Title: APPARATUS AND METHOD FOR DETECTING CRACKS IN METAL ARTICLES

Abstract: An apparatus suitable for use in detecting cracks or other discontinuities in metal articles includes a plurality of spaced-apart eddy current probes (4), each having a probe end (9) for contacting the article, supported by a common housing (6). Helical compression springs urge each probe (4) towards an extended position in which all the probe ends (9) lie outside the housing (6), and in which each probe end (9) is independently movable towards the housing (6) against the action of the springs (50). Each eddy current probe (4) forms at least part of an inductive load (84) of a respective, independent, self-oscillating circuit (80) which circuit (80) provides an output voltage (Vout) which varies with the oscillatory state of the self-oscillating circuit (80) being adjustable by an input voltage (Vin). This apparatus is particularly suitable for checking quickly and efficiently the large areas of metal that form large typical food processing vessels, such as milk holders and the like.
APPARATUS AND METHOD FOR DETECTING CRACKS IN METAL ARTICLES

This invention relates to apparatus and methods for detecting discontinuities in metal articles.

One industry where the integrity of metal components needs to be tested is the food industry and, in particular, of food processing vessels. Cracks, pinholes and corrosion could lead to contamination of the product with concomitant ingress of bacteria or chemical coolants leading to possible reduced shelf life, rejection of the product or at worst food poisoning. Testing of processing vessels can involve shut down of the process line, and cleaning of the internal surface possibly requiring erection of scaffolding.

Fluorescent and colour contrast liquid dye penetrant techniques are well established in the field of non-destructive testing. The fluorescent method is generally more sensitive than the colour contrast method.

The method adopted in the food processing industry, for the integrity examination of processing vessels, is to clean in-place (CIP) clean, erect access equipment into the vessel interior, apply fluorescent chemical dyes to the surface, normally by spraying and allow 20 minutes dwell time. Some of the many problems encountered in these methods include product residues remaining in defects, dyes
may be prevented from penetrating the defects, defects that open under pressure when full of product, then close when empty, so not allowing dye to penetrate. Also, no pressure can be applied to dye side of the test, and surface tension may prevent penetration.

The operator then re-enters the vessel to wash off the excess dye from the surface, often finding that the detection dye has been washed away out of larger defects, and so is no longer visible to find the cracks.

These methods also involve additional time and costs associated with proper disposal of the flushed dye or, if simply washed away into a drain, risking possible damage to the controlled bacterial systems within an effluent plant and release of chemicals into the waterways.

The use of such eddy current probes to detect discontinuities in the structure of a metal article, be they due to cracks, differential heat treatment or welding for example, has found wide application in a number of industries.

Generally, these eddy current probes comprise a coil mounted in a probe head through which is passed an alternating current. The alternating currents generally have frequencies from 10kHz to 2MHz and beyond. The alternating current conducted through the coil generates an
oscillating magnetic field whose magnitude and polarity changes in accordance with the frequency of the current. When the coil of the probe is positioned close to an electrically conductive object article, the changing magnetic flux generated by the coil induces eddy currents in the object. The particular voltage, amperage and direction of the eddy currents produced are dependent in part upon the characteristics of the object material which conducts the eddy current. Because the direction of flow of the eddy currents generated by the coil is opposite to the current flowing through the probe coil, the magnetic field created by the eddy currents creates an impedance in the probe coil. The characteristics of the eddy currents are dependent upon the resistance these currents encounter as they circulate in the object. Discontinuity in the metal such as cracks, pits or regions of local thinning create regions of higher resistances at these locations so reducing their effect on the coil. Thus, eddy current probes may be used to locate flaws by constantly monitoring the impedances of the coils, directly or indirectly, as the probe coils are moved across the object.

While the use of an eddy current probe system would avoid these disadvantages of the above described currently used dye methods of crack detection, known devices are not suitable for checking quickly and efficiently the large areas of metal that form large typical food processing vessels, such as milk holders and the like.
The present invention addresses this requirement by providing an apparatus suitable for use in detecting cracks or other discontinuities in metal articles which includes a plurality of spaced-apart eddy current probes, each having a probe end for contacting the article, supported by a common housing, resilient biasing means urging each probe towards an extended position in which all the probe ends lie outside the housing, and in which each probe end is independently movable towards the housing against the action of the resilient biasing means.

