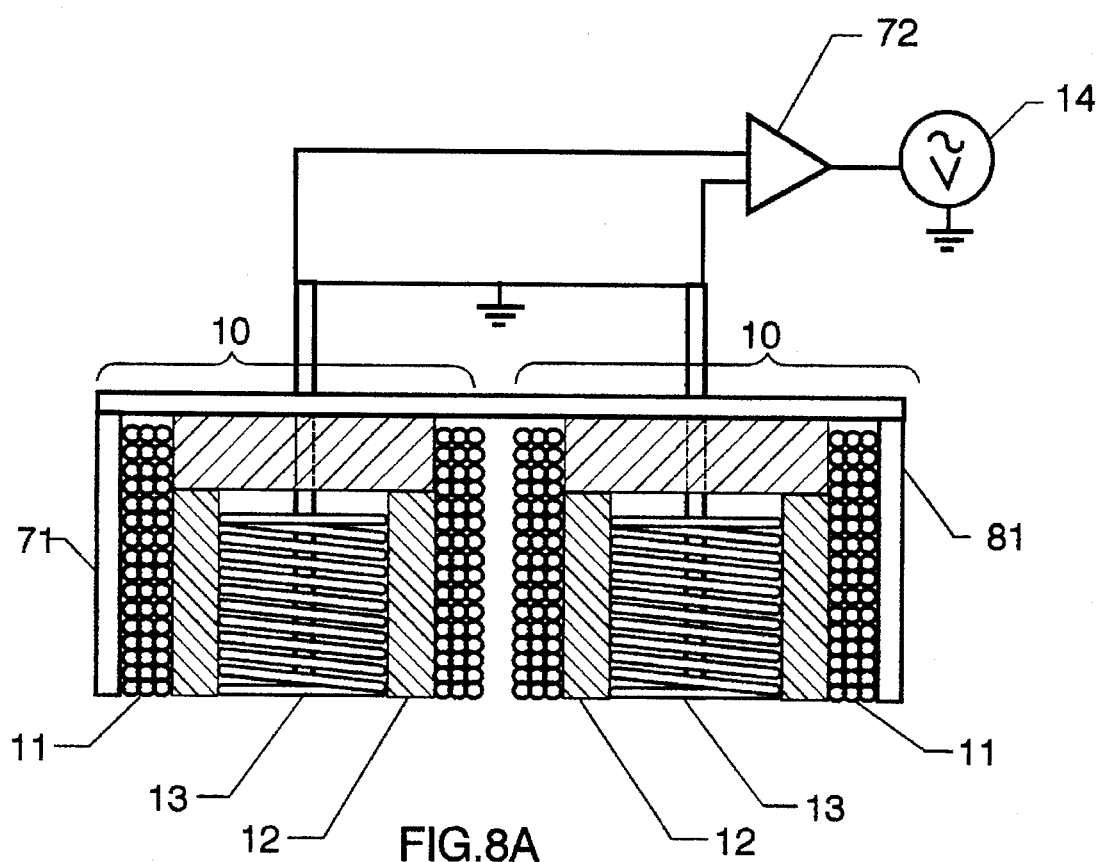
10.0 μS/div
0.10 v/div

FIG. 5A

10.0 μS/div
0.10 v/div

FIG. 5B

10.0 μS/div
0.10 v/div

FIG. 5C

0.20mS/div
0.10 V/div

FIG. 6C

0.20mS/div
0.10 V/div

FIG.6B

0.20mS/div
0.10 V/div

FIG.6C

FIG. 6D

FIG. 7

FIG.8A

FIG.8B

85

86

83

X AXIS
MOTOR DRIVER

Y AXIS
MOTOR DRIVER

84

SYSTEM CONTROLLER

82

LOADED FRAME CONTROLLER

87

16B

16

16A

81

FIG. 9

FIG. 10

FIG. 11

94

13

90

90

FIG. 12

FIG. 13(a)

FIG. 13(b)

Voltage peak at EDM notch extending 0.3mm
beyond rivet head (1.8 mm from rivet shank)

Background
voltage

Probe

.5π

0

π

1.5π

Angular location

Crack

Output Voltage (mV rms)

