# Usage of Magnetic Field Sensors for Low Frequency Eddy Current Testing

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*Keywords: eddy current testing, GMR sensors, AMR sensors, inductive coils*

## 1 Introduction

In the past there were several attempts to use highly sophisticated magnetic field sensors like SQUID and Fluxgate sensors for sensitive low frequency eddy current (EC) testing to detect deep buried defects in metal parts [1–3]. Although very good results could be achieved such testing systems can hardly be used in real industrial applications because of the complexity and costs of such systems and their insufficient robustness.

This situation stimulated us to perform a comparative study of the application of traditional inductive coils with improved sensitivity and of commercially available magnetic field sensors like AMR and GMR sensors in order to produce low cost EC probes with high sensitivity, acceptable lateral resolution and with sufficiently high robustness for usage in real industrial environment.

Some results of these studies were already reported in [4]. Very promising sensor performance could be obtained by using highly sensitive inductive coils. The problem is that such sensors have to be produced by skilful specially trained operators, which is resulting in low reproducibility and low productivity. In this paper we will present new results of using commercially available GMR and AMR sensors in low frequency EC probes allowing to increase reproducibility and productivity of sensor production and maintaining the performance of EC probes on the level of those probes using highly sensitive inductive coils. We will especially concentrate on the problem how to overcome limitations arising from low dynamic range, nonlinearity and hysteresis in sensor characteristics of commercially available AMR and GMR sensors.

## 2 Methods for Comparison of Results

Dealing with high sensitive EC probes there always arises the question of objective comparison of results obtained by several groups of investigators. According to our experience there is no objective criteria. This is due to the high complexity of EC systems including excitation coils with different efficiency, different sensing elements (coils, magnetic field sensors), different probe geometry, different read out electronics, different mechanical systems for EC imaging, different post-processing of EC raw data etc. The organisation of Round Robbin tests can help to estimate the performance of EC probes of different working groups, but it seems to be quite difficult to organise such comparative tests.

In order to compare the performance of our different sensors we perform tests on various test specimens specially produced for comparative studies. This helps us to estimate the behaviour of our probes in terms of their ability to detect various test defects and in terms of lateral resolution.

To end up with this discussion we have to keep in mind that the main criteria for sensitivity of EC probes is their ability to successfully perform tests on real industrial applications.

## 3 Means for Increasing the Sensitivity of Low Frequency Eddy Current Probes

### 3.1 Inductive Pick-up Coils

Although inductive pick-up coils show decreasing sensitivity at lower frequencies they can successfully be used for sensitive low frequency EC testing. There are several means for increasing the sensitivity of inductive pick-up coils:

- larger coil diameter (limited by the desired lateral resolution)
- increased number of turns (usage of thin enamelled copper wire d = 20 μm), quite small sized pick-up coils with number of turns up to 8000 could be produced
- well compensated differential arrangements of pick-up coils for optimal usage of the dynamic range of the read out electronics
- shielding from external electromagnetic noise sources

Several sensor layouts with inductive pickup coils were tested.

The usage of inductive pickup coils has some clear advantages in comparison with magnetic field sensors:

- very good linearity, very small hysteresis and no saturation even at quite large excitation levels
- high flexibility in sensor configuration
- easy adaptation to available EC read out electronics

As mentioned above, the most significant disadvantages of inductive pickup coils are the limited reproducibility and the very time consuming technology of their production resulting in a quite high price.

### 3.2 AMR Sensors

There are commercially available quite sensitive AMR sensors (for example sensor type Philips KMZ10A1). Their field resolution at low frequencies (100÷1000 HZ) is better than 1 nT. Noise spectra of Philips KMZ10A1, GMR sensor NVE AA002-02 and of a Hall sensor NHE 220-53 were measured for comparison (see Fig. 1).