The presence of a plurality of spaced-apart eddy current probes means a larger area of metal can be tested in one sweep of the apparatus. The independent movement of the probes relative to housing allows the probes to conform to and so maintain contact with a changing metal surface profile as the probes are swept over the surface.

The probes may be connected to any suitable known eddy current detector systems, each independently monitoring a characteristic of a probe in a known manner. It is preferred, however, that the probes' characteristics are monitored by a single common detector system, an example of which will be described later in relation to the illustrated specific embodiment.

The probes may be mounted so that a front portion of each probe is mounted as a sliding fit in a respective aperture
in an outer wall of the housing, the probe including a stop rearward of the probe end and dimensioned to prevent the probe from passing through the aperture. In this arrangement each probe is held captive in the housing whilst being able to move forwards and backwards through the aperture to accommodate test surface variations.

Other ways of mounting the probes on the housing so the probe ends are movable to conform to a changing surface profile may be adopted. For example, the probes could be mounted on a series of externally mounted lever arms hinged to the outer wall of the housing, the lever arms being urged away from the housing by the resilient biasing means and provided with stops located to align the probe ends when fully extended outward from the housing.

The apparatus may include a first inner wall parallel to the outer wall and in which the rear portion of each probe is mounted as a sliding fit in a respective aperture in the second wall. The addition of such guiding apertures provides each probe with a pair of spaced-apart guides so orienting the probe relative to the housing more positively. Conveniently such an apparatus also includes a second inner wall parallel to said first inner wall, the resilient biasing means being located between the first and second inner walls.

The preferred resilient biasing means is a plurality of
springs each of which is a helical compression spring supported at one end of the second wall by a respective elongate member extending from the second inner wall towards the first inner wall, the other end of each spring pressing against the rear of the respective probe. However, other biasing means may be employed, for example leaf springs or a strip resilient elastomeric material extending behind the probes and located between the probes and housing in any convenient manner.

The force acting on the probes should be chosen so the probes can be readily depressed from their extended position on pressing the device against the surface being tested whilst providing sufficient force to firmly press them against the surface and overcome the frictional forces associated with their movements relative to the housing.

The housing preferably also includes means for removably attaching an elongate support member to the housing to allow ready access to otherwise inaccessible areas of the article under test. The housing ideally also includes control circuitry, a power supply and indicators so providing a self-contained and mobile apparatus.

Whilst other methods of monitoring inductance changes in the probe coils may be used, it is preferred that each eddy current probe forms at least part of an inductive load of a respective, independent, self-oscillating circuit which
circuit provides an output voltage which varies with the oscillatory state of the self-oscillating circuit being adjustable by in input voltage. Indeed, this is an independent invention from the above described multiprobe apparatus which may be used, generally, as a basis for other eddy current detectors, eg single probe detector apparatus.

The use of a self-oscillating circuit which provides an output voltage which is dependent, at least in part, on an input voltage in this manner provides a probe which can, as will be explained in detail below, be readily calibrated and subsequently monitored by a microprocessor based system. Once calibrated the input voltages are held constant and variations in the metal under test will cause variations in the output voltages from each probe circuit due to the variations in inductance of the probe. In this way, irregularities in the metal can be detected by corresponding variations in the output voltage.

The self-oscillating circuit may include a capacitative sub-circuit the capacitance of which is adjustable by the input voltage and the output voltage obtained by rectifying an AC voltage at a point of the self-oscillating circuit intermediate the capacitative sub-circuit and the inductive load.
The apparatus may include a probe calibration means comprising a monitor for monitoring the output voltage from each probe and means for setting the input voltage to each self-oscillating circuit so as to obtain a predetermined calibration output voltage from each self-oscillating circuit. This permits each probe signal to be monitored relative to a single reference threshold value. That is, the apparatus may be arranged to compare the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage changes from a corresponding self-oscillating circuit calibration output voltage by a predetermined voltage magnitude in a first sense. The value of the predetermined voltage drop is, preferably, stored and is adjustable by the user to provide a variable sensitivity detector.