11.1

10.1

9.2

7.9

6.4

0   90   180   270   360

Angle (Degrees)
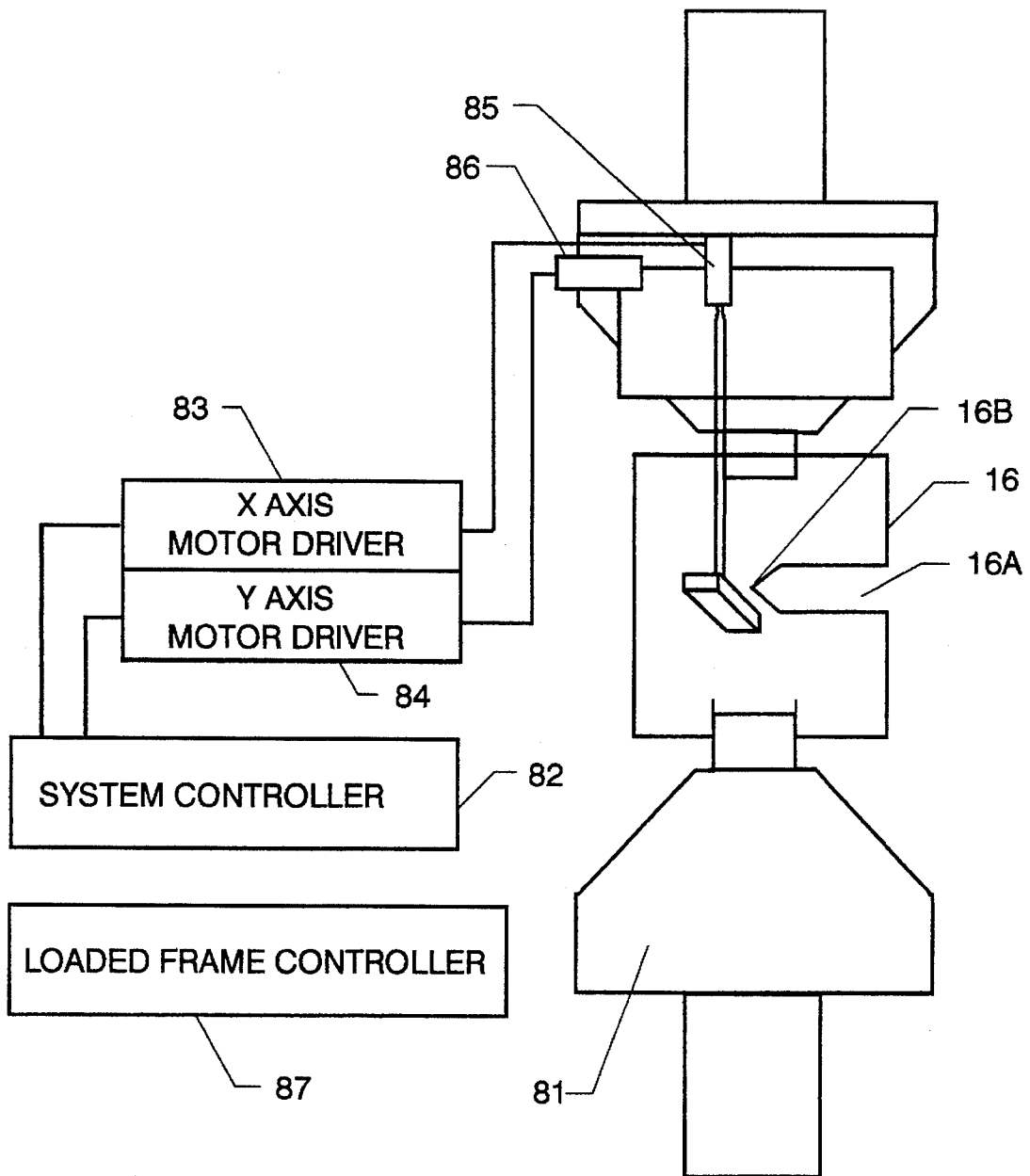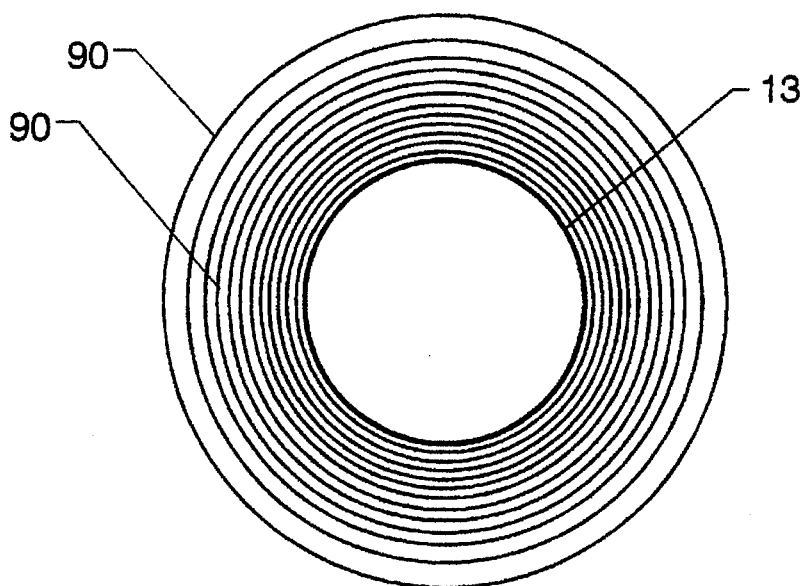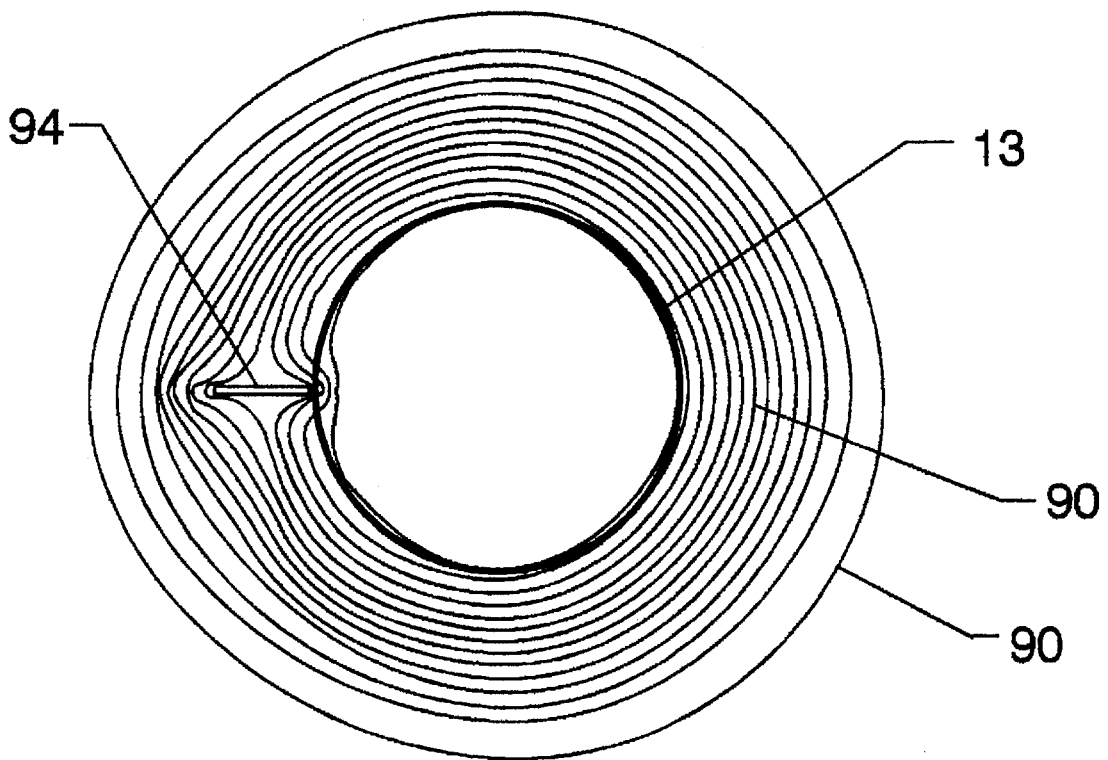
FIG. 14

FIG. 15(c)

FIG. 15(b)

FIG. 16

FIG. 15(a)

FIG. 17

ROTATING FLUX-FOCUSING EDDY CURRENT PROBE FOR FLAW DETECTION

CROSS-REFERENCE

This is a continuation-in-part of application Ser. No. 08/134,444, filed Oct. 12, 1993, now abandoned.

ORIGIN OF THE INVENTION

The invention described herein was jointly made by employees of the United States Government and contract employees during the performance of work under NASA contracts and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, as amended, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457) and 35 USC 202 in which the contractor elected not to retain title.