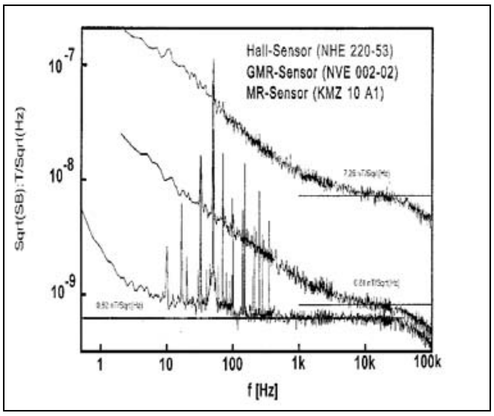



Fig. 1 – Noise spectra of Philips KMZ10A1, GMR sensor NVE AA002-02 and Hall sensor NHE 220-53

A detailed description of physical principles of sensor function of AMR sensors can be found in [5]. For usage in EC probes we have to keep in mind:

- their limited dynamic range (saturation field of ...)
- the influence of magnetic field changes in the sensitive direction of the sensor element on the demodulated signal

- their sensitivity to heterogeneity of permanent magnetic fields with direction perpendicular to the sensitive direction and in plane with the permalloy sensor stripes, which can lead to strong disturbances of sensor characteristics

To overcome this situation it is necessary:

- to use these sensors with zero detector readout electronics (negative magnetic field feedback)
- to use gradiometric arrangements of at least two sensing elements
- to stabilise the sensor characteristics by applying a stabilising magnetic field with direction perpendicular to the sensitive direction and in plane with the permalloy sensor stripes; this will slightly decrease the sensitivity of the sensing element, but it is necessary because the sensor characteristics can be disturbed both from external sources and from the EC excitation itself
- to avoid direct coupling of the excitation field to the sensing element, besides a more stable sensor behaviour this will help to use the dynamic range of the EC read out electronics more effectively

An integrated sensor module normally used for contactless current measurement is available. It includes gradiometric layout of the AMR sensing element, zero detection readout electronics with on-chip field feedback inductors and a sensor stripe premagnetisation by calibrated permanent magnets precisely placed onto the sensor module. The module has an acceptable size for integration into EC sensors. The functional scheme of the module is shown on Fig. 2. More detailed information about this module can be found in [6].

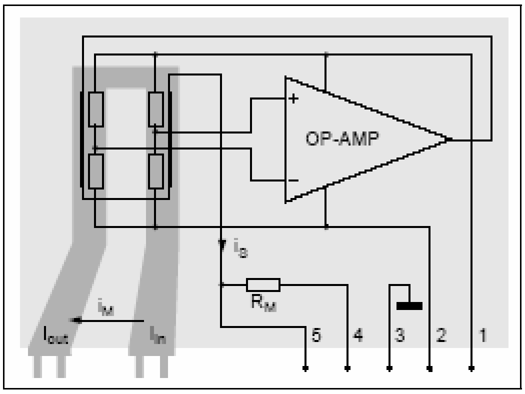



Fig. 2 – The functional scheme of the module Sensitec CMS2000 [6]

The base length of the gradiometer in this module is 3 mm. To detect deep buried defects we have to work on very low excitation frequencies. This will lead to a more and more blurred field inhomogeneity caused by the defect causing weaker field gradient. It seems to be desirable to increase the base length of the gradiometer. Modelling of this situation is required to get a clearer understanding how to optimise the gradiometer layout. It seems to be obvious to increase the base length when defects at larger depth have to be detected. We will try to solve this problem experimentally, but it is quite difficult to produce a gradiometer module on discrete elements as well compensated and balanced as on the CMS2000 module.