The apparatus may also be arranged to compare the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage from a corresponding self-oscillating circuit changes from the calibration output voltage by a predetermined voltage magnitude in a second sense so indicating the probe has lifted from the metal being tested.

The probe ends may be positioned so as to lie in a straight line in their extended positions but other arrangements may
be used, eg an arcuate array or two straight lines, the probe ends being staggered between the two.

Embodiments of the invention of this application, in both its aspects, will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a diagrammatic perspective view of an embodiment of the present invention;

Figure 2 is a diagrammatic cross-sectional view of a probe of the apparatus of Figure 1;

Figure 3 is a diagrammatic plan view showing the probe array of the apparatus of Figure 1;

Figure 4 is a schematic plan view of the internal arrangement of the apparatus of Figure 1;

Figure 5 is a schematic circuit block diagram of a self-oscillating probe circuit of the apparatus of Figure 1; and

Figures 6a and 6b together form a schematic circuit block diagram of the probe system of the apparatus of Figure 1.

For convenience, the same feature will be given the same reference numeral in each figure.
Referring to Figures 1 to 4, an eddy current detector 2 according the present invention has a linear array of a set of eight, equally spaced eddy current probes 4 mounted in a plastics housing 6. As will be discussed in detail with reference to Figures 3 and 4, the probes are biased to their extended positions protruding from the housing 6 as shown in Figure 1. Fewer or more probes may be provided if desired.

The circular ends of the probes 4 lie in a common plane parallel to a faceplate 9 which forms the front of the housing. The faceplate helps ensure the probe ends 9 are held so as to be flat against the article under test so avoiding "lift-off".

A bracket 10 is screwed to the bottom wall 12 of the housing 6. It has a tubular portion 14 provided for receiving, as a push fit, the end of a telescopic pole 16. When fitted, the pole 16 permits access to areas beyond the normal reach of the user of the apparatus and can avoid the need for scaffolding or ladders in some cases.

Referring now to Figure 2, each probe 4 was fabricated from a commonly available radio frequency tuning coil having a cubic plastics base 20 supporting a 4mm diameter, 25-coil tuning coil 22 wound round a cylindrical ferrite core 24. A plastics sleeve 26 in the form of a tube 28 with a
rearward flange 30 was fixed about the tuning coil 22 by a hard setting resin 32.

Referring now to Figures 3 and 4, there is shown the method of mounting the probes 4 in the housing 6. The front section of the housing 6 includes the faceplate 9 which is held in place on a first inner wall 40 which wall 40 is formed as an integral with the base 12 of the housing 6. Fixed to the base 12 is a plastics member 4 having a base section 46 parallel to the base 12 and an upstanding portion 48 forming a second inner wall.

The probes 4 are mounted in apertures in the first faceplate 8 and in the inner wall 40 which respectively accept as sliding fits the cylindrical portion 28 of the probe 4 and the square cross-section base 20 of the probe 4. The flange 30 of the probe acts as a stop defining the extent of travel of the probe 4 within the housing 6. The probes 4 can extend about 5mm beyond the faceplate 8 and can be pressed into the housing until their ends 9 are flush with the outer surface of the faceplate 8.

Each probe 4 is biased to its extended position (as shown in the Figures) by an individual helical compression spring 50 held in position between the rear probe 4 and the second inner wall 44 which acts as a thrust plate, by a screw 52 fast in the second inner wall 44 and extending towards the probe part way to the first inner wall 40. Wire pairs 54
from the coil 22 of each probe 4 extend through notches 56 in the top of the second inner wall 44.

Turning now to Figure 4, there is shown diagrammatically further features of the apparatus of Figure 1. In particular, there is shown in plan view the rear panel 58 which includes an array of eight, dual-colour (red/green) LEDs, L1 to L8, a push button 60 for increasing the sensitivity of detection, a push button 62 for decreasing the sensitivity of detection, a push button 64 for starting self-calibration of the apparatus, a push button 66 for powering up and powering down the apparatus, a headphone socket 68 and an external probe/battery charging connector 70. The apparatus also includes a rechargeable battery 72, an internal sounder 74 and a circuit board 76 as well as components of the circuit as will be described below.