BACKGROUND OF THE INVENTION

The present invention relates generally to a device and method for detecting material flaws using the eddy current principle, and more particularly to a flux focusing eddy current probe having separate excitation and pick-up coils, magnetically isolated from one another by a highly permeable flux focusing lens, for detecting different types of flaws or discontinuities at various depths within an electrically conductive material, and an automated method of monitoring crack growth rate and trajectory during fatigue testing. The automated method is not limitative and the invention can also be used for manual testing and fault isolation. In addition, the present invention relates to a method of detecting flaws about circular fasteners or other circular inhomogeneities in electrically conductive material. The eddy current probe of this invention is simple in construction and operation while providing unambiguous signals of fault indication simplifying support equipment requirements, supporting self hulling capability in no fault conditions during surface faul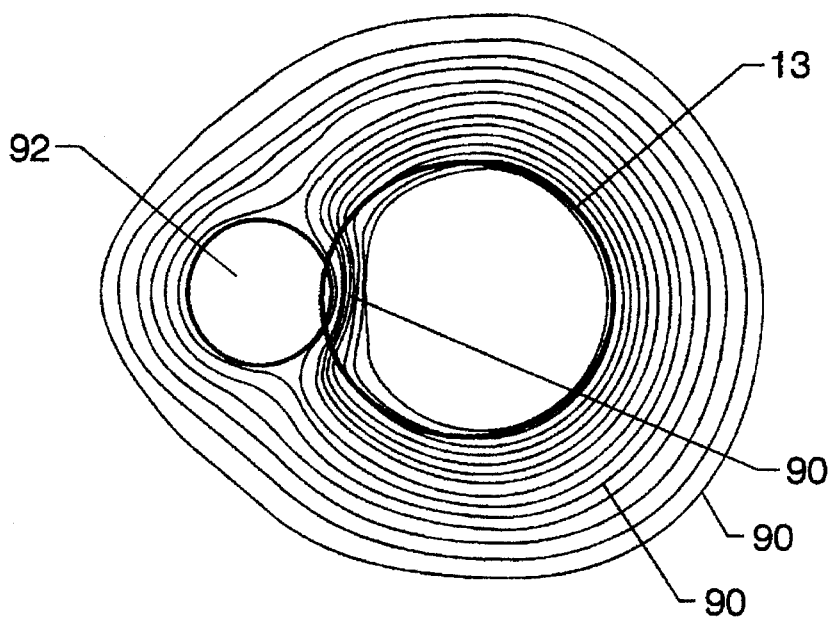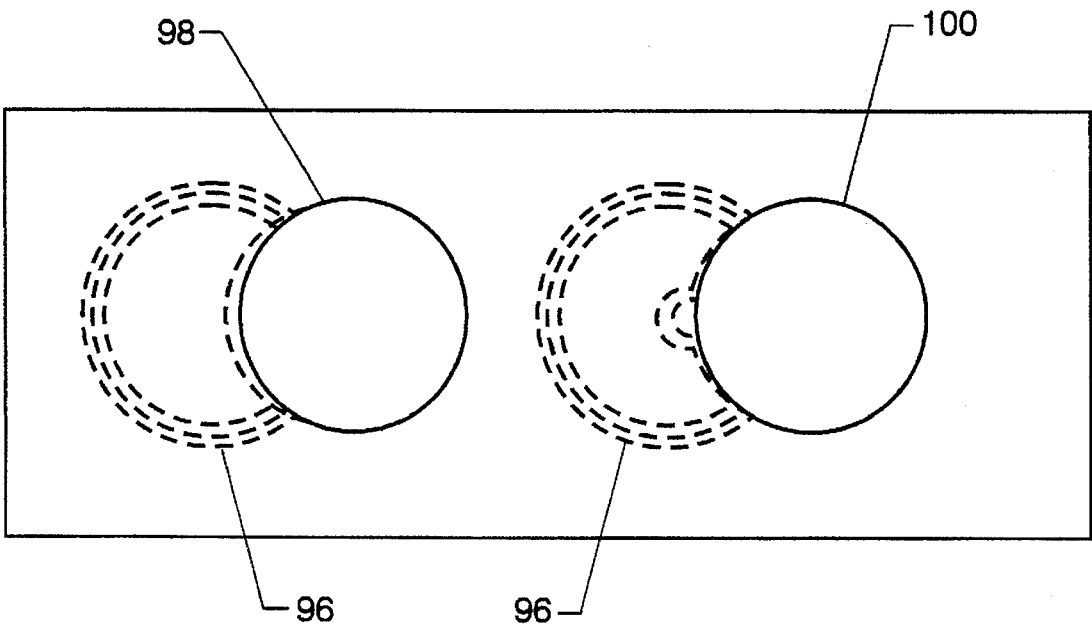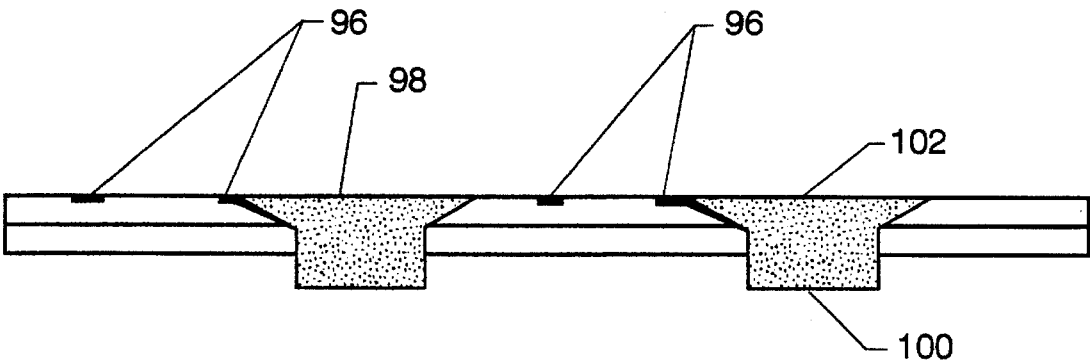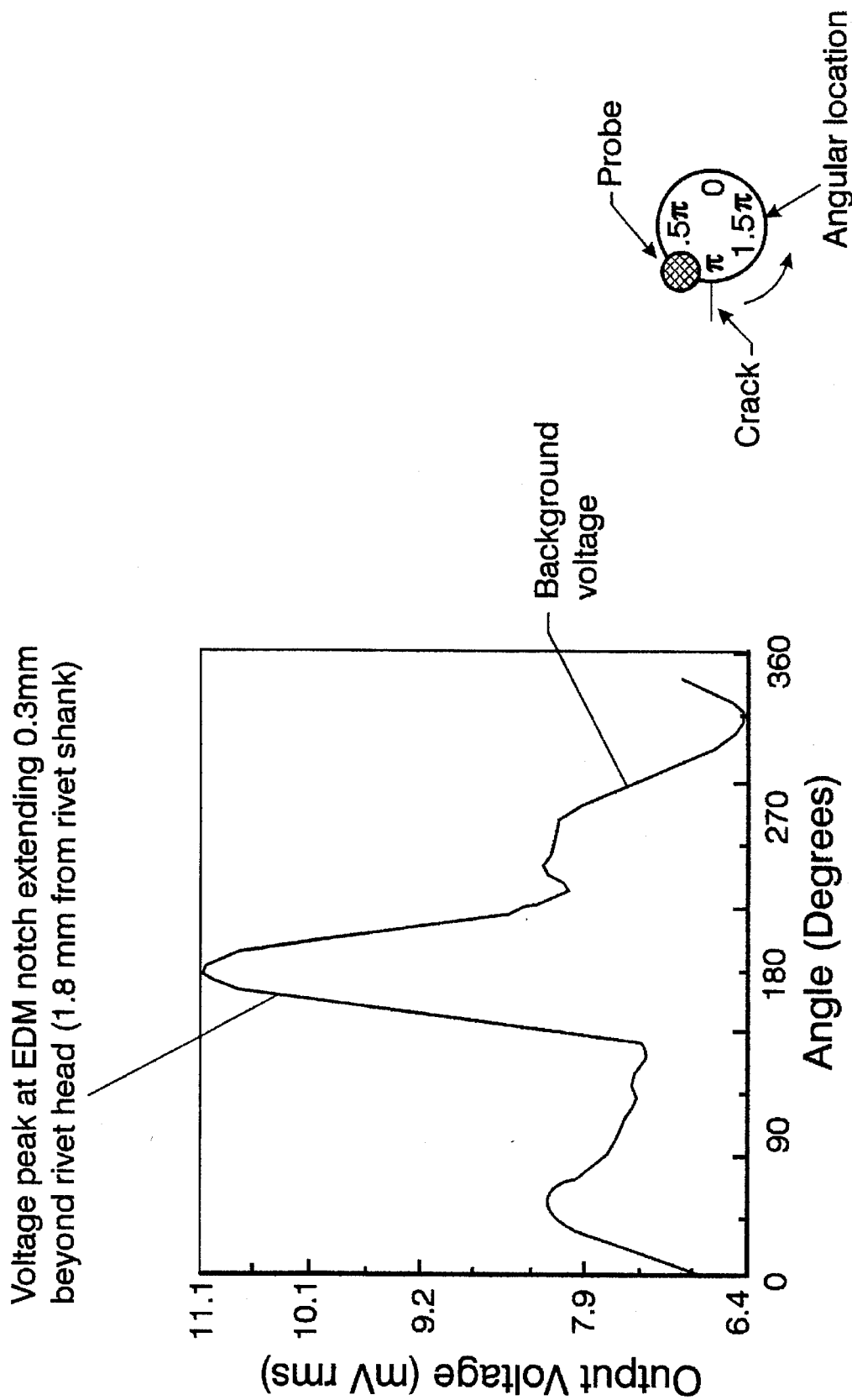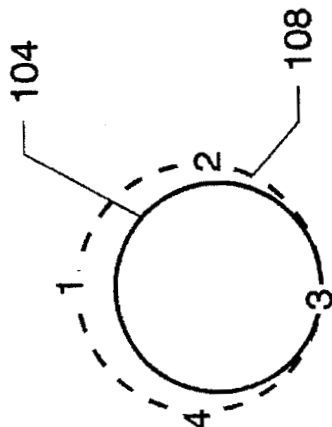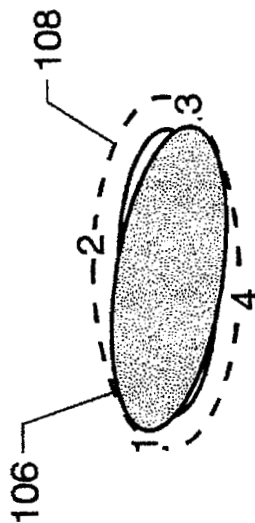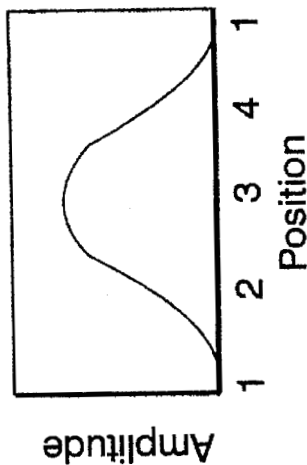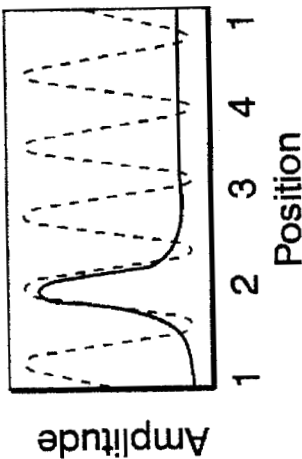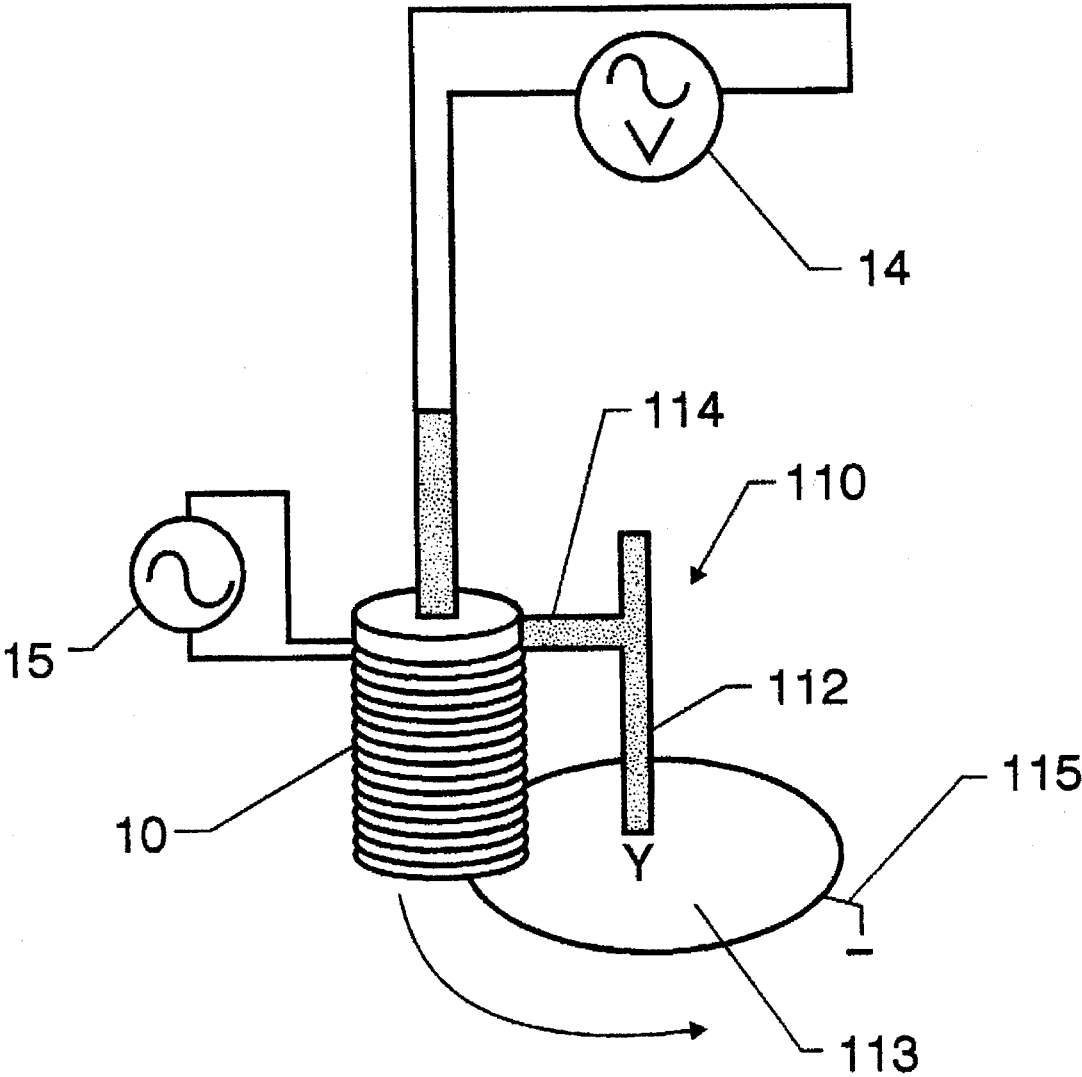t detection negating the need for calibration standards, maintaining highly resistant lift-off characteristics, and providing highest signal levels at fault tips.

