Surface and Subsurface Material Characterisation using Eddy Current Arrays

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Abstract. Low frequency eddy current arrays may provide information from the material’s surface and subsurface region.

First, the paper discusses the challenge of combining high penetration and high resolution in a single array. For good penetration the array elements have to work at low frequencies. Therefore, the element should be of high inductance requiring big number of turns. Even with very thin copper wire many turns require significant space. This is the reason why low frequency eddy current probes often are large and suffer from low geometric resolution.

For high geometric resolution the array elements should be small leaving less space for windings. Less windings provide less inductance and less sensitivity at low frequencies. For their effective use higher frequencies are needed not penetrating deep enough into the material. The paper presents solutions for these contradictory demands.

Second, the paper presents probe response of such probes for surface and subsurface characterisation. A first example is given for thickness assessment of ferromagnetic layers on non-ferromagnetic substrate. Here, the penetration of ferromagnetic material is a prerequisite for sufficient thickness evaluation. In a second example subsurface pores and oxide particles have to be detected and characterised in aluminium alloys. Diameter and underlying of pores decide whether the workpiece will be worth further treating.

Third, the paper presents results of austenitic heat exchanger tube inspection for inner and outer defects. The tubes are welded into the bottom sheet to prevent leakage. But this welding reduces the tube diameter at the inlet. The array probe consists of four flexible suspended parts letting the probe pass below the welds and afterwards pressing them onto the inner wall.

1. Introduction

Eddy current method brings up the distribution of conductivity, magnetic permeability and some geometric parameters of the object under inspection. Usually, a single open coil system fed by an alternating current induces eddy currents in a conductive material. The eddy currents build up a response field interfering with the exciting field. The complex measurement signals may be used for imaging. One of the pioneers in this field was Thomas [1] who used mechanical scanners to systematically move the probe along the object. Scholz already suggested a two-dimensional array probe [2]. From that point eddy current array probes started to develop [3-24]. Today, even flexible probe arrays are available [25].
For hidden defect detection and characterisation one has to use low inspection frequencies. Low frequency receiver coils should get more windings, high permeable ferrite cores or sophisticated balancing of two or more coils. On the other hand, anisotropic magneto-resistors (AMR) [26] and giant magneto-resistors (GMR) [27, 28] were tested to substitute inductive receivers by new magneto-resistors. These elements are able to sense even DC fields. Their drawbacks are non-linearity, saturation, hysteresis effects and the demand for DC offset. For eddy current applications, special inductive receivers perform not worse than magneto-resistors and are easier to handle.

2. Probe Elements

Not a single eddy current probe type can meet all demands occurring in imaging tasks. On the one hand, good spatial resolution is possible with small coils and high inspection frequencies. But such probes are characterised by low penetration. On the other hand, for good penetration lower frequencies with bigger coils are needed not providing sufficient spatial resolution.

2.1 Probe Types

One kind of inductive probes with increased inspection depth is the non-axial transmit-receive type sometimes called half transmission, pitch-catch or even remote field probe. This probe type offers the opportunity to optimize the distance between the transmitting and the receiving coil. Figure 1 brings up the principle of these probes. The magnetic field of the exciting coil penetrates accordingly to the well known rules of alternating field spreading into the material. The receiving coil only picks up this part of the flux, which has penetrated deeply into the material. The larger the spacing between the two coils the deeper the detected flux lines have penetrated into the material but the lower becomes the measurement signal.

This system of two non-axial coils may be considered as an axial coil system with a diameter corresponding to the coil distance of the non-axial system. With increasing distance (or diameter) of the coils the defect volume decreases relatively to the volume of interaction lowering the signal amplitude. One has to trade off between these parameters.

![Fig. 1. Non-axial probe selects deep penetration field trajectories](image-url)
2.2 Point Spread Function

Figure 2 displays the Point Spread Function of this probe type. It differs significantly from that of common axial eddy current probes [4] and is most suitable for imaging applications.

![Figure 2](image)

Fig. 2. Calculated signal distribution of a small hidden pore, z - signal magnitude (arb. units), x and y - position of the pore, calculated using VIC-3D code

3. Probe Response for Surface and Subsurface Characterisation

3.1 Thickness of Ferrous Layers on Non-Ferrous Substrate

Thickness assessment of ferrous coatings on non-ferrous substrate is a very demanding task. The sensor’s magnetic field should penetrate the coating what is possible for 0.5 mm coatings with non-axial probes even at 20 kHz. The investigation should clarify how the lift-off signal could be separated from the coating thickness.

![Figure 3](image)

Fig. 3. Comparison of probe responses from ferromagnetic coatings on non-ferrous substrate at 20 kHz. The numbers represent the coating thickness in micrometers.

Figure 3 a) shows the measurement points directly on the coating together with the lift-off trajectories. It can be seen, that this probe provides an almost linear signal when the permeability in the zone of interaction remains constant. The lift-off signal becomes curved when the permeability changes with depth. Coating and lift-off can be separated only at
medium thickness. Very thin or very thick coatings provide a similar signal direction like lift-off.