Referring now to Figure 5, a self-oscillating circuit 70 is formed from a variable capacitance sub-circuit 82 and an inductive sub-circuit 84 in well-known manner. The sub-circuit 82 is such that its capacitance can be adjusted by adjusting the value of the applied voltage Vin. Variations in the oscillatory condition of circuit 80 can be monitored by monitoring Vout, the rectified voltage from rectifier circuit 86 of a voltage at a point between the sub-circuits 82 and 84. The component values were chosen so that frequency of oscillation of the circuit is about 2MHz and
to provide a probe which can detect cracks down to about 3mm in austenitic stainless steel.

The suitable component values can be readily determined by simple trial and error. For example, the value of a capacitor in parallel with a probe may be adjusted until Vout departs from a preset value in a first sense when the probe is moved along a surface of a test piece from a sound area to an area with a fine surface slot simulating a crack and in a second sense when the probe is lifted off from the test piece. Tolerances in the component values of each of the probe circuits are accommodated by a calibration step which is described below.

Referring now to Figures 6a and 6b there is shown, schematically, the control circuitry of the illustrated embodiment in which a microprocessor 88 is arranged to control the values of Vin to each probe 4 independently via data bus 90 and a pair of digital to analogue converters 92 and 94. The output voltages Vout from each self-oscillating circuit 80 are carried to microprocessor 88 via lines 100.

An optional external probe 102 can be connected to the connector 70 which grounds a line 104 causing a relay 106 to trip and so switch out the Vin and Vout lines from one probe circuit of the apparatus (numbered 80(1) in Figure
6a) and switch in, in their place, the Vin and Vout lines 108 from the external probe 102.

The microprocessor 88 detects depressions of the push button switches 60, 62 and 64. The microprocessor 88 also provides outputs to the on-board sounder 74 (provided with a connection to the external headphone socket 68) and to the array of dual colour LED pairs L1 to L8 via bi-directional buffer 110 which, in known manner, allows the microprocessor 88 to set each LED pair, individually, to a chosen colour (green or red) or off. A data store 110 is provided for storing data to be used by the microprocessor during operation of the apparatus, which operation will now be described.

The apparatus is first switched on by pressing the power on/off button 66 which "wakes" the microprocessor 88 up from its low power, sleeping mode. The microprocessor 88 causes the on-board sounder 74 to beep briefly to indicate to the user the apparatus 2 is ready for use. All the LED pairs L1 to L8 are off at this time.

The detection sensitivity is set by pressing the sensitivity up button 60 and sensitivity down button 62 to put the apparatus at the desired one of eight discrete sensitivity setting, which current value is shown to the user by causing a corresponding one of the LED pairs L1 to L8 to turn red, all under control of the microprocessor 88.
The microprocessor 88 stores in the data store 110 a value representative of the sensitivity level and is indicative of the value of the drop in Vout from a probe 4 which is to be taken as indicative of the presence of a crack or other discontinuity in the metal under test.

The probes 4 are then pressed against a sound portion of the metal surface to be tested and the calibrate button 64 is pressed. The microprocessor 88 then increments the value of Vin applied to the self-oscillatory circuit 80 of each probe to that required to obtain a preset value of Vout from each self-oscillatory circuit 80. The Vin for each probe 4 may be different.

The actual values of Vout and Vin are arbitrary but the circuit components may be conveniently chosen so they will lie towards the midpoint of the operating voltage of the circuits in normal circumstances, in this case about 2V for a 5V operating voltage.

Once the microprocessor 88 determines calibration has been effected for each probe 4, or it failed to do so for a given probe 4 because of a fault, the calibration sequence is complete. The microprocessor turns the LED pairs L1 to L5 to green in continuous rotation to form a "racing" set of green lights to indicate calibration is completed. The LED corresponding to a faulty probe will never be lit,
however, to indicate to the user that the corresponding probe is faulty.