The use of eddy currents to inspect electrically conductive material for flaws is known in the art. Such methods are particularly useful in the non-destructive evaluation of conducting material for surface or internal faults and material thinning. An eddy current probe generally consists of a coil electrically connected to a current generator producing an alternating current within the coil. This generates a time-varying primary magnetic field which in turn induces current flow (eddy currents) in an electrically conductive material positioned in the vicinity of the coil. As described by Lenz's Law, the eddy currents, during their return path, create an opposing secondary magnetic field superimposed on the coil's primary magnetic field decreasing the coil's flux and modifying the coil's voltage effecting the impedance of the coil.

The eddy current's power and direction are dependent upon the specific impedance of the conductive material. In unflawed conditions, eddy current flow is generally parallel to the magnetizing coil's windings. Flaws, such as cracks, pits, and material thinning, in the conductive material create regions of higher resistances at the flaw location which affect eddy current flow. The direction change in eddy current flow reduces the opposing secondary magnetic field and consequently the voltage in the coil. An impedance detecting circuit, which may take the form of an inductive bridge,

monitors coil voltage which, if different from an established no-fault condition, indicates a conductive material flaw. Sharp changes in impedance over a localized area would indicate the existence of cracks or other relatively small area flaws, whereas gradual changes in impedance over a broad region of the conductive material might indicate large-area flaws such as a grain change in the metal, an area of material creep, or material thinning. Though traditional eddy current probes use the same coil for magnetizing the conductive material and for detecting impedance variations caused by changes to eddy current flow, use of separate magnetizing and pick-up coils is known in the prior art. The same principle, however, of monitoring for variations in coil impedance as indicative of a conductive material flaw is applied. This conventional eddy current flaw detection technique often involves complex impedance planes necessitating special test electronics to achieve null balancing and known standards to calibrate probe responses to each type of flaw.

Multiple coils within a single probe can be used as separate magnetizing and sensing means, or they may be used in a more traditional fashion and independently operate the coils as bi-function magnetizing-sensing coils. In the case of a multiple coil probe, the coils can be juxtaposed in a matrix to provide a large detection area, or concentrically arranged to simultaneously detect flaws at various depths. Each coil of multiple coil probes is energized and monitored for impedance variations independently. Multiple coil probes use a shielding material high in magnetic permeability to provide a low reluctance path and divert potentially interfering magnetic fields to separate the coils from one another. The shielding is designed to isolate all interfering signals so that each cows impedance can be independently balanced. This design provides an ability to perform material testing at several frequencies simultaneously. The conventional eddy current flaw detection techniques are employed which require special test equipment to analyze probe signals.

As the conventional eddy current probe separates from the test material, the eddy currents induced within the material rapidly decrease resulting in a similarly decreasing opposing magnetic field which directly affects the resistance and inductance of the probe's coil. Abrupt changes occur to the impedance balance being monitored for fault indications making traditional eddy current probes unusable during these lift-off conditions.

In addition to detecting existing flaws in conductive material, determination of fatigue crack growth criteria in structural materials is important to predict material fatigue failure limits. Current approaches to testing fatigue cracking include optical methods and other length measuring techniques such as crack mouth opening displacement gauge and four point potential drop method. Each of these procedures requires long periods of continuous monitoring by well trained operators to record fatigue crack tip locations and to adjust experimental controls in compliance with experimental designs. Though the crack mouth opening displacement gauge and four point potential drop method could potentially be automated to reduce operator time requirements, only overall crack length data can be provided and the fatiguing process must usually be stopped to make the crack length measurements.

Eddy current devices have also been used to monitor fatigue crack growth during fatigue. This approach to monitoring fatigue crack growth has been automated, though, again, only overall crack length data can be provided. The traditional eddy current probe which implements impedance

measurement techniques to identify the presence of test material faults is not conducive to tracking the crack tip which supports crack trajectory as well as crack growth rate.

A variety of non-destructive evaluation techniques are currently used to inspect rivet joints. However, eddy current testing is currently the most widely used technique to find flaws which are not readily visible. Several different types of eddy current probes have been developed for the specific purpose of rivet inspection. The Sliding Probe is one such probe. A method using pencil probes and templates to trace around the fastener head is also used.

The sensitivity of the Sliding Probe is often lower than required by industry standards. In addition, a preferred orientation of this probe may lead to false calls or undetected flaws for rivets which are not aligned in a row. Template methods using pencil probes are very time consuming, and lift off or probe wobble can produce false signals.

OBJECTS

Therefore, it is an object of the present invention to overcome or mitigate these problems and to provide a flux-focusing eddy current probe whose fault detection characteristics provide unambiguous fault detection signals enhancing the confidence level of fault detection and reducing the need for special test electronics. Through the use of the present invention, a flux-focusing characteristic of probe signals during surface fault detection eliminates the need for known standards of specific types of flaws. Further, a single probe design and instrument configuration performs surface and subsurface eddy current fault detection.

It is a further object of the invention to establish a method which supports automated monitoring of faults in conducting material. The use of this method will perform continuous tracking and archiving of fatigue crack growth rates and trajectory during the fatigue process as well as automatically controlling conducting material loading conditions based on measured fatigue data and experimental designs.

It is a further object of the invention to establish a device and method for detecting flaws about circular fasteners and other circular inhomogeneities in electrically conductive material.

SUMMARY OF THE INVENTION

The present invention is directed to a flux-focusing eddy current probe that satisfies the need for unambiguous signals of fault detection, reducing the need for special test equipment. The flux-focusing eddy current probe performs non-destructive evaluation of electrically conductive material. The probe uses an excitation coil to induce eddy currents in conducting material perpendicularly oriented to the coil's longitudinal axis. A separate pick-up coil, surrounded by the excitation coil, is used to detect generated fields. Between the excitation coil and pick-up coil is a flux focusing lens which magnetically separates the two coils and produces high flux density at the outer edge of the pick-up coil.

The present invention is further directed to an automated eddy current system that satisfies the need to perform continuous fatigue testing. This system performs fatigue evaluation of conducting material and is dependent upon the use and characteristics of the flux-focusing eddy current probe. A computer interprets the signal from the probe to control the probe's position over the conducting material and to control the loading of the conducting material under test. A method for performing the automated testing requires a load to be applied to the conducting material to produce a

fault. The flux-focusing eddy current probe scans the conducting material and signals the computer once a fault is detected. The computer then adjusts the loading on the material and position of the probe to continue the test to completion.