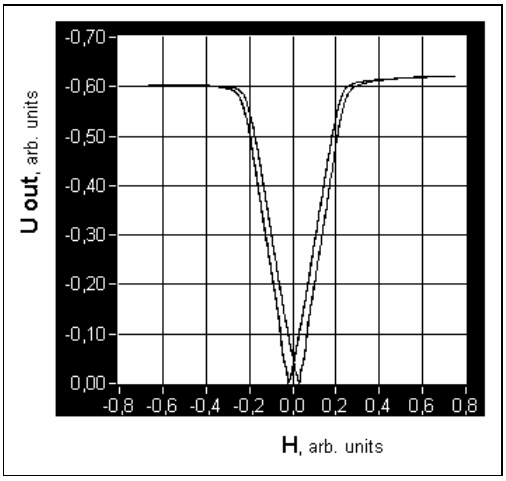
### 3.3 GMR Sensors

Very sensitive GMR sensors are available (for descriptions of physical function principles see [7]). Their sensitivity is clearly better than that of AMR sensors, but if we compare their noise limited field resolution with that of AMR sensors we will see, that at low frequencies it is one order of magnitude below that of AMR. Several restrictions have to be kept in mind when using these sensors in EC probes:

- their limited dynamic range (saturation field of ...) and quite narrow linear branch of the sensor characteristics
- the influence of magnetic field changes in the sensitive direction of the sensor element on the demodulated signal
- their V-shaped sensor characteristics, meaning that the output signal does not depend on the field direction
- hysteresis of sensor characteristics

Despite the fact that the field limited resolution of GMR sensors is below that of AMR sensors there are advantages of GMR sensors, which makes them interesting for usage in EC sensors. They are insensitive to magnetic fields perpendicular to their direction of sensitivity and their sensor characteristics will not be disturbed if they were placed to strong magnetic fields. In that way more robust EC probe behaviour in industrial noisy environment can be expected.

For usage of GMR sensors in EC probes it would be desirable to work in gradiometric arrangement and with zero detection read out electronics. Furthermore a permanent field offset has to be chosen to reduce non-linear distortions in the output signal and to maximise the AC field sensitivity.



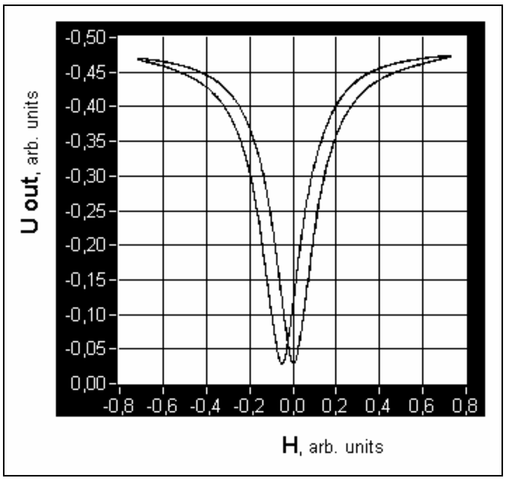




Fig. 3 – Sensor characteristics example of two commercially available GMR sensors

As we can see from the sensor characteristics of two commercially available GMR sensors (Fig. 3), it is difficult to balance them in gradiometric arrangement due to the nonlinearity of their sensor characteristics and hysteresis. In our comparative studies we first of all used single sensor configurations. As with AMR the sensors had a layout avoiding direct coupling of the excitation field to the sensing element.

## 4 Practical Results

### 4.1 Test Specimens

As we already stated comparison of the performance of different sensors should be done on well-defined test specimens. Test specimens used in our comparative study can be seen on Fig. 4.