The probes 4 can then be moved over the surface to be tested. If a probe meets a discontinuity sufficiently close to the surface of the metal the inductance of the probe will change causing, in this embodiment, a decrease in Vout. The Vout from each self-oscillatory circuit 80 is monitored by the microprocessor 88 against its initial calibration value that has been stored in data store 110. If the value drops by an amount greater than determined by the sensitivity setting, the LED pair corresponding to that probe 4 is turned red indicating a crack or other discontinuity has been detected. Typically, a drop of 0.05V to 1.5V will indicate a relevant discontinuity is present. The sensitivity can be set so as not to give false readings if the surface is rough or to ignore cracks below a certain size and only indicate if larger cracks are present. The maximum available sensitivity for a given use of the device is ideally present so as not to give a crack indication in the presence of minor surface scratches.

If a probe 4 should lift-off from the surface under test, as indicated in this embodiment by an increase in Vout, the microprocessor 88 sets the LED pairs L1 to L8 corresponding to that probe 4 a steady green indicating lift-off has occurred.
The microprocessor 88 also causes the sounder 74 to emit a tone in the event of any probe 4 detecting a discontinuity or suffering lift-off of -1kHz and -100Hz respectively. These tones are also audible in headphones (not shown) when plugged into headphone socket 68. This is particularly useful if the apparatus is being used at the end of the pole extension 16 when the LED pairs L1 to L8 may be difficult to see clearly or at all.

If an area of an article is inaccessible to the array of probes 4, the external probe 102 with a connecting cable can be plugged into the connector 70. The external probe 102 contains the same self-oscillating circuit 80 as the apparatus-mounted probes 4. In this mode of operation there is no requirement for all eight LED pairs L1 to L8 to be used for discontinuity/lift-off indication. The apparatus is therefore arranged to switch to a mode in which the row of eight LEDs L1 to L8 acts as a bar graph to indicate the change in Vout from the probe 102 so giving the user an indication of the magnitude of the defect by lighting the appropriate LED red.

Connector 70 also includes an electrical connection to the rechargeable battery 72 so it can be recharged without removing it from the housing 6.

The spacing of the probes 4 is not critical. There is a small chance a small defect may miss detection if it is
small and shallow and passes between two probes. The preferred method of testing an article is therefore to do at least two scans over every region in at least two different directions, preferably approaching orthogonal directions and preferably not less than about 45° apart. The probes 4 are repeatedly interrogated by the microprocessor 88 in sequence and at a rate which provides that for a normal manual sweep speed each probe will move a distance across the article no bigger than the inter-probe spacing distance.

When the sweeps are finished the apparatus is returned to the quiescent state by pressing the power push button 66 once more. The microprocessor 88 monitors the switch to ensure it is depressed for about 4 seconds, an arbitrary period chosen to ensure accidental brief pressure on the power button 66 will not switch off the apparatus. The apparatus is also configured to power down if inactive for a predetermined period, typically 15 minutes.

It will be noted that other variations from the specific design of the above described embodiment and within the scope of the present invention may be employed. For example, the probe array may take the form of two staggered linear arrays. Similarly, other approaches to the user interface may be adopted, the arrangement of LEDs and their various lighting modes being entirely optional. Clearly any other method determining a probe is proximate a
discontinuity and indicating the fact to the user may be adopted when implementing the apparatus present invention.

The apparatus may include seals to waterproof the housing against ingress of water.
CLAIMS

1. An apparatus including a plurality of spaced-apart eddy current probes, each having a probe end, supported by a common housing, resilient biasing means urging each probe towards an extended position in which all the probe ends lie outside the housing, and in which each probe end is independently movable towards the housing against the action of the resilient biasing means.

2. An apparatus as claimed in claim 1 in which the front portion of each probe is mounted as a sliding fit in a respective aperture in an outer wall of the housing, the probe including a stop dimensioned to prevent the probe from passing through the aperture.

3. An apparatus as claimed in claim 1 or 2 and including a first inner wall parallel to said outer wall and in which the rear portion of each probe is mounted as a sliding fit in a respective aperture in said second wall.

4. An apparatus as claimed in claim 3 and including a second inner wall parallel to said first inner wall, the resilient biasing means being located between the first and second inner walls.