The present invention is further directed to a flux-focusing eddy current probe that satisfies the need to detect flaws about any circular fasteners or inhomogeneities in a material. This system performs non-destructive evaluation of conducting material and is dependent upon the use and characteristics of the flux-focusing eddy current probe. The signal due to current flow about the fastener is detected as the probe is rotated around the fastener, keeping a constant distance between the center of the probe and the center of the fastener. Changes in the current distribution, such as due to fatigue cracks at a rivet joint, are detected as an increase in the output voltage above that due to the flow about the rivet head.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings where:

FIG. 1 shows a cross sectional view across line 1—1 of FIG. 2 for an elevation view of a flux-focusing eddy current probe constructed in accordance with the principles of this invention;

FIG. 2 shows a plan view of the flux-focusing eddy current probe illustrated in FIG. 1 with the receiving coil shown in phantom;

FIG. 3A shows a cross sectional view across line 3—3 of FIGS. 1 and 2 of the magnetic flux lines when the flux-focusing eddy current probe is energized in free space;

FIG. 3B shows a cross sectional view across line 3—3 of FIGS. 1 and 2 of the magnetic flux lines when the flux-focusing eddy current probe is energized and in contact with an unflawed electrically conductive material;

FIG. 4A shows an elevation view for the magnetic field of the excitation coil which generates eddy currents in conductive material as focused by the ferromagnetic lens;

FIG. 4B shows a plan view of the eddy current flow in unflawed electrically conductive material;

FIG. 4C shows a plan view of the eddy current flow in flawed electrically conductive material where the flaw divides the probe's circumference;

FIG. 4D shows a plan view of the eddy current flow in flawed electrically conductive material where the flaw tip lies within the probe's circumference;

FIG. 5A shows a flux-focusing eddy current probe's signal level response for a 50 KHz, 10.0 V p-p excitation coil signal when the probe is in contact with an unflawed aluminum alloy plate;

FIG. 5B shows a flux-focusing eddy current probe's signal level response for a 50 KHz, 10.0 V p-p excitation coil signal when the probe is in free space;

FIG. 5C shows a flux-focusing eddy current probe's signal level response for a 50 KHz, 10.0 V p-p excitation coil signal when the probe is in contact with a flawed aluminum alloy plate;

FIG. 6A shows a flux-focusing eddy current probe's signal level response for a 2 KHz, 10.0 V p-p excitation coil signal when the probe is in contact with a 2 mm unflawed aluminum alloy plate;

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FIG. 6B shows a flux-focusing eddy current probe's signal level response for a 2 KHz, 10.0 V p-p excitation coil signal when the probe is in contact with a 1 mm unflawed aluminum alloy plate;

FIG. 6C shows a flux-focusing eddy current probe's signal level response for a 2 KHz, 10.0 V p-p excitation coil signal when the probe is in free space;

FIG. 6D shows a flux-focusing eddy current probe's signal level response to thickness variations in aluminum as a function of frequency;

FIG. 7 shows another version of the flux-focusing eddy current probe embodying features of the present invention which provides additional resistance to edge effects and other conductive material discontinuities.

FIG. 8A shows another version of the flux-focusing eddy current probe embodying features of the present invention which provides additional resistance to lift-off response indicating conductive material fault;

FIG. 8B shows another version of the flux-focusing eddy current probe embodying features of the present invention which provides additional resistance to lift-off response indicating conductive material fault; and

FIG. 9 shows the eddy current probe system for locating crack tips;

FIG. 10 shows the induced current in an unflawed sample;

FIG. 11 shows the induced current flow about a rivet in an otherwise uniform sample;

FIG. 12 shows the induced current flow about a fatigue crack in an otherwise uniform sample;

FIG. 13A shows a top view of the eddy current distributions about an unflawed rivet and a rivet above a buried fatigue crack;

FIG. 13B shows a side view of the eddy current distributions about an unflawed rivet and a rivet above a buried fatigue crack;

FIG. 14 shows the pickup coil voltage for a probe rotating around a fastener;

FIG. 15A shows probe misalignment with respect to a circular fastener;

FIG. 15B shows fastener misfit;

FIG. 15C shows voltage variations caused by probe misalignment and fastener misfit at the frequency of the probe rotation;

FIG. 16 illustrates the effect of spatial filtering to distinguish signals due to geometrical effects from signals due to fatigue damage; and

FIG. 17 illustrates the probe attached to a rotator.

DETAILED DESCRIPTION

With reference now to FIG. 1, wherein like numbers designate like components throughout all the several figures, the flux-focusing eddy current probe of the invention is particularly well adapted for non-destructive evaluation, and for fatigue testing of electrically conductive material. The flux-focusing eddy current probe generally designated at 10 includes an excitation coil, a flux focusing lens, and a pick-up coil. The probe 10 applies the eddy current principle to evaluate electrically conductive material 16 for faults. An alternating current supplied by a current source 15 electrically connected to the excitation coil 11 produces eddy currents within conductive material 16 placed in proximity with the probe 10. Magnetic fields created in the pick-up coil 13 are registered by an A.C. voltmeter 14 electrically connected to the pick-up coil 13. The flux focusing lens 12

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magnetically separates the excitation coil 11 from the pick-up coil 13 and produces high flux density at the edge of the pick-up coil 13.

With reference now to FIG. 2, the excitation coil 11, the flux focusing lens 12, and the pick-up coil 13 are circular and concentrically arranged with the excitation coil 11 at the exterior of the probe 10, the pick-up coil 13 at the innermost position of the probe 10, and the flux focusing lens 12 between the coils 11 and 13. The overall size of the probe 10 is primarily determined by the diameter of the flux focusing lens 12 which is a function of fault depth and fault isolation accuracy. The diameter of the lens 12 is minimized to reduce the overall size of the probe 10 and to provide accurate location information of identified faults, though it must be of sufficient size to support test frequencies of the applied current from the current source 15 and to maximize search area covered by the probe. Likewise, the thickness of the flux focusing lens is minimized to ensure energy created by the magnetic field of the excitation coil 11 produces energy in the pick-up coil 13 when the probe 10 is in free space or a flaw in the conductive material 16 crosses the boundary established by the lens 12, though the lens 12 must provide isolation from direct magnetic energy of the excitation coil 11 from producing an alternating current in the pick-up coil 13 when the probe 10 is in contact with unflawed conductive material 16. Direct energy transfer is avoided when the thickness of the lens is several (e.g., 2 or 3) times the skin depth of the magnetic flux within the lens. The size of the pick-up coil 13 is simply maximized to achieve the largest possible surface area for greatest signal sensitivity within the constraints dictated by the excitation coil 11 and the flux focusing lens 12. It must be noted, however, that the smallest detectable flaw is approximately equal in size to one-half the inner diameter of the flux-focusing lens 12.