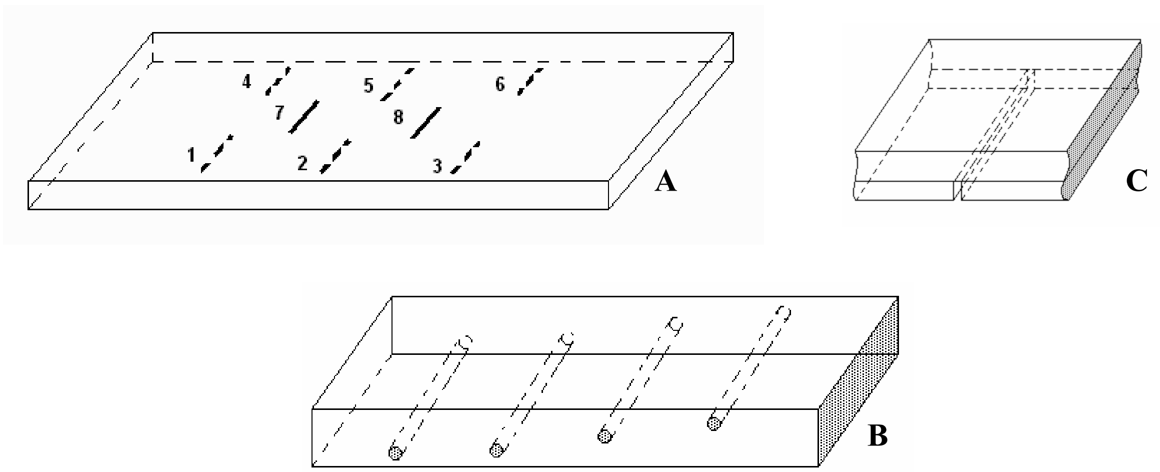



Fig. 4 – Test situation: A – aluminium test plate with slots (220x120x5 mm, slots 1÷6 on bottom, slots 7 and 8 on top; depth of the slots: 1: 3 mm; 2: 2 mm; 3: 1 mm; 4: 0,8 mm, 5: 0,6 mm; 6: 0,4 mm; 7: 0,8 mm; 8: 0,6 mm; conductivity of the alloy is 19 MS/m), B – aluminium block 410×100×25 mm with through holes ∅3 mm on depth 2,5 / 5 / 7,5 / 10 mm, C – border line between two aluminium plates through aluminium plates of various thickness placed on top

The test defects in these specimens do not really simulate any defect from real industrial applications. But they are very helpful to assess and compare the sensitivity of various EC probes produced in laboratory.

### 4.2 Experimental equipment

For read out of the EC sensors we used a PC based system with signal generator card and demodulator card. The power amplifier feeds the excitation coils in order to get sufficiently high excitation current. The demodulator card includes a power supply output for magnetic field sensors. On the input of the demodulator there is a differential amplifier with input resistance of several kΩ. So we are able to use a broad range of pick up sensors for sensing EC distribution like coils, Hall, GMR, AMR etc. The experiments normally were performed as 2D scans in order to get EC images of the specimens under test. For this purpose a simple 2D scanner with stepper motor drives was used. The lateral resolution of this X-Y-stage is approximately 0,15 mm.

### 4.3 Test results

#### 4.3.1 Inductive Coils

Best results in our comparative study could be obtained with a differential inductive EC probe using two well-compensated inductive coils with number of turns of 8000 each. Working frequencies of down to 350 Hz were used in order to achieve very high depth of penetration. Obviously such kind of sensor is very difficult to be produced and rather expensive.

Fig. 5 shows results of testing the above-described 3 test situations. All test slots on the bottom surface of the aluminium test specimen 1 (Fig. 4) could be detected (Fig. 5a). Holes parallel to the surface in the test block 2 at a depth of 15 mm can be seen on EC images of this test block (Fig. 5b). The borderline of 2 aluminium plates could be detected through another aluminium plate on top with a thickness of 15 mm (Fig. 5c).