5. An apparatus as claimed in any preceding claim in which the resilient biasing means is a plurality of springs
each spring being mounted between a respective probe and the housing.

6. An apparatus as claimed in claim 5 in which the resilient biasing means is a plurality of each spring is a helical compression spring supported at one end of the second wall by a respective elongate member extending from the second inner wall towards the first inner wall, the other end of each spring pressing against the rear of the respective probe.

7. An apparatus as claimed in any preceding claim in which the resilient biasing is such as to require a force of about 1 Newton to start to move each probe from its extended position towards the housing.

8. An apparatus as claimed in any preceding claim in which the housing includes means for removably attaching an elongate support member to the housing.

9. An apparatus as claimed in any preceding claim in which the housing further includes control circuitry, a power supply and indicators so providing a self-contained, mobile crack detecting apparatus.

10. An apparatus as claimed in any preceding claim in which each eddy current probe forms at least part an inductive load of a respective, independent, self-
oscillating circuit which circuit provides an output voltage which varies with the oscillatory state of the self-oscillating circuit being adjustable by in input voltage.

11. An apparatus as claimed in claim 10, in which the self-oscillating circuit includes a capacitative sub-circuit the capacitance of which is adjustable by the input voltage.

12. An apparatus as claimed in claim 10 or 11, in which the output voltage is obtained by rectifying an AC voltage at a point of the self-oscillating circuit intermediate the capacitative sub-circuit and the inductive load.

13. An apparatus as claimed in any one of claims 10 to 12 including probe calibration means comprising a monitor for monitoring the output voltage from each probe and means for setting the input voltage to self-oscillating circuit so as to obtain a predetermined calibration output voltage from each self-oscillating circuit.

14. An apparatus as claimed in claim 13 including a comparator for comparing the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage changes from a corresponding self-oscillating
circuit calibration output voltage by a predetermined voltage magnitude in a first sense.

15. An apparatus as claimed in claim 14 in which the value of the predetermined voltage drop is stored and is adjustable by the user.

16. An apparatus as claimed in any one of claims 10 to 15 including a comparator for comparing the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage from a corresponding self-oscillating circuit changes from the calibration output voltage by a predetermined voltage magnitude in a second sense so indicating the probe has lifted from the metal being tested.

17. An apparatus as claimed in claim 1 in which the probe ends lie in a straight line in their extended positions.

18. An eddy current detector including an eddy current probe which forms at least part an inductive load of a respective, independent, self-oscillating circuit which circuit provides an output voltage which varies with the oscillatory state of the self-oscillating circuit, the output voltage being adjustable by an input voltage to the self-oscillating circuit.
19. A detector as claimed in claim 18, in which the self-oscillating circuit includes a capacitive sub-circuit the capacitance of which is adjustable by the input voltage.

20. A detector as claimed in claim 18 or 19, in which the output voltage is obtained by rectifying an AC voltage at a point of the self-oscillating circuit intermediate the capacitive sub-circuit and the inductive load.

21. A detector as claimed in any one of claims 18 to 20 including probe calibration means comprising a monitor for monitoring the output voltage from each probe and means for setting the input voltage to self-oscillating circuit so as to obtain a predetermined calibration output voltage from each self-oscillating circuit.

22. An apparatus as claimed in claim 21 including a comparator for comparing the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage changes from a corresponding self-oscillating circuit calibration output voltage by a predetermined voltage magnitude in a first sense.

23. An apparatus as claimed in claim 22 in which the value of the predetermined voltage drop is stored and is adjustable by the user.
24. An apparatus as claimed in any one of claims 18 to 23 including a comparator for comparing the output voltage from each probe to the calibration output voltage and plurality of indicators for indicating to the user when the output voltage from a corresponding self-oscillating circuit changes from the calibration output voltage by a predetermined voltage magnitude in a second sense so indicating the probe has lifted from the metal being tested.

25. An apparatus suitable for use in detecting cracks or other discontinuities in metal articles substantially as hereinbefore described with reference to the accompanying drawings.

26. A method of detecting cracks or other discontinuities in metal articles substantially as hereinbefore described with reference to the accompanying drawings.