With reference now to FIGS. 3, 4 and 5, an alternating current applied to the excitation coil 11 creates a magnetic field 41 which in turn creates eddy currents within conductive material 16, FIG. 4A. The depth of penetration of the magnetic field 41 into the test material 16 is dependent upon the conductivity of the material 16 and the frequency of the applied current source. Consequently, the frequency of the drive signal is predetermined by the type of inspection being performed. Inspection for surface breaking flaws requires high frequency so as to concentrate the eddy currents at the surface of the material, whereas inspection for interior or back surface flaws requires low frequency such that the skin depth of the induced currents penetrate to the desired depth.

The magnetic field 41 is also established in the flux focusing lens 12. The lens 12 is formed of a conducting material (resistivity on the order of 100 microhm-cm or less) that is also high in magnetic permeability (initial permeability of at least 100) which provides a low reluctance path to divert the magnetic field away from the pick-up coil 13. Examples of such materials include the inexpensive and easy-to-machine carbon steels 1018 and 1020, as well as a variety of other materials listed by R. M. Bozorth in "Ferromagnetism", IEEE Press, 1978, in "Table 2 Some Properties of High Permeability Materials" on pages 870–871, which is hereby incorporated by reference. The point of maximum penetration of the concentrated magnetic field 41 within the lens 12 is at one half the height of the excitation coil 11, FIG. 4A. In the preferred embodiment, the top of the pick-up coil 13 falls below this maximum penetration point.

In the absence of a conducting material test sample 16, some leakage of the magnetic flux 31 around the lens 12 results, FIG. 3A. The leakage flux 32 produces a current in

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the pick-up coil **13** which provides a signal, FIG. 5B, to the A.C. voltmeter. When the probe is placed above a non-flawed electrically conductive surface, however, a complete electromagnetic separation of the pick-up coil **13** from the excitation coil **11** can be achieved, FIG. 3B. The flux **33** is concentrated within the conductive material **16** and generates eddy currents **42**, FIG. 4B. The induced eddy currents **42** work to stop any change in the magnetic state of the system so that the leakage field within the interior of the flux focusing lens **12** is canceled, resulting in a null signal, FIG. 5A, to the A.C. voltmeter.

In the presence of a conductive material fault **43** which divides the area covered by the probe **10**, a change in eddy current flow results, FIG. 4C. The field produced by the eddy currents **44** and **45** pass through the area of the pick-up coil resulting in an alternating current being established in the pick-up coil **13**. The presence of a current in the pick-up coil **13** provides an unambiguous voltage signal as indicative of the presence of a conductive material fault. Where the tip of a fault **46** falls within the area covered by the pick-up coil **13**, FIG. 4D, the field produced by eddy current flow **47** is additive to the field of the excitation coil **11** and is greater than that produced by in air leakage flux **32** resulting in a higher voltage signal level, FIG. 5C, thus providing a maximum signal level.

With reference now to FIG. 6, operation of the flux-focusing eddy current probe at reduced frequencies increases the penetration of the magnetic field and supports evaluation of conductive material thickness variations. As material thins, (from a 2 mm thick unflawed aluminum alloy plate which was used to generate the graph of FIG. 6A to a 1 mm thick unflawed aluminum alloy plate which was used to generate the graph of FIG. 6B to free space which was used to generate the graph of FIG. 6C) eddy currents in the conducting material are directed to within the area covered by the pick-up coil producing a voltage increase in the coil. Consequently, decreased material thickness produces increased flux-focusing eddy current probe output levels. As is apparent in FIG. 6D, the output level of the pick-up coil is directly related to the thickness of a specific material allowing measurement of the material's actual thickness.

With reference now to FIG. 7, an alternate probe configuration supports detecting faults close to an edge of the conductive material under test or near other conductive material discontinuities. An exterior shield **70** made of conductive material high in magnetic permeability focuses magnetic flux around the outside edge of the probe to prevent eddy currents from reflecting off a nearby conductive material edge and into the area of the pick-up coil. This allows the flux-focusing eddy current probe to be used near conductive material edges, however, the exterior shield **70** reduces the probe's overall sensitivity performance. Examples of materials for the external shield **70** are the same as those specified for the flux focusing lens **12**.

With reference now to FIG. 8, though the preferred embodiment is resistant to lift-off problems, alternate probe configurations are possible which provide further protection from lift-off conditions incorrectly indicating the presence of a conductive material fault. In the alternate embodiments, signals from a plurality of probes **10** combined within a casing **81**, FIG. 8A, or a plurality of pick-up coils **73A** and **73B** within a single excitation coil **11** and flux focusing lens **12**, FIG. 8B, are compared to one another. Equal, non-zero signal levels signify probe lift-off from the test material. Pick-up coils **13** or **73A** and **73B** are electrically connected to a differential amplifier **72**. Lift-off conditions result in equal signal level outputs such that the difference is zero and no fault indication is provided by the A.C. voltmeter **14**.

With reference now to FIG. 9, the eddy current probe system for fatigue evaluation of conductive material incorporates the flux-focusing eddy current probe **10** as a means of tracking fatigue crack growth in a conductive material **16** installed in a load frame **81**. The unambiguous flaw signal of the eddy current probe supports automated computer searching and identifying fatigue cracks. The probe **10** is used to scan conductive material **16** installed in the load frame **81**. A computer **82** controls the probe's location over the conductive material by means of x-axis **83** and y-axis **84** motor drives which power their respective stepping motors **85** and **86**. Additionally, the computer **82** continuously monitors the output of the probe **10** as it is scanned about the stress riser **16B** in the sample and directs the load frame controller **87** as it cyclically fatigues the conductive material sample.

The area of the probe scan is initiated around a notch **16A** in the conductive material sample. This location gives rise to high stress concentrations as the sample undergoes fatigue. Upon detection of crack growth, a large output signal from the probe **10** is received by the computer **82**. The computer adjusts the position of the probe such that it is centered about the region of crack initiation. As the crack continues to grow, the computer updates the probe's position to trace the fatigue crack tip throughout the fatigue process. The position of the crack tip is determined by the peak output level of the probe as the crack path is traversed. The peak search routine using an algorithm similar to the grid-search chi-square minimization scheme increments the probe's location in the direction of the crack growth as determined by previous crack tip locations. The scan is continued until the new crack tip is found. Upon locating the crack tip, the probe is moved a short distance back along the path of the crack and the search is repeated. By continuously reevaluating the path of the crack near the crack tip, errors in crack tip location due to signal noise and crack branching are avoided. As the crack grows to predetermined lengths, experimental parameters such as the load level applied to the conductive material sample are adjusted by the computer. This method allows for completely automated experimental control of fatigue studies which saves time, allows continuous unattended testing, and archives fatigue growth rates and trajectories.

An alternate embodiment of the present invention supports detecting flaws about any circular fastener such as rivets, or about circular inhomogeneities. When the probe is scanned over a rivet joint the discontinuity in the material at the rivet will cause some of the current induced in the sample to flow under the pickup coil **13**. This will result in a voltage being measured at the A.C. voltmeter **14** as explained above. It has been found that this rivet signal can mask the signal from a small flaw originating from the shank of the rivet. FIGS. 10–12 display the induced current distribution in unflawed material, at a rivet joint, and about a fatigue crack, respectively. The location of the pickup coil **13** is indicated by a black circle in each figure. The lighter rings are the current streamlines **90**, where the induced current will flow along the streamlines **90**, with the current density inversely proportional to the spacing between adjacent streamlines.