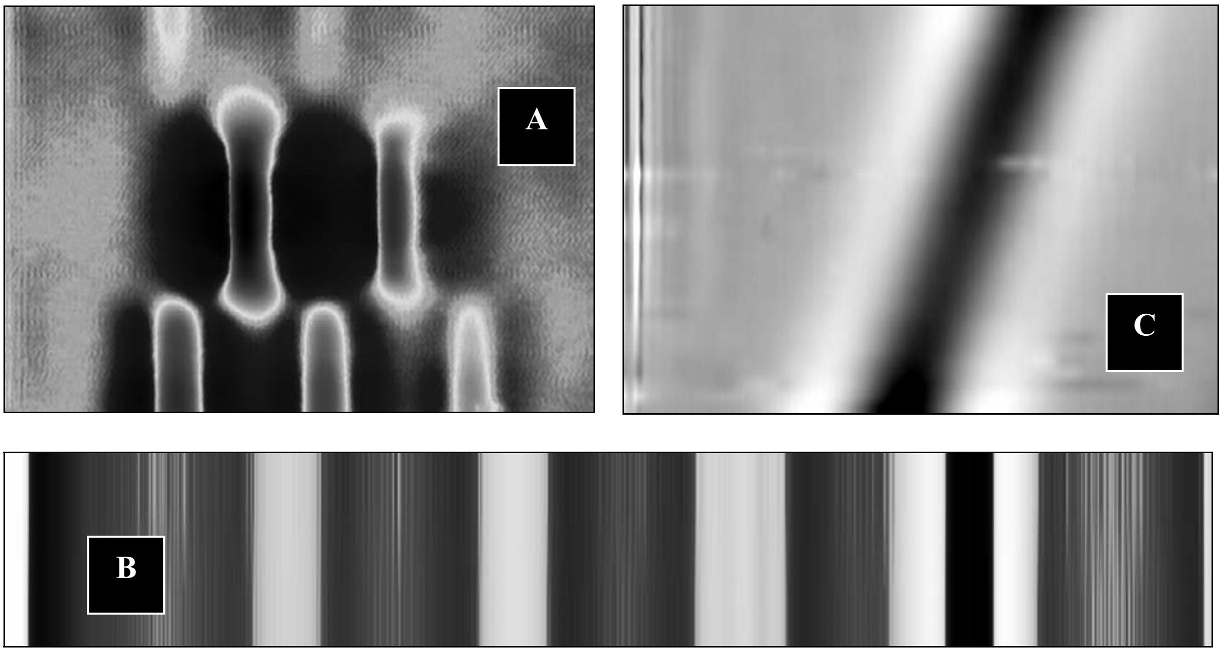



Fig. 5 – Testing results for situations on Fig. 4 in case of inductive coils usage

### 4.3.2 AMR modules (CMS2000)

These sensor modules were used in our first attempt to integrate industrial available magnetic field sensors into EC probes. Due to some specifics of these modules we obtained rather good but not overwhelming results, which were much improved then by usage of GMR and inductive sensors. Recently we tried to use these modules with standard EC equipment from Rohmann (Elotest B1) in a special test arrangement. It seems possible to significantly improve the performance of EC probes with CMS2000 and we will continue to get maximum performance out of these sensor modules.

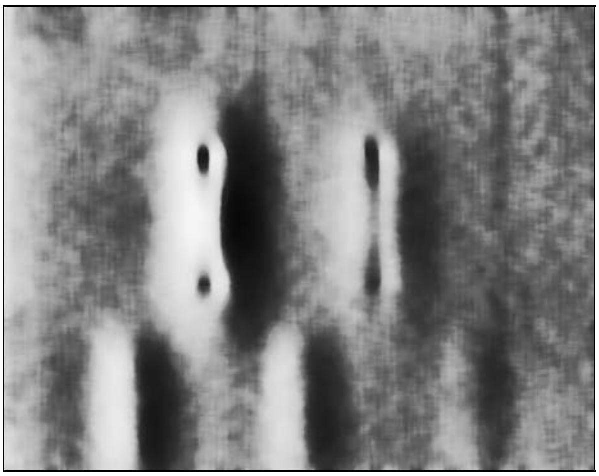


Fig. 6 – Testing results for situation A on Fig. 4 in case of AMR modules usage

On Fig. 6 we demonstrate our first results obtained on the test specimen with slots (test situation A on Fig. 4).