The lift-off signals of the non-axial probe in figure 3 b) are curved at every coating thickness making hard its suppression. The advantage of this probe is a big difference in signal directions between lift-off and coating at every thickness.

3.2 Hidden Pores in Aluminium

Hidden defects in aluminium provide noticeable signals when the underlying is not too deep and the defect size is large enough. Figure 4 compares signals of 1 mm pores at different underlying. The axial probe’s signals are significantly curved at the closest probe position over the defect tending to return to the defect-free material. This effect can be understood taking into account that the eddy current paths are circles not being affected when the defect is centred in the middle.

![Fig. 4. Comparison of probe responses from hidden pores in aluminium at 5 kHz](image)

The non-axial probe’s signals are curved at the beginning of the defect trace and remain straight over the defect. The receiver only picks up the field of the eddy currents being displaced by the defect. This displacement becomes maximal directly over the defect.

The non-axial probe signal may be processed according to its amplitude and phase offering good chances for defect characterisation.

![Fig. 5. Signal processing for defect characterisation in eddy current images](image)

Figure 5 provides an opportunity of signal coding for easy interpretation of detected defects. The colour depends on underlying and the saturation depends on defect size. In an eddy current image defects close to the surface are marked red and those far from the surface tend to yellow and green.
4. Array Application

Instead of a single sensor many sensors may be combined into a sensor array. The principle of such sensor arrays has been presented by the authors in [18-23]. The speed of electronic field movement ranges from 0.4 to 3 m/s according to the inspection requirements. The arrays may be fitted for flat and curved surfaces. Figure 6 gives some ideas for convex objects like pipes, rods or rails.

![Fig. 6. Potential applications of probe arrays for curved surfaces](image)

The fixed shape arrays provide a constant geometry and low wear. It is easy to guide them manually. A position encoder wheel is the bases for imaging.

4.1 Linear Arrays

The linear array in figure 7 is guided over the area of inspection and provides eddy current images in real time. A rotary encoder picks up the displacement of the array and cares for correct imaging. All necessary electronics is located in the array’s housing, so that a single USB-cable to the notebook is sufficient for energy supply and data transfer. The photograph on the left shows an array over an engraved aluminium sheet as reference piece. The image on the right shows the probe arrangement and gives some result images. The graphic user interface may be used like single probe interfaces.

![Fig. 7. Sensor array, left: control window, right: array over the reference sheet. Eddy current images of the sensor array, from left to right: raw data, data with y-threshold, false colour image, high pass filtered image](image)

The engraving is clearly readable from the front side and the back side also. The first image on the left represents the original data, the second includes a threshold and the third is a false colour representation. For edge enhancement may be used filters, e.g. band or high pass filters. A common band pass has to be adopted to the velocity of array over the object. Spatial filtering avoids this disadvantage. Not the time but the displacement is the filter base. The spatial frequency is given by the number of repetition per length. This way, this filter does not depend on the velocity of the movement. On the right side of the result
image the effect of high pass filtering is demonstrated. At the same time, this filter eliminates the need of balancing each sensor of the array.

Figure 8 displays a real aluminium cast with hidden anomalies. The photograph in 8 a) does not give any evidence of material anomalies. The eddy current image in 8 b) shows a bright loop of conductivity disturbance. After rework of one millimetre of the material surface even the photograph brings up inclusions of aluminium oxide.

4.2 Circular Array

The arrays are also suited for concave objects like tube inspection from the inner surface. Figure 9 displays a probe for 21 mm inner diameter tubes.

Four spring-loaded heads cover the complete circumference. Additional sensors record the wall thickness. The inspection speed reaches up to 120 mm/s. The probe contains all analogue and digital hardware for the arrays and is connected to a notebook by an extended USB cable of up to 30 m length. No additional power supply is required making the handling most comfortable.

Figure 10 shows one of the heads and its measurement in the complex plane. All sensor signals may be watched simultaneously either in the complex plane or in the C-Scan display. If necessary each sensor may be adjusted individually. The head carrier is made from titanium for minimal wear out. Flexible strips connect each head to its electronics.
The C-Scans are recorded from the x- and the y-components of all sensors. The travel distance is recorded by a cable driven wheel encoder. The encoder itself is also plugged in a USB-port of the notebook.

![Image](image_url)

**Fig. 11.** Circumferential C-Scan image of an austenitic steel tube of 21 mm inner diameter with standard calibration defects of different distance. The scan consists of 36 sensor tracks.

Figure 11 displays a 600 mm section of an austenitic steel tube of 21 mm inner diameter. Groups of standard calibration defects with different distance become visible.

5. Conclusion

Eddy current arrays offer new opportunities in surface and subsurface characterization. The arrays may be guided mechanically or manually. Their shape may be adopted to the objects surface and it is possible to provide images very easy. All advantages of eddy current method like non-contact, single sided and easy to handle are united in the array technique.

References