It is customary in eddy current testing to use lower frequencies (i.e., <100 kHz) to inspect for subsurface flaws in highly conducting materials such as aluminum. This is because the depth of penetration of the eddy currents into the sample decays exponentially with frequency. However, use of the flux-focusing probe of the present invention permits the use of a higher frequency drive (i.e., ~750 kHz) to inspect for fatigue damage buried under the rivet head. The use of a high frequency field is preferable to low frequency

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because the pickup coil output of the probe is proportional to the frequency, and because spatial resolution is improved at high frequencies.

The distribution of the induced current pictured in FIG. 10 is characteristic of the flux-focusing eddy current probe of the present invention. A high density eddy current ring is located just beyond the outer diameter of the pickup coil 13. In FIG. 11, conformal mapping techniques were used to determine the flow of the current when a circular obstacle such as a rivet 92 is introduced into the flow displayed in FIG. 10. A portion of the induced current now flows directly under the pickup coil 13, as shown by the large concentration of streamlines 90 which travel into the interior of the pickup coil location. In FIG. 12 the current distribution about a fatigue crack 94 is shown. The current flow once again travels beneath the pickup coil location, although a lower current density is seen to extend beneath the pickup coil as compared to the flow pictured in FIG. 11. The resulting output voltage would therefore be smaller for the fatigue crack (~4 mm length) of FIG. 12 than for the rivet (~3 mm) of FIG. 11.

FIGS. 13a and 13b illustrate the use of the probe to inspect under a rivet head. The eddy current distributions 96 are shown in FIGS. 13a and 13b for an unflawed rivet 98 and a rivet 100 above a buried fatigue crack 102. As shown, the presence of a crack pushes the eddy current distribution 96 further under the probe so that a local increase in the probe output will be detected at the angular location corresponding to the crack position.

Since the rivet fit may vary greatly from one rivet to the next, changes in the rivet signal are expected and have been seen experimentally. In some cases, the change in the signal from one rivet to the next is larger than the contribution due to a fatigue crack at the rivet joint. For this reason, small flaws can be hidden under the larger output voltage due to the current flow around the rivet head.

It has been determined that by maintaining a constant distance between the probe center and rivet center the signal due to the current flow about the rivet can be held constant. Any further changes in the current distribution, such as due to a fatigue crack at the rivet joint, can then be detected as an increase in the output voltage above that due to the flow about the rivet head. In addition, the high current density at the location along the rivet circumference where the radius vector is along the line joining the rivet and probe centers enhances the flaw detection capabilities of the probe over that of an isolated flaw.

FIG. 14 displays the results of scanning a 12 mm inside diameter probe about a 8 mm diameter rivet head. The crack detection limit for isolated flaws has been shown to be approximately 4 mm. The data of FIG. 14 shows that the rotating probe method is able to clearly identify an EDM notch extending less than 0.3 mm beyond the rivet head. A mechanical translation table was used to accurately position the probe a fixed radial distance from the center of the rivet and an A.C. voltmeter recorded the induced voltage across the pickup coil as the circumference of the rivet was traversed. Any suitable means may be used to rotate the probe at a constant distance from the center of the rivet or circular inhomogeneity. For example, FIG. 17 illustrates placement of the probe 10 on a rotator 110 comprising a pivot leg 112 positioned at the center of a rivet 113. The pivot leg 112 is connected to an arm 114 which supports the probe 10 as it circles the rivet and passes over a crack 115.

The presence of rivet misfit or probe misalignment, as illustrated in FIGS. 15a and 15b, respectively, will cause

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voltage variations at the frequency of the probe rotation, as illustrated in FIG. 15c. In FIG. 15a, the rivet 104 is not centered with respect to the path of the probe center 108. In FIG. 15b, the rivet is tilted with respect to the path of the probe center 108. Spatial filtering can be used to separate signals due to the effects of rivet tilt and misfit from those of fatigue damage at the rivet interface. This decreases the minimum detectable flaw size. Spatial filtering is illustrated in FIG. 16 which shows voltage increases caused by the presence of a fatigue crack 112 will occur at a frequency given by:

$$f_f\text{-}(f_r*(2\pi R_{rev}/P_{dia}))/2$$

where:

f_f=flaw frequency
f_r=rotation frequency
P_{dia}=probe diameter
R_{rev}=radius of probe revolution.

High pass filtering of the data with a cutoff frequency determined by the probe diameter, rotation frequency and radius of probe revolution will therefore distinguish signals due to geometrical effects from those due to fatigue damage.

Although our invention has been illustrated and described with reference to the preferred embodiment thereof, we wish to have it understood that it is in no way limited to the details of such embodiment, but is capable of numerous modifications for many mechanisms, and is capable of numerous modifications within the scope of the appended claims.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A flux-focusing eddy current probe for non-destructive evaluation of an electrically conductive material surrounding circular inhomogeneities comprising:

(a) an excitation coil for inducing eddy currents within the electrically conductive material, said excitation coil having windings wherein said excitation coil's longitudinal axis is perpendicular to the surface of the electrically conductive material, said excitation coil having a first end and a second end;

(b) a pick-up coil surrounded by said windings of said excitation coil, said pick-up coil having a first end and a second end, said first end of said pick-up coil and said first end of said excitation coil being in coplanar alignment with one another, said pick-up coil being of a height that is no more than one-half the height of said excitation coil;

(c) a flux focusing lens formed as a cylinder of conducting material high in magnetic permeability, said cylinder having an open first end and a closed second end, said cylinder being concentric with and disposed between said excitation coil and said pick-up coil such that said open first end terminates in co-planar alignment with said first end of said excitation coil and said first end of said pick-up coil, said flux focusing lens preventing magnetic coupling between said excitation coil and said pick-up coil when said probe is placed above an unflawed electrically conductive material and said flux focusing lens producing high flux density at the outer edge of said pick-up coil; and

(d) rotator means for rotating the probe about the circular inhomogeneity such that the center of the probe remains a constant distance from the center of the circular inhomogeneity.

2. A flux-focusing eddy current probe as in claim 1 wherein said excitation coil causes magnetic flux to penetrate a radial depth into said flux focusing lens, and wherein radial thickness of said flux focusing lens is 2–3 times said radial depth.

3. A flux-focusing eddy current probe as in claim 1 wherein said flux focusing lens is electrically conductive and has a magnetic permeability of at least 100.

4. A flux-focusing eddy current probe as in claim 3 wherein said flux-focusing lens has a resistivity on the order of 100 microhm-centimeters or less.

5. A flux-focusing eddy current probe as in claim 1 further comprising an electrically conductive cylinder having a magnetic permeability of at least 100, said cylinder concentric with and disposed about said excitation coil.

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