#### 4.3.3 GMR Sensors

Good results could be obtained by using less sensitive GMR sensors in absolute probe arrangement. Gradiometer configurations are under test now and probably may improve these results. The attempt to use the more sensitive sensor type was not very successful yet, probably because of their very non-linear behaviour.

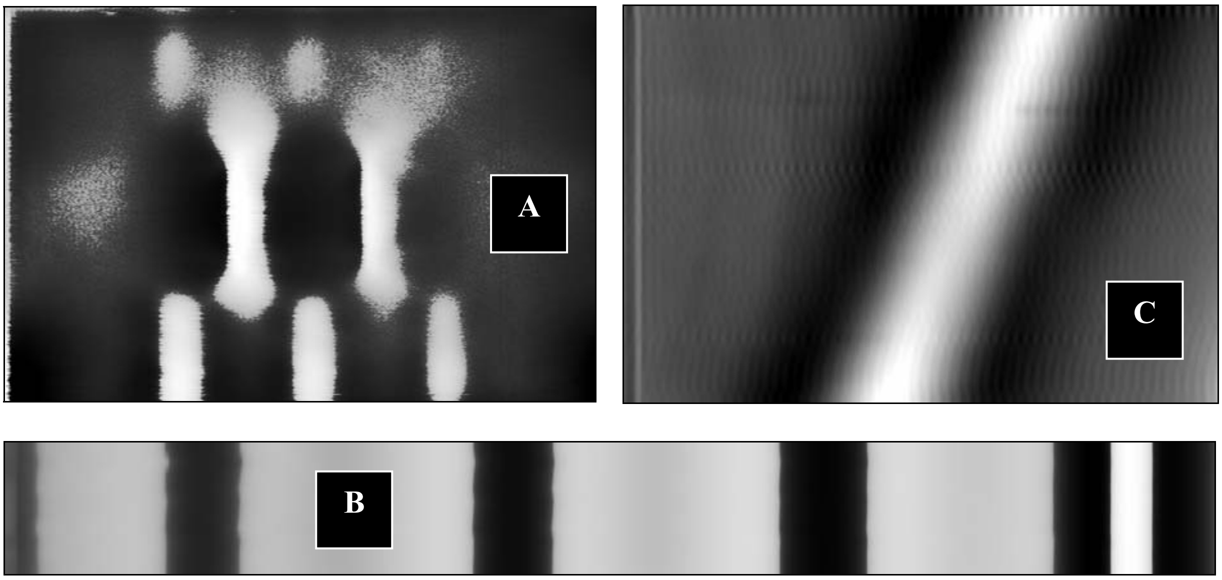



Fig. 7 – Testing results for situations on Fig. 4 in case of GMR sensors usage

Fig. 7 shows results of testing the above-described 3 test situations in case of GMR sensors usage. 5 out of 6 test slots on the bottom surface of the aluminium test specimen 1 could be detected (Fig. 7a). Through holes in the test block 2 at a depth of 15 mm can be seen on EC images of this test block (Fig. 7b). The borderline of 2 aluminium plates could be detected through another aluminium plate on top with a thickness of 15 mm (Fig, 7c).

## 5 Conclusion and outlook

Inductive EC probes allow performing low frequency EC testing with very high sensitivity. But such probes are rather difficult to produce. The reproducibility of their production is quite low.

Usage of GMR sensors allowed obtaining similar results even with a slightly better lateral resolution than that of inductive probes. We hope to improve sensor performance by gradiometer configuration and integrating more sensitive sensor types.

Concerning CMS2000 AMR sensor modules we will try to use them with standard EC Amplifier Elotest B1. Probably this will help to improve their performance in EC probes.

## 6 Acknowledgement

These works were supported by the German Federal Ministry BMWA in programs „Support of R/D and innovation in SME...“ grant № 1105/05 and “Innovation and scientific exchange” grant № P 0019602 PBN3B. We also would like to thank Sensitec GmbH company for advice and usage of CMS2000 sensor modules.

## 7 